Soil Pressure and Deformation Analysis of Small Size Deep Foundation Pit

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Abstract. In this paper, the influence of space effect on soil pressure and deformation of deep foundation pit was considered, and the finite soil pressure calculation model was established. The soil pressure of deep foundation pit was calculated by assuming the slip surface and using the finite soil limit equilibrium theory. Then, PLAXIS 3D finite element software was used to establish finite element models of different plane sizes and depths. The distribution regulation of side wall soil pressure and deformation of deep foundation pit was calculated. Finally, the results of finite soil pressure calculation was compared with finite element method. The results shown that: The soil pressure of small deep foundation pit was affected by space effect, and the soil pressure and deformation decrease significantly along the foundation pit depth. Shear fracture Angle was related to the ratio of width to depth of foundation pit, and it was no longer a constant value of $45^\circ + \phi/2$. Therefore, the spatial effect should be considered in the calculation of soil pressure of small deep foundation pit. The research results can provide some guidance for the design and calculation of similar small size deep foundation pit.

1. Introduction
With the continuous acceleration of urbanization in China, a large number of small size deep foundation pit projects, such as pipe jacking shaft and subway shaft, have encountered in municipal engineering construction. The main characteristics of this kind of deep foundation pit had small excavation section size, large depth, complex surrounding environment. All these factors bring some difficulties to the excavation and support of foundation pit. In the design of foundation pit support, the distribution of earth pressure along the depth of foundation pit should analysis. Since the small size deep foundation pit was obviously affected by size effect, the calculation of earth pressure by traditional method was inevitably different from the actual earth pressure. Therefore, it had great engineering and practical significance to study the soil pressure calculation and deformation distribution regulation of small deep foundation pit.

At present, some scholars have studied the earth pressure distribution of caisson working well, and the calculation formula of earth pressure and deformation distribution regulation under different conditions had be proposed [1-2]. Through indoor model test and FLAC 3D numerical simulation, the spatial distribution of earth pressure behind pit wall and the influence of earth pressure Angle effect on internal force of retaining structure were studied [3]. The pit Angle effect and its main influencing factors of retaining structure deformation were studied by using FLAC-3D software, and a calculation method of retaining structure deformation considering pit Angle effect was proposed [4]. The
influence of different width-depth ratio on foundation pit deformation and the control measures based on scale effect were analysed [5]. With the development of earth pressure research, different earth pressure calculation methods were developed according to actual engineering conditions [6-8]. Considering the friction force between the wall back and soil, the formula for calculating Rankine passive earth pressure of vertical retaining wall and inverting retaining wall was derived by using limit equilibrium theory [9]. The relation between friction Angle and relative displacement of rigid retaining wall in non-limit state was deduced, and the calculation formula of active earth pressure in non-limit state was obtained [10]. By establishing the relationship between the internal friction Angle, cohesion and displacement of finite viscous soil, the force analysis was carried out by horizontal stratification method [11]. Based on the theory of limit equilibrium and the assumption of plane sliding, the formula for calculating the active earth pressure of finite soil was obtained considering the cohesion of soil [12]. The active earth pressure of retaining wall adjacent to bedrock was studied by PLAXIS finite element software. The earth pressure of retaining wall under different dip angles of bedrock was calculated and analysed [13]. Based on the assumption that a circular arc earth arch was formed in the soil, a formula for calculating the active earth pressure strength of finite non-viscous fill was obtained by using the equilibrium condition of horizontal micro-element force [14]. The formula for calculating soil pressure in finite range was derived by limit analysis method. It was concluded that there was a certain difference between the finite earth pressure obtained by traditional Rankine earth pressure theory and finite analysis method [15].

In this paper, based on the influence of finite soil on sliding crack surface, a calculation model of soil pressure for small deep foundation pit was established. Based on the limit equilibrium theory and assuming that the sliding surface was a plane, the formula for calculating active earth pressure of small size deep foundation pit was derived. Then PLAXIS 3D finite element software was used to establish calculation models with different plane sizes and depths. Finite element calculation of soil pressure and deformation was carried out. The distribution of soil pressure along the depth and width was analyzed by comparing the results of finite element calculation with Rankine active earth pressure theory. The research results can provide a basis for the calculation of soil pressure and the optimization of retaining structure design of small size deep foundation pit.

