Applied research on slope reinforcement with cement mixing pile in deep soft soil foundation pit

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Abstract. Deep Quaternary soft soil layer with poor mechanical properties are widely distributed in the Pearl River Delta. In this paper, based on engineering examples, a numerical simulation method was used to study the action mechanism of new reinforcing techniques of grading slope combined with cement mixing piles. The effect of construction conditions, the thickness of the cement mixing piles, and reinforcement of the passive zone on the deformation and overall stability of a foundation pit were analyzed. Finally, the simulation results and the actual monitoring data were compared and analyzed to further verify the rationality of the model. The research reveals that the step-slope combined with cement mixing pile reinforcement has significant effects on limiting the deformation of deep foundation pit and ensuring the stability of the pit. The findings of this study can serve as a reference for similar researches[1].

Keywords: Deep soft soil, Step-slope, Cement mixing pile, Foundation pit reinforcement, Numerical simulation.

1. Introduction
The deep Quaternary soft soil layer in the Pearl River Delta is mainly composed of fluidic plastic silt, silty soil, loose silty sand, and soft clayey plastic soil, and it has high water content, high compressibility, low permeability, poor mechanical properties such as low strength and rheology. For example, shallow foundation pits with an excavation depth of 4–6 m are susceptible to excessive deformation or instability. Consequently, extremely strong reinforcements are applied to control
potential deformation; however, they are expensive and affect the later construction stages of the main structure\(^{[2]}\).

Step-slope combined with cement mixing pile reinforcement in deep and soft soil areas is often used due to its advantages such as convenient construction, short construction period, and low cost. However, there is presently limited research and engineering practice on this kind of simple foundation support\(^{[3,4]}\). Hence, this paper studies the design and construction of a deep soft soil support of a structure in the deep soft soil area of Zhuhai. Numerical simulation was performed to analyze the displacement and settlement at the top of the slope support and the results were consistent with onsite monitoring data. The results of this study can serve as a reference to similar studies.

2. Project Overview

A foundation pit located in the southeast region of the intersection of Shanhuai and Jinhong Roads in Jinwan District, Zhuhai City was considered in this study. Several commercial, residential, and comprehensive buildings are proposed to be built in this region. There is a basement underneath. The total excavation depth of the foundation pit is 4.25–4.5 m, and it comprises mainly artificial fill and silt layer. The bottom of the pit largely consists of the silt layer with poor geological properties. The total circumference of the pit support is approximately 545 m.

The foundation pit is close to municipal roads with many pipelines buried underneath; thus, uncompromising deformation control is required to ensure the stability and safety of the pit. The northern region of the foundation pit is largely in 1:2 slope. The slope surface and its foot are reinforced with \( \Phi 550@450 \) cement–soil mixing pile. The structural layout of the pit support is presented in Figure 1.

3. Finite Element Analysis Model

3.1. Parameters of soil constitutive model

The hardened soil (HS) model was employed to simulate the stress–strain relationship between the soil and the cement mixing pile\(^{[5-10]}\). The parameter values are presented in Table 1. According to the regional experience, the elastic modulus is 3–5 times the compression modulus \( E_S \). The relationship between the three-axis secant stiffness \( E_{\text{ref}} \), the tangent stiffness of the main consolidometer \( E_{\text{ref}} \), the
unloading modulus $E_{ur}^{ref}$, and other parameters in the HS model according to the engineering and regional experience is presented as follows:

