Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 6316499, 13 pages
https://doi.org/10.1155/2023/6316499

Research Article

Numerical Analysis of Influences of Engineering Piles for Anti-Inrush of Deep Excavation under Confined Water

Zehai Cheng,[1] **Liujun Jin**,[1] **Chaojie