2. Finite Soil Pressure Calculation

At present, the earth pressure theory of Rankine and Coulomb was widely used in geotechnical engineering. The application condition of the theory was that the soil behind the wall was assumed to be a semi-infinite space. Therefore, the above theory has a large error in the calculation of soil pressure of deep foundation pit with a small width to depth ratio. When there was an existing building basement or a small deep foundation pit near the excavation (as shown in figure 1), the shear fracture Angle θ of the sliding surface of the side wall of the excavation will no longer be 45°+φ/2. In this case, it was obviously problematic to apply the classical Rankine or Coulomb earth pressure theory to calculate the soil pressure of the side wall of foundation pit.

![Diagram](image)

(a) Affected by existing buildings (b) Affected by spatial effects

**Figure 1.** Diagram of slippage surface with limited soils.
2.1. Calculation and Analysis of Finite Soil Pressure in Foundation Pit

Foundation pit belongs to spatial stress system, and its stress and deformation have obvious spatial effect. The plane size, excavation depth, soil distribution and geometric shape of excavation have direct influence on the calculation and distribution of soil pressure on the side wall. According to the engineering experience, when the traditional method was used for the support design and calculate of pipe jacking Wells, the earth pressure value was too large, which led to the large section and reinforcement of the support structure. The monitoring data often deviate from the calculation. The results shown that the soil pressure and deformation regulation of foundation pit with different plane size and depth were obviously different due to the size effect of foundation pit. Therefore, this paper mainly consider the deep foundation pit with excavation depth greater than 1.0 times the excavation plane size, and calculates the magnitude and distribution of earth pressure along the depth direction of the foundation pit. The three-dimensional finite element calculation of soil pressure along the depth and width of foundation pit was carried out by using finite element mode.

2.2. The Basic Assumptions

In order to simplify the calculation, the following assumptions were made:

(1) Shear failure surface was plane;
(2) The influence of groundwater was not considered;
(3) Soil was considered as an ideal elastoplastic material and only a single layer of soil was considered. The friction between soil and support structure was not considered;
(4) The top load around the foundation pit was not considered;
(5) The soil behind the wall was horizontal and the back of the wall was vertical and smooth.

2.3. Establishment of Computational Model

For the small-size deep foundation pit as shown in Fig1 (b), the shear slip surface failure model was established as shown in figure 2. The slip Angle $\theta$ was assumed to be a variable affected by the plane size and excavation depth of the foundation pit. Then the sliding soil ABC was in the ultimate equilibrium state under the action of the support structure resistance E, the sliding weight force W and the force R of the lower soil on the sliding body. The relationship between the resistance of supporting structure and the earth pressure exerted by sliding body on the supporting structure was acting force and reaction force. R was related to the internal friction Angle $\varphi$ of the soil. The Angle between the direction of the acting force R and the normal line of the slip surface was $\varphi$, and the magnitude was unknown.

![Figure 2. Diagram of soil pressure calculation.](image)

2.4. Soil Pressure Calculation of Small Size Deep Foundation Pit

As shown in figure 2, the following formula can be obtained according to the limit equilibrium principle and the triangle sine theorem:

$$\frac{E}{\sin(\theta - \varphi)} = \frac{W}{\sin[90^\circ - (\theta - \varphi)]}$$  (1)
The calculation expression of earth pressure can be obtained from the above formula as follows:

\[ E = \frac{W \sin(\theta - \varphi)}{\cos(\theta - \varphi)} = W \tan(\theta - \varphi) \]  

(2)

Gravity \( W \) of the triangular sliding body ABC per meter of soil can be expressed as:

\[ W = \gamma V = \gamma \cdot \frac{1}{2} H \cdot \frac{H}{\tan \theta} = \frac{\gamma H^2}{2 \tan \theta} \]  

(3)

Substitute (3) into Equation (2) to obtain:

\[ E_a = f(\theta, \varphi, \gamma, H) = \gamma V \tan(\theta - \varphi) = \frac{1}{2} \gamma H^2 \tan(\theta - \varphi) \]  

(4)

In the above types, \( \gamma \) was the weight of soil, and \( \varphi \) was the internal friction Angle of soil. \( H \) was the excavation depth of the foundation pit, and \( \theta \) was the Angle between the sliding crack surface and the horizontal surface.

