Numerical Analysis of Deformation of Deep Foundation Excavation in Soft Clay Considering Influences of Time-effect

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Abstract. The traditional foundation pit design generally only considers the transient deformation. However, the excavation deformation characteristics of deep foundation pits in soft soil layers not only consider the small strain characteristics during the excavation, but also consider the time effect. Taking a foundation pit in Wenzhou as the engineering background, based on the HSS model and the SSC model, PLAXIS finite element software was used to simulate the excavation process of the deep foundation pit. The deformation characteristics of retaining structures and deep excavation are compared and analyzed. Calculations prove that: The deformation rules of the foundation pit with the time effect is basically the same as those without the time effect. During the excavation of the foundation pit, the horizontal displacement of the diaphragm wall, the ground settlement and the foundation upheaval calculated based on the SSC model are larger than those calculated based on the HSS model. The calculation results based on the SSC model show that after the completion of the excavation, the deformations of the foundation pit continue to increase with time, showing a rheological effect. The conclusion can provide theoretical guidance for the construction of foundation pit excavation in Wenzhou area to ensure the safe implementation of the construction process.

1. Introduction
The soil strain of foundation pit engineering belongs to the small strain range⁴⁻². In the analysis of foundation pit deformation, a constitutive model is needed that can reflect the mechanical properties of the soil in a small strain range. Liang Fayun⁵ et al. performed numerical analysis on engineering
examples based on the HSS model. The simulated results of horizontal displacement of retaining wall approximately equal to the measured data. The HSS model and the determination method for parameters are proved to be applicable in numerical simulation of excavation engineering in Shanghai. Jiang Xiaoting[4] et al. verified that the small strain response of soils should be taken into account during the settlement investigation of buildings and ground surface induced by shield tunneling. However, the stress-strain relationship of soft clay has obvious time dependence[5]. The excavation simulation of engineering using a constitutive model that does not consider time effects cannot reflect the influence of soft soil rheological properties on the deformation of the foundation pit. Therefore, in the numerical analysis of deep foundation pit excavation in soft soil, a constitutive model capable of characterizing the creep effect of soft clay needs to be selected.

In order to analyze the effect of time effect in the excavation of soft soil foundation pits, this paper uses HSS model and SSC model to numerically simulate the foundation pit excavation in deep soft soils of Wenzhou. The change rules of the horizontal displacement of diaphragm wall, the ground settlement and the foundation upheaval during the excavation of the foundation pit are analyzed. The effect of time on the excavation of soft soil foundation pits is studied.

2. Introduction to the constitutive model

2.1. The hardening small-strain model

The HSS model[6] is a constitutive model based on the HS model, which considers the nonlinear change in stiffness of the soil with strain in a small strain region. The HSS model can consider the hardening characteristics of soft clay and can distinguish the difference between loading and unloading. Stiffness depends on stress history and stress path. The shapes of the HSS model’s shear yield surface and cap yield surface in the principal stress space are shown in Figure 1:

![Figure 1. Shear yield surface and cap yield surface of the HSS model](image)

The HSS model contains a total of 11 HS parameters and 2 small strain parameters. As shown in the following table:
| Parameter | Name | Unit | Remark |
|-----------|------|------|--------|
| $E_{ur}^{ref}$ | Unloading–reloading Young’s modulus | MPa | |
| $E_{80}$ | Triaxial loading Young’s modulus | MPa | |
| $E_{oed}^{ref}$ | Oedometric loading Young’s modulus | MPa | |
| $p_{ref}$ | Reference mean pressure | kPa | |
| $m$ | A Janbu-type parameter | - | |
| $n$ | Unloading–reloading poisson’s ratio | - | |
| $R_d$ | Destruction ratio | - | |
| $c'$ | Effective cohesion | kPa | |
| $\varphi'$ | Effective angle of friction | ° | |
| $\Psi$ | Angle of dilatancy | ° | |
| $K_0$ | Ratio of initial horizontal to vertical effective stress | - | |
| $G_0^{ref}$ | Reference shear stiffness modulus | MPa | HSS model parameter |
| $\gamma_{0.7}$ | Level of strains where the shear modulus reaches 70% of its initial value | - | HSS model parameter |

