Analysis of Stress Path in the Whole Process of Foundation Pit Excavation and Heavy Lifting

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Abstract. Based on a foundation pit in Jinan City, this paper uses ABAQUS to conduct numerical simulations based on actual construction on site. Considering the rotation of the main stress axis, the corresponding stress path and discharge law are obtained in different affecting areas. The results show that whether inside or outside the pit, the horizontal and vertical stresses decrease with the excavation of the foundation pit, but the amount of soil unloading inside the pit is much greater than outside the pit; the passive zone \( p_\bar{p} \) in the pit keeps decreasing, and \( q_\bar{q} \) keeps increasing. The range of rotation angle of large principal stress is 0~89.39°, the transition zone outside the pit and the active zone \( p_\bar{p} \) keep decreasing, while \( q_\bar{q} \) is almost unchanged, the change range is 0~44.78°, and all rotate clockwise. When a crane load is applied to the side of the pit, it will have a greater impact on the soil elements in the active zone directly below the load outside the pit. The principal stress rotation angle will rotate counterclockwise, which is about 1/3 of the final deflection angle. The impact is relatively small.

1. Introduction
Many scholars at home and abroad have studied the stress-strain relationship of unused stress paths. Zeng Guoxi[1] The initial tangent slope of the normalized stress-strain has a good linear relationship with the stress path parameter \( \alpha \), and he derives the modulus equations under two different stress path conditions. Sun Yuesong[2] conducted a triaxial test study of different stress paths and stress history. The stress-strain curves under different stress paths are completely different lines. Liu Guobin[3] studied the stress paths and unloading deformation modulus expressions of several typical soft soils in Shanghai area based on a large number of stress path tests. Wu Hongwei[4] compared the stress path observed in the field with the stress path obtained from the indoor test and found that the stress path in front of the continuous wall is the same as that of the indoor undrained elongation test, while the stress path behind the wall is the same as that of the indoor undrained compression test. The results are also different. He Shixiu[5] simulated the stress path of the soil around the excavation pit through true triaxial tests and found that due to the influence of the intermediate principal stress, the stress-strain curve becomes steeper, the ultimate strain becomes smaller, and the soil can withstand greater failure stress. Liu Yuanxue and Zheng Yingren[6] used matrix theory to analyze the stress increment characteristics of the principal stress axis rotation, divided the stress increment into a rotating part, and a common principal axis part, and established a generalized plastic model considering the principal stress axis rotation.
Aiming at the stress-strain relationship of the complex stress path, this paper uses the finite element numerical simulation software ABAQUS to simulate foundation pit excavation and crane load according to engineering examples, obtain the stress path of the soil element at different positions in different construction stages, and study its change law, providing a reference for the indoor test to simulate the stress path of the field soil element.

2. Stress path analysis of foundation pit excavation
When analyzing the mechanical properties of soil, the stress path is usually used to describe the stress change of the soil element under the action of external load[8].

This paper uses three three-dimensional parameters to describe the change of stress state at a point in a two-dimensional plane. In order to better express the influence of different stress components on the stress path, the simplified medium principal stress is equal to the small principal stress, assuming that the stress state of a certain point in the soil is \( \{ \sigma \} = \{ \sigma_x, \sigma_y, \tau_{xy} \} \). Then there are:

\[
p = \frac{1}{3}(\sigma_1 + 2\sigma_3) = \frac{1}{3}(\sigma_x + 2\sigma_y)
\]

\[
q = \frac{1}{2}(\sigma_1 - \sigma_3) = \left[\left(\frac{\sigma_y - \sigma_x}{2}\right)^2 + \tau_{xy}^2\right]^{1/2}
\]

\[
\alpha = \arctan\left(\frac{\tau_{xy}}{\sigma_y - \sigma_x}\right)
\]

Where: \( p \) is the average compressive stress, \( q \) is the generalized shear stress, \( \alpha \) is the rotation angle of the large principal stress, defined as the angle between the large principal stress and the vertical direction, and the value of \( \alpha \) for clockwise deflection is positive[9], as shown in Figure 2.