According to Equation (4), active earth pressure \( E_a \) was related to shear fracture Angle \( \theta \), foundation pit depth and soil shear strength parameters. To calculate earth pressure using limit equilibrium theory, the rupture Angle should be determined first. In this paper, the influence of space effect on soil pressure of foundation pit was considered, and the failure Angle was assumed to be a variable affected by the ratio of width to depth of foundation pit, rather than the traditional \( 45^\circ + \varphi/2 \). Therefore, the earth pressure calculation of small size deep foundation pit affected by space effect can be optimized according to the following finite element calculation results and formula (4) to make the calculation results more reasonable.

When the pit depth \( H \) was constant and the soil parameters was known, the active earth pressure \( E \) was only the function of the fracture Angle \( \theta \). According to the limit equilibrium principle, when \( dE/d\theta=0 \), the extreme value of the active earth pressure \( E \) can be obtained. The calculated result was the active earth pressure under this condition. By substituting it into the above equation, the corresponding shear fracture Angle \( \theta \) value can also be obtained. The derivative of Equation (4) can be obtained as follows:

\[ \frac{dE_a}{d\theta} = \frac{\gamma H^2 \sec^2(\theta - \varphi) \tan \theta - \tan(\theta - \varphi) \sec^2 \theta}{2 \tan^2 \theta} \]  

(5)

If \( dE/d\theta=0 \), the expression of \( \theta \) can be obtained as follows:

\[ \theta' = f(\varphi, \gamma, H) \]  

(6)

In order to explain the rationality of the above calculation process, a special case was considered. When the plane size of foundation pit was large and the size effect was not taken into account. Rankine or Coulomb active earth-moving pressure theory was satisfied according to fracture Angle \( \theta \). When \( \theta=45^\circ + \varphi/2 \), it can be obtained by substituting it into Equation (4):

\[ E_a = \frac{1}{2} \gamma H^2 \tan(45^\circ + \varphi/2 - \varphi) = \frac{1}{2} \gamma H^2 \tan(45^\circ + \varphi/2 - \varphi) = \frac{1}{2} \gamma H^2 \cot(45^\circ + \varphi/2) = \frac{1}{2} \gamma H^2 \tan(45^\circ - \varphi/2) \]  

Put the active earth pressure coefficient \( K_a \) into the equation above, and get: \( E_a = \frac{1}{2} \gamma H^2 K_a \)

The above formula was the calculation formula of active earth pressure resultant force obtained by Rankine earth pressure theory. Therefore, it was reasonable to use the above formula to calculate earth pressure of small size deep foundation pit affected by size effect.

The above calculation process was two dimensional plane calculation with fracture Angle \( \theta \) as the variable. The theoretical calculation results cannot reflect the influence of foundation pit width on
earth pressure. Therefore, it was necessary to combine three-dimensional calculation or model test to calculate the soil pressure of small deep foundation pit. The model test was time-consuming and labor-intensive, so the model test should be carried out on the basis of certain research. Therefore, this paper mainly calculated the earth pressure and deformation of small size deep foundation pit by establishing a three-dimensional finite element model, and the change distribution regulation was obtained.

3. Finite Element Analysis Model

Combined with engineering experience and existing studies, the spatial effect had a significant impact on the soil pressure of foundation pit. In order to correspond to the above calculation in this paper, firstly, considering the sand layer of non-cohesive soil, foundation pit models with different width-depth ratios was established by using PLAXIS 3D finite element software. The lateral earth pressure and lateral movement of foundation pit were calculated. According to the calculated results, the relationship between the soil pressure and the ratio of width to depth of foundation pit was analyzed. By comparing the finite element calculation results with the classical Rankine earth pressure calculation results, the influence of foundation pit size effect on the size and distribution of soil pressure of small deep foundation pit was obtained.