2.2. Soft soil creep model

SSC model\cite{7} assumes soil is homogeneous and isotropic. Soil strain is composed of elastic strain and creep strain. The two strains were analyzed using Hook’s law and flow law, respectively. The yield function is similar to the modified Cambridge model. The parameters $\lambda^*$, $\kappa^*$ and $\mu^*$ that apply to the critical state soil mechanics framework are used to represent the creep rheology law. The expression is:

$$\dot{\varepsilon} = D^{-1} \sigma + \frac{1}{\alpha} \mu^* \left( \frac{p_{eq}^{ref}}{p_{eq}^p} \right)^{\frac{\lambda^* - \kappa^*}{\mu^*}} \frac{\partial p_{eq}^{ref}}{\partial \sigma}$$

(1)

The parameters $\lambda^*$, $\kappa^*$ and $\mu^*$ are the modified compression index, rebound index, and creep index, respectively. They can be obtained by one-dimensional or triaxial consolidation tests. The parameters $\lambda^*$ and $\kappa^*$ respectively indicate the slopes of the normal consolidation line and the expansion line. Parameter $\mu^*$ reflects the change in long-term volume strain. $\tau$ is the sum of consolidation time. $\alpha$ is the flow vector.

$$\lambda^* = \frac{C_c}{2.3(1+e)} \quad \kappa^* = \frac{2C_c}{2.3(1+e)} \quad \mu^* = \frac{C_a}{2.3(1+e)}$$

(2)

In the formula, $C_c$, $C_e$, and $C_a$ are the compression index, rebound index, and creep index obtained from the consolidation test, respectively.

When there is no test data, $\lambda^*$, $\kappa^*$ and $\mu^*$ can be obtained according to the following empirical formula:

$$\lambda^* \approx I_p / 500 \quad \lambda^*/\mu^* = 15-25 \quad \lambda^*/\kappa^* = 5-12$$

(3)

3. Numerical calculation

3.1. Engineering background

The paper takes a certain construction section with open excavation method in Wenzhou as the engineering background. The excavation width and depth of the foundation pit is about 14m. The foundation pit is supported by an 800mm diaphragm wall. The diaphragm wall is about 24m deep, and the concrete strength grade used for the wall is C35. The internal support system uses 1 reinforced
concrete support and 3 steel supports. The first support is a reinforced concrete support with a concrete strength grade of C30, and the remaining three supports are steel supports.

3.2. Calculation model and parameters

A two-dimensional finite element model was established using the finite element software Plaxis2D. In order to reduce the influence of the boundary effect, the model “length × height” is: 60m × 60m. The distribution of soil below the surface is as follows: filled soil (2.5m), muddy clay (26.5m), silty clay (29m) and sand (2m). The groundwater level is 2m below the ground. The excavation depth of the foundation pit is 13.5m, and the excavation width is 14m. Considering the geometric symmetry of the foundation pit, half of the foundation pit was selected to establish a calculation model.

The soil is modeled with solid elements. The diaphragm wall is simulated by a slab unit. The internal support is simulated by an anchor rod. A 15-node high-order triangular element is used for meshing, with a total of 1082 elements and 9066 nodes. The model is shown in Figure 2.

Constitutive models of muddy clay and silty clay layers adopt HSS model and SSC model, respectively. Others use M-C model. The time effect of the SSC model is set according to the actual excavation of the foundation pit. Tables 2 and 3 show the soil and structural parameters.
Table 2. Parameters of structure and soils (SSC model and M-C model)