$$E = E_{50}^{ref} = E_{oed}^{ref} = \frac{1}{5} E_{ur}^{ref}$$

**Table 1. Model calculation parameters**

| Attribute name                  | Plain fill | silt | Cement mixing pile | Passive zone reinforced soil |
|---------------------------------|------------|------|--------------------|-----------------------------|
| Thickness (m)                   | 3.5        | 16.5 | —                  | —                           |
| Poisson's ratio $\mu$           | 0.3        | 0.42 | 0.27               | 0.27                        |
| Severe $\gamma$ (kN/m$^3$)      | 18         | 16   | 18.5               | 18.5                        |
| Cohesion $c$ (kN/m$^2$)         | 15         | 6    | 25                 | 25                          |
| Internal friction angle $\phi$ ($^\circ$) | 14         | 5    | 22                 | 22                          |
| $E_{50}^{ref}$ (kN/m$^2$)       | 8×10$^3$   | 3×10$^3$ | 1×10$^5$           | 1×10$^5$                    |
| $E_{oed}^{ref}$ (kN/m$^2$)      | 8×10$^3$   | 3×10$^3$ | 1×10$^5$           | 1×10$^5$                    |
| $E_{ur}^{ref}$ (kN/m$^2$)       | 4×10$^4$   | 1.5×10$^4$ | 5×10$^5$           | 5×10$^5$                    |

3.2. Model size and construction conditions

The slope excavation depth is 4.5 m (Fig. 2) and the expanse of the soil affected by the excavation of the foundation pit is 3–5 times the excavation depth, so the model height was taken as 20 m and length 39 m (including the length of the slope top line and the pit bottom line of 15 m) (Fig. 3). The grading ratio is 1:2. The single-row slope of the cement mixing pile is equivalent to a cement–soil wall with a thickness of 500 mm, and the depth of the wall is uniformly 10 m below $\pm 0$. The calculation steps of the model are presented in Table 2.
Fig. 2. Schematic diagram

Fig. 3. Simulation model diagram

Tab. 2 Calculation steps of the model

| Sequence | Construction stage               | Remarks                                                                 |
|----------|----------------------------------|--------------------------------------------------------------------------|
| 1        | Initial ground stress balance    | Restore the in situ stress state before construction                      |
| 2        | Activate the cement–soil unit    | Perform the simulation of cement mixing pile construction                 |
| 3        | First excavation                 | Passivate the soil mass in the excavation area within 0–2 m along the slope. |
| 4        | Second excavation                | Passivate the soil mass in the excavation area within 2–3.5 m along the slope |
| 5        | Third excavation                 | Passivate the soil unit in the excavation area within                    |
3.5–4.5 m along the slope

4. Finite element results and analysis

4.1. Effect of the number of the mixing pile rows (wall thickness)

Based on the influence of the change of the single-row pile-wall thickness, the cement mixing pile-wall was set at the foot of the slope, and the thickness of the cross-sectional changes within the range of 0.5–3 m and other conditions remained unchanged. Analysis of the influence of the pile-wall thickness change on the deformation and stability of the foundation pit is presented in Figures 4 and 5. Multiple rows of the pile-walls were constructed to enhance the resistance of the foundation pit to deformation, and the number of rows was varied by changing the distance between two adjacent rows of the cement mixing pile-walls on the slope. The number of rows was designated as n and it was considered as an unreinforced state when n = 0. The distance between adjacent rows at n = 2–5 is 9, 4.5, 3, and 2.25 m, and the effect of n on the deformation of the foundation pit is presented in Figures 6–8.

![Factor of safety under the change of wall thickness](image1)

**Fig. 4.** Factor of safety under the change of wall thickness

![Maximum lateral displacement of the pile-wall under the change of wall thickness](image2)

**Fig. 5.** Maximum lateral displacement of the pile-wall under the change of wall thickness
Figure 4 illustrates the relationship between the factor of safety (FOS) of the sloped foundation pit and the thickness of the cement mixing pile-wall. The FOS increases as the width of the cement mixing pile wall increases during the excavation process. Under the third excavation stage, when the thickness of the mixing pile increases from 0.5 to 3 m wide, the FOS increases from 1.21 to 1.40, indicating that the increase in the thickness of the cement mixing pile-wall has a significant contribution in the slope stability.
As shown in Figure 5, when the lateral displacement of the mixing pile wall decreased from 187.1 to 169.9 mm, the decrease in amplitude was 9.2%. When the width of the wall exceeded 2.5 m, the decrease in amplitude of the lateral displacement of the wall was 1.2% (Fig. 5). This indicates that the constraining capacity due to the thickness of the slope-mixed piles against the horizontal deformation of the foundation pits was weakened.