3.1. Soil Pressure Calculation of Small Size Deep Foundation Pit

The constitutive model of soil had great influence on the calculation of soil pressure. This paper mainly carried out the simulation calculation of the excavation problem of foundation pit engineering, so the soil hardening model was adopted in the finite element calculation of soil constitutive relation. The model can consider the change of soil stiffness during initial loading and unloading and reloading, so it was suitable for the simulation calculation of foundation pit excavation. The main soil parameters were shown in table 1.

| soil   | γ(kN/m³) | E(MPa) | c(kPa) | φ(°) |
|--------|----------|--------|--------|------|
| sand   | 16.8     | 40     | 2      | 35   |

3.2. Soil Pressure Calculation of Small Size Deep Foundation Pit

Foundation pit engineering was a temporary project, so the finite element stress calculation was set as the condition of no drainage. In order to eliminate the influence of model size on calculation results, the model plane size and model height were 3 times of the excavation depth. Finite element model of small size deep foundation pit was established as shown in figure 3.

Figure 3. Finite element calculation model of foundation pit.

In order to analysis and explain the influence of size effect on soil pressure and lateral movement of deep foundation pit, six three-dimensional finite element models with different plane sizes and depths were established in this paper, and the calculated results were compared and analyzed. The
finite element models size were as follows: (1) Plane dimension: 8m×8m, 12m×12m, 50m×50m; (2) Depth of foundation pit: 8m, 12m.

3.3. Parameter Setting of Support Structure
In the calculation models, the supporting structure was simulated by 6-node plate element converted according to the equivalent stiffness. The soil-structure interaction was simulated by 12-node interface element. The interface strength was connected with the soil strength by setting the interface reduction coefficient. Based on previous experience, the interface reduction coefficient was set as 0.70. By setting reduction coefficient, both strength and stiffness were reduced by default in finite element calculation. Then, the interface cohesion and internal friction Angle were calculated according to Equation (7).

\[ c_i = 0.70c_{soil}; \quad \tan \varphi = 0.70 \tan \varphi_{soil} \]  

Parameter setting of plate element in the model was calculated as follows:

\[ D = 0.838d \sqrt{\frac{1}{1+t/d}} = 0.838 \times 0.8 \sqrt{\frac{1}{1+1.2/0.8}} = 0.424 \text{m} \]

\[ EA = E_cD = 1.5\times10^7 \times 0.424 = 6.36 \times 10^6 \text{kN/m} \]

\[ EI = \frac{1}{12} E_cD^3 = 9.53 \times 10^4 \text{kN} \cdot \text{m}^2/\text{m} \]

4. Analysis of Finite Element Calculation Results

4.1. Spatial Distribution of Horizontal Lateral Movement of Foundation Pit
The three-dimensional finite element models of different sizes were respectively calculated. The horizontal lateral distribution of the calculation results with the plane size of 12m×12m and depth of 12m at the same depth was shown in figure 4. The shadow width in the horizontal lateral movement cloud image only represented the relative lateral movement at the same depth. The distribution rule of horizontal lateral movement along the depth of foundation pit with different plane dimensions and depth of 12m shown in figure 5.

As shown in figure 4, the horizontal displacement of the side wall along the width direction of the foundation pit at different excavation depths roughly presented a broken line distribution. According to the calculation results, the maximum displacements at sections of different pit depths were as follows: 31 mm, 43 mm, 49 mm, 66 mm, 69 mm, 62 mm. In the same foundation pit depth plane, the maximum displacement roughly appeared in the middle of each edge, and the minimum displacement appeared in the pit Angle. It shown that the horizontal lateral movement of foundation pit was obviously influenced by the size effect of foundation pit and adjacent supporting structure. According to the comparison results of horizontal lateral displacement of foundation pits of different plane sizes in this paper, it was also found that the larger the width to depth ratio of foundation pits, the more obvious the spatial effect.

(a)z=-12 (m)  
(b)z=-10 (m)  
(c)z=-8 (m)
As shown in figure 5, along the direction of foundation pit depth, the horizontal lateral movement along the foundation pit depth presents a gradually decreasing distribution regulation. There was obvious difference in displacement of foundation pit with different plane dimensions. The maximum displacements all appeared at approximately the top of the pit, and the variation regulation was consistent with the deformation law of the cantilever rigid support structure, which also indicated the rationality of the calculated results. The maximum displacements of the three models in figure 5 were 0.035m, 0.069m and 0.107m, respectively. The comparison results also shown that the displacement of foundation pit with the same depth decreased obviously with the decrease of plane size. The main reason was that under the influence of foundation pit size effect, the deformation of adjacent side wall of small deep foundation pit had a certain mutual restraint. The distribution of earth pressure was obviously different from traditional semi-infinite space calculation. Finally, the horizontal displacement of foundation pit decreased obviously. It shown that the size effect of foundation pit had a significant effect on deformation.