| Stratum / Structure       | $\gamma$ (kN·m$^{-3}$) | $c$ (kPa) | $\phi$ | $\rho$ | $E_I$ (MPa) | $\nu$ | $\lambda^*$ | $\kappa^*$ | $\mu^*$ | $E_A$ (kN·m$^{-1}$) | $k_0$ (m·d$^{-1}$) |
|---------------------------|-------------------------|-----------|--------|--------|-------------|-------|-------------|------------|---------|-------------------|-------------------|
| Filled soil               | 17                      | 10        | 15     | 20     | 0.35        |       | -           | -          | -       | -                 | 0.1               |
| Muddy clay                | 16.7                    | 12        | 14     | -      | -           | 0.05  | 3.3×10$^{-3}$| 2.0×10$^{-3}$| -       | -                 | 4.0×10$^{-3}$     |
| Silty clay                | 17.65                   | 28        | 15     | -      | -           | 0.04  | 4.0×10$^{-3}$| 1.6×10$^{-3}$| -       | -                 | 2.0×10$^{-3}$     |
| Sand                      | 19.5                    | 5         | 33     | 30     | 0.3         | -     | -           | -          | -       | -                 | 1.2               |
| The diaphragm wall        | 23                      | -         | -      | -      | -           | 0.2   | -           | -          | -       | 1.34×10$^6$       | 25.20×10$^6$      |
| Reinforced concrete support| -                       | -         | -      | -      | -           | -     | -           | -          | -       | -                 | 19.20×10$^6$      |
| Steel support             | -                       | -         | -      | -      | -           | -     | -           | -          | -       | -                 | 8.28×10$^6$       |

Table 3. Parameters of soils (HSS model)

| Stratum       | Depth /m | $\gamma$ /kN·m$^{-3}$ | $c'$ /kPa | $\phi'$ /º | $\rho'$ /º | $E_{ur}^{ref}$ /MPa | $E_{ur}^{ref}$ /MPa | $E_{ur}$ /MPa | $E_{ur}$ /MPa | $\gamma_{0.7}$ /10$^{-4}$ | $m$ | $\nu_{ur}$ | $R_f$ |
|---------------|----------|------------------------|-----------|-------------|-------------|----------------------|---------------------|--------------|--------------|--------------------------|----|-----------|-------|
| Muddy clay    | 38.6     | 16.7                   | 12        | 12          | 0           | 4.20                 | 5.04                | 20.16        | 80.64        | 4                        | 0.8| 0.2       | 0.9   |
| Silty clay    | 20       | 17.65                  | 12        | 15          | 0           | 6.5                   | 7.8                 | 31.2         | 124.8        | 3                        | 0.8| 0.2       | 0.9   |

4. Analysis of calculation results

4.1. Horizontal displacement of diaphragm wall analysis

Figure 3 shows the horizontal displacement curves of the diaphragm wall at different excavation depths using the HSS model and the SSC model of the soil, respectively. Figure 4 shows the horizontal displacement of the diaphragm wall after the excavation completed when the soils are calculated using the SSC model. It can be seen from the calculation results that although the soil constitutive model is different, the horizontal displacement of the diaphragm wall in different excavation stage shows the characteristics of "bow-shaped". The maximum horizontal displacement value also gradually increases with the excavation step. At the same time, with the increase of the excavation depth, the position of the maximum displacement of the diaphragm wall gradually decreases.

After the excavation is completed, the maximum horizontal displacement of the diaphragm wall calculated by the HSS model is 34.4mm. The position of the maximum horizontal displacement is about 5m below the excavation surface. After the excavation is completed, the maximum horizontal displacement of the diaphragm wall calculated by SSC model is 53.7mm, which appears 6.5m below the excavation surface. The calculation result of horizontal displacement of diaphragm wall calculated by SSC model is larger than that calculated by HSS model. It can be seen in Figure 4 that the horizontal displacement of the diaphragm wall shows an obvious time effect. During the interim period after the excavation of the foundation pit is completed, the horizontal displacement of the diaphragm wall calculated by the SSC model continues to increase. The maximum horizontal
displacement of the diaphragm wall within 30 days after the excavation increased by 4.5mm. The maximum value of the horizontal displacement within subsequent 30d increased by 2.1mm.