3. Numerical simulation

3.1 Model establishment and constitutive selection
In this paper, the standard section of the foundation pit is selected as the research object, and simplified simulation is carried out according to the actual construction on site. The soil is simulated by a two-dimensional variable shell element, the ground wall and support are simulated by a two-dimensional line element, and the contact type between the ground wall and the support, and the ground wall and the soil are all Tie. For specific simulation conditions, see below Table 1.

| Working procedure | Content | Working procedure | Content |
|-------------------|---------|-------------------|---------|
| 1                 | Ground stress balance | 8             | Erection of the third support |
| 2                 | Diaphragm Wall         | 9             | Excavation of the fourth layer soil |
3.2 Soil element selection

Select 6 typical soil elements for analysis, draw the stress path and use the $\bar{p}-\bar{q}-\alpha$ three-dimensional coordinates to analyze the stress path[7]. Reference point selection and coordinates are detailed in Figure 3.

4. Stress path analysis

4.1 Active zone

Soil unit A1, A2 is located in the active area behind the support wall, as shown in Figure 4, as the pit is dug, $\bar{p}$ is decreasing, $\bar{q}$ is increasing, the rotation angle of the large main stress is increasing, and are clockwise rotation, the range of change is 0 to 29.95 degrees. The rotation angle of the two main stresses is mainly influenced by the first and second excavation stages, and then changes slowly. When the crane load is applied, the rotation angle of the large main stress decreases sharply because point A1 is directly below the load, and the values of $\bar{p}$ and $\bar{q}$ both increase, but the soil unit A2 is relatively not affected.
It can be seen from Figure 5 that the blue line is the large principal stress and the light green line is the small principal stress. The deflection angle of the principal stress of the soil elements A1 and A2 in the final construction stage is very small, and the deflection angle is within 30°.

4.2 Transition zone

The soil element is B1, B2 located in the transition area of foundation pit excavation. As shown in figure 6, the \( \bar{p} \) decreases with the excavation of the foundation pit, but the range of \( \bar{q} \) values are very small, almost unchanged, and the rotation angle of large principal stress increases clockwise. The rotation angle of two-point principal stress increases linearly in the excavation stage and decreases only slightly in the crane load stage. The deflection angle is about 42° from figure 7 to the relationship between the principal stress position of soil element B1, B2 in the final construction stage.

4.3 Passive zone

The soil elements C1 and C2 are located in the transition zone, as shown in Figure 8, with the excavation of the base pit, \( \bar{p} \) is decreasing, \( \bar{q} \) is increasing, but the \( \bar{q} \) rate of change is significantly greater than, \( \bar{p} \), the main stress. The rotation angle change range is 0 to 89.39, all clockwise rotation, the first and second excavation stage has little impact, but in the third and fourth excavation stage, the main stress rotation angle has step-by-step growth, lack of intermediate transition stage, The fifth excavation stage and the application of crane load tend to level, the final large principal stress deflection angle of C1 is slightly larger than C2 in Figure 9, this is due to the removal of the upper soil, the main stress direction of the soil unit is similar to the horizontal direction, it can be seen that the excavation and unloading load on the pit bottom soil stress changes have a huge impact, so at this time stress changes on the soil characteristics, otherwise the results of the calculation have a greater impact.
5. Analysis of the influence range of crane load

According to the stress path, when the crane load acts, the large principal stress will rotate anticlockwise, resulting in a "rebound" phenomenon. Taking the horizontal distance from the crane load of 0m, 3m, 9m, 12m, 18m, 24m as 6 sections, with the section depth as the ordinate, and the deflection angle difference before and after the load acting as the abscissa, the analysis chart of the deviation angle difference of the major principal stress is drawn. The range of 0~9 m width and 0~20 m depth is defined as the main influence area, the range of 12 m~18 m width and 0~15 m depth is the secondary influence area, and the range of 24 m width and 25 m depth is no influence area. The difference of large principal stress deflection angle of soil element in each affected area is about 0~1/3 of the final deflection angle.

6. Conclusion
1) Combining with the traditional two-dimensional stress path $p-q$, and considering the rotation of the main stress axis, the three-dimensional stress path $\mathbf{p-q-}\alpha$ can more concretely reflect the stress path state of different soil elements under different construction conditions.
2) During the excavation of the foundation pit, the vertical and horizontal stresses decrease relative to the stress state before the excavation. It can be seen from the comparison of the unloading capacity in the pit.
3) The rotation of the main stress axis of the soil unit in the pit is obvious, with the step increase with the excavation of the foundation pit, the intermediate transition stage is lacking, and the final principal stress deflection angle is close to 90°.
4) Pit-side crane load has a greater impact on the active area soil directly below the load, the main stress rotation angle rotates counterclockwise, and the deflection angle difference is about 0 to 1/3 of the final deflection angle, but has little effect on the transition zone and passive zone.

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