When the plane size of the foundation pit was smaller than the pit depth, although the plane size decreased slightly, the horizontal lateral movement had an obvious downward trend. This shown that the size effect was quite obvious, which was beneficial to the stability of the foundation pit. In the support design of municipal small size deep foundation pit, the displacement can be appropriately reduced when the traditional method was used to calculate.

4.2. Spatial Distribution of Horizontal Lateral Movement of Foundation Pit

Neither the classical earth pressure theory nor the two-dimensional finite element calculation can consider the spatial effect of foundation pit on the foundation pit deformation and earth pressure distribution. In order to analysis and explain the size effect of small size deep foundation pit deformation and earth pressure distribution, PLAXIS 3D, PLAXIS 2D and classic Rankine active
earth pressure theory were respectively used to calculate the earth pressure on the side wall of foundation pit. The calculation results were shown in table 2.

Rankine active earth pressure can be calculated as follows:

\[ e_a = \gamma HK_a = \gamma H \tan^2(45 - \varphi / 2) \]

(8)

Table 2. Calculation results of normal effective stress of base.

| Plane dimension (m) | Depth /m | PLAXIS 3D /kN/m² | PLAXIS 2D /kN/m² | Rankine Theory /kN/m² |
|--------------------|----------|------------------|------------------|----------------------|
| 8×8                | 8        | 49.42            | 61.69            | 58.88                |
| 12×12              | 8        | 50.90            | 61.69            | 58.88                |
| 50×50              | 8        | 60.78            | 61.69            | 58.88                |
| 8×8                | 12       | 72.40            | 90.36            | 88.30                |
| 12×12              | 12       | 75.50            | 90.36            | 88.30                |
| 50×50              | 12       | 97.20            | 90.36            | 88.30                |

As seen from the calculation results in table 2, when the plane size of foundation pit was close to or smaller than the excavation depth, the finite element calculation results of the normal effective stress of the foundation were significantly smaller than the theoretical calculation value of Rankine earth pressure. When the plane size was much larger than the excavation depth, the finite element calculation results were close to those of Rankine earth pressure. The results indicated that due to the size effect, the surrounding soil deformation caused by the small size deep excavation was small and the influence range was reduced, which lead to the change of the potential failure angle and the reduction of side wall earth pressure. It was also proved that the calculation of soil pressure of small deep foundation pit was considered as finite soil.

4.3. Spatial Distribution of Horizontal Lateral Movement of Foundation Pit

In order to analysis the influence of size effect of foundation pit with different plane size on the stress of supporting structure, different foundation pit models were calculated respectively. According to the calculation results, the cloud diagram of the variation regulation of the normal force of the supporting structure along the horizontal section at a depth of 8m in different models was shown in figure 6.

![Figure 6. Normal force diagram of support structure.](image)

As shown in figure 6, the spatial effect of foundation pit had an obvious influence on the stress situation and distribution of supporting structure. The maximum normal force of the three model support structures at 8m pit depth was 100.9kN /m, 89.42kN /m and 81.78kN /m, respectively. The distribution regulation of normal stress on supporting structure was large pit Angle and small in the middle. The maximum normal stress of supporting structure appeared in the corner of foundation pit, and the minimum stress appeared in the middle of foundation pit. The main reason was that: affected by the spatial effect, the pit corner position was like adding a slanting brace inside the supporting structure, which inhibited the deformation of the supporting structure. In the middle position, the
restraining effect weaken, the displacement of supporting structure increased, and the active earth pressure decreases. This phenomenon was also consistent with the above horizontal lateral displacement results, indicating the rationality of the calculation results.

5. Conclusions
In this paper, the earth pressure of small deep foundation pit was solved by considering the influence of space effect on the slip angle of foundation pit. Three finite element models of foundation pit with different plane dimensions were established to calculate the soil pressure and deformation. The influence of space effect on soil pressure and deformation of foundation pit was compared and analyzed. The main conclusions were as follows.