4.2. Ground settlement analysis
Figure 5 shows the ground settlement curves at different excavation depths using the HSS model and the SSC model respectively. Figure 6 shows the change of ground settlement after excavation of the foundation pit when the soils are calculated using the SSC model. In general, the shape of the ground settlement curve is grooved. The location of the maximum ground settlement is not the closest to the foundation pit, but a certain distance from the foundation pit. As the distance from the wall increases, the ground settlement value also increases. After reaching a certain peak value, the ground settlement value gradually decreases as it moves away from the wall. The maximum ground settlement occurs at a location about 14m from the foundation pit.

After the excavation is completed, the maximum ground settlement calculated by the HSS model is 19.8mm. The maximum value of ground settlement calculated by the SSC model is 29.2mm. The calculated ground settlement influence range is within 30m from the foundation pit. Similarly, compared with the calculation result of the HSS model, the calculation result of the SSC model is larger. During the interim period after the excavation of the foundation pit, the surface settlement value continues to increase. After the excavation is completed within 30 days, the maximum ground settlement is 32.9mm. Compared with the maximum ground settlement after excavation, it increased by 3.7mm. After the excavation is completed within 60 days, the maximum ground settlement is 34.5mm. Compared with the previous results, it increased by 1.6mm, and the increase rate of ground settlement decreases.
4.3. Foundation upheaval analysis

Figure 7 shows the upheaval deformation curve of pit bottom after the excavation of the foundation pit when the HSS model and the SSC model are used for the soil. Figure 8 shows the change of foundation upheaval after the excavation of the foundation pit when the soils are calculated using the SSC model. During the construction of the foundation pit, due to the unloading of the soil's own gravitational stress, the soil in the pit exhibits an upward rebound deformation. It can be seen from Fig.7 that the upheaval deformation curve of pit bottom presents a gradually increasing parabolic shape. The value of the foundation upheaval gradually increases with the distance from the ground to the diaphragm wall. When excavated to the bottom of the pit, the maximum upheaval deformation curve of pit bottom calculated by the HSS model reaches 85.4mm. It occurs farthest from the diaphragm wall. The maximum upheaval deformation curve of pit bottom calculated by the SSC model reaches 140.3mm. It occurs farthest from the diaphragm wall, too. Because half of the foundation pit was selected to establish the model, the maximum value of foundation upheaval actually appears in the middle of the bottom. The calculation result of the foundation upheaval calculated by the SSC model is larger than that calculated by the HSS model. Within 30 days after the excavation of the foundation pit, the upheaval deformation curve of pit bottom moves up as a whole. The value of the foundation upheaval generally increases by about 11mm. After the excavation is completed, the value of the foundation upheaval at 60d increases by about 5.4mm compared to 30d, and the increase rate is slower than before. In general, the foundation upheaval shows relatively obvious rheological characteristics of soft soil.

5. Conclusion

This paper takes a foundation pit excavation project in Wenzhou as the background, and simulate the excavation project in soft soil with Plaxis finite element software. Rules of the change of the horizontal displacement of diaphragm wall, the ground settlement and the foundation upheaval when muddy clay and silty clay layers select HSS model and SSC model respectively are compared and analyzed. The result shows:

The calculation results of the horizontal displacement of diaphragm wall, the ground settlement and the foundation upheaval calculated by the HSS model for the soils are generally smaller than those calculated by the SSC model for the soils.

During the interim period, values of the horizontal displacement of diaphragm wall, the ground settlement and the foundation upheaval calculated by the SSC model continue to increase. But the increment decreases over time. The calculation results verify the time effect phenomenon in soft soil foundation pit engineering.

During the excavation of the foundation pit, an excessively long intermittent period or construction delay will adversely affect the stability of the foundation pit. Shortening the construction interval can control the creep deformation of the foundation pit.
Acknowledgements
This work was supported by the National Key Basic Research Program of China (973 Program) under Grant 2015CB057905; National Natural Science Foundation of China (Grant No. U1402231, No. 51909259); Hubei Technical Innovation Project (Grant No. 2017ACA186).

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