Figures 6–8 show that the horizontal displacement of the slope top, its settlement, and the uplift of the slope bottom gradually decreases when the number of pile-wall rows increases from 0 to 5. The maximum change occurs after adding the first row of the cement mixing pile-walls, indicating that increase in the rows of the slope surface cement mixing pile-walls allows better control of the deformation of the slope.

4.2. Effect of reinforcement of the passive zone at the pit bottom

（1）Effect of reinforcement depth in the passive zone
By changing the soil properties and boundary conditions at the bottom of the pit reinforcement, the depth of the reinforcement was increased from 3 to 8 m under the same reinforcement width (5 m). The impact of the changes in the passive reinforcement depth on the deformation and stability of the foundation pit was analyzed.

![Fig 9. Relationship between the depth of reinforcement in the passive zone and the factor of safety](image)

Figure 9 indicates that the change trend of the overall FOS of the foundation pit increases with the reinforcement depth based on the same passive zone reinforcement width. Increasing the reinforcement depth from 3 to 8 m corresponds to a maximum increase of 0.086 in the FOS of the foundation pit, and the change interval of 1.30–1.40 indicates that the reinforcement depth of the passive zone has little effect on the pit FOS. Note that the change trend line when the reinforcement depth is above 6 m is less undulating than that when the depth is less than 6 m; therefore, it is more appropriate to adopt the reinforcement depth of 1.2–1.5 H in the passive zone, where H is the depth of the foundation pit.

（2）Effect of reinforcement width in the passive zone
With constant parameters and boundary conditions, the width of the reinforcement was increased from 3 to 8 m under the same reinforcement depth, and the effect of the passive reinforcement width on the deformation of the foundation pit was analyzed.
Figure 10. Relationship between the reinforcement width of the passive zone and the factor of safety

Figure 10 shows that based on the same reinforcement depth in the passive zone, the overall FOS change trend of the foundation pit also increased with the reinforcement width, but the growth rate was significantly reduced. An increase in the reinforcement width from 3 to 8 m corresponds to a maximum increase of 0.023 in the FOS of the foundation pit. The comparison chart reveals that the FOS of the foundation pit is more sensitive to the reinforcement depth than the width in the passive area, indicating that priority should be given to increase in the passive area reinforcement depth to prevent excess digging. Here, the passive zone reinforcement width is H to satisfy the design requirements, where H is the depth of the foundation pit.

5. Comparative analysis between the numerical simulation and monitoring data

Before the actual project construction, the horizontal displacement of the monitoring point established in advance at the slope top was compared with the simulated data (Figs. 11 and 12).

Fig 11. Comparison of the horizontal displacement of the foundation pit slope top
Fig 12. Comparison of the settlement of the foundation pit slope top

Figure 12 reveals that the change trend of the numerical simulation was consistent with the monitoring data, and a minute deformation was achieved, which satisfies the design requirements.

6. Conclusion

(1) The construction of cement mixing piles can limit the deformation of the foundation pit and improve the overall stability; the larger the width of the single-row cement mixing pile-wall on the slope, the smaller the deformation of the foundation pit and the stronger the overall stability.

(2) Increase in the excavation depth corresponds to an increase in the settlement of the slope top and the lateral displacement of the slope. The settlement is mainly concentrated in a certain region behind the slope top, and the distance between the maximum settlement point and the slope top is approximately equal to 1.5 H, where H is the depth of the foundation pit.

(3) The construction of the cement mixing pile reinforcement in the passive zone can further limit the deformation of the soft soil foundation pit and improve the overall stability; the reinforcement depth and width of the passive zone have little effect on the FOS, where the reinforcement depth and width of the passive zone were 1.2–1.5 and 1 times the excavation depth, respectively, to satisfy the design requirements.

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