1) The soil pressure of small deep foundation pit was affected by the space effect, and the shear fracture angle cannot be calculated as $45^\circ + \phi/2$. It was affected by the depth and plane size of the foundation pit.

Along the horizontal direction, the maximum horizontal lateral movement occurred in the middle of each side, and the minimum horizontal lateral movement occurred in the pit angle. It shown that the larger the ratio of depth to width, the more obvious of spatial effect.

3) Along the direction of foundation pit depth, the horizontal lateral movement presented a gradually decreasing distribution regulation. The calculation results of different models were quite different. It shown that the deformation of adjacent side wall of small deep foundation pit was mutually restricted by the spatial effect of foundation pit. The spatial effect of foundation pit had a direct and significant influence on the earth pressure and deformation.

4) The size and distribution of soil pressure on the side wall of foundation pit were closely related to the plane size of foundation pit. The actual earth pressure of small size deep foundation pit was less than that of Rankine active earth pressure. The two dimensional finite element calculation of foundation pit earth pressure was close to that of Rankine theory. It shown that the small size deep foundation pit can be calculated according to the theory of finite soil pressure.

References
[1] Ying H W, Liang W P. 2018 Spatial Active Earth Pressure Against Translating Retaining Walls in Square Shaft Excavations [J] Journal of Shanghai Jiao Tong University 11 (52) 1459-1566.
[2] Wei G, Xu R Q, Gong C. 2004 Research on earth counterforce calculation for circular caisson working well during pipe jacking project [J] Journal of Zhejiang University (Engineering Science) 11 (38) 1474-1478.
[3] Jia M C, Yang X H, Ye J Z. 2016 Corner effect of active earth pressure for small-sized excavation [J] Journal of harbin institute of technology 11 (48) 95-102.
[4] Wang X W, Tong H W. 2011 Deformation Calculation of Supporting Structure Considering Deep Excavation Pit Corner [J] Chinese Journal of Underground Space and Engineering 3 (7) 479-484.
[5] Wang H, Jia M C, Yang X H. 2016 Influence of size effect on deformation of foundation pit and control measures [J] Sichuan Building Science 1 (42) 69-74.
[6] Xie M X, Zheng J J, Cao W Z. 2019 Study of active earth pressure against embankment retaining wall of limited backfill [J] J Huazhong Univ of Sci & Tech (Natural Science Edition) 2 (47) 1-6.
[7] Xie T, Luo Q, Zhang L. 2018 Relation of Wall Displacement earth Pressure from Active to Passive State [J] China Journal of Highway and Transport 2 (31) 181-190.
[8] Wang D J, Tang H M, Wu Q. 2016 Method for Calculating Active Earth Pressure of Unsaturated Soil Considering Arching Effect [J] Journal of Yangtze River Scientific Research Institute 8 (33) 69-74.
[9] Zhu Y P, Wei P Y, Ma X R. 2019 Exploration of Rankine Passive Earth Pressure Based on Sliding-cracking Surface of the Soil Behind the Wall [J] Science Technology and Engineering 8 (19) 225-230.
[10] Huang B, Yang H, He X M. 2007 Research on Active Earth Pressure under Non-limit State [J] Journal of Yangtze River Scientific Research Institute 4 46-49.

[11] Zhao X, Ma S Z, Tang W M. 2017 A Computation Method for Earth Pressure of Limited Soils under Non-limit State [J] Journal of Yangtze River Scientific Research Institute 12 (34) 89-93.

[12] Ma P, Qin S Q, Qian H T 2008 Calculation of active earth pressure for limited soils [J] Chinese Journal of Rock Mechanics and Engineering 27(S1) 3070-3074.

[13] Fan C C, Fang Y S 2010 Numerical solution of active earth pressures on rigid retaining walls built near rock faces [J] Computer and Geotechnics 6 (37) 1023-1029.

[14] Liu Z Y 2018 Active Earth Pressure Calculation of Rigid Retaining Walls with Limited Granular Backfill Space [J] China journal of Highway and transport 2 (31) 154-164.

[15] Gao Y L 2001 Calculation of finite earth pressure by limit analysis [J] Building Structures 8 (31) 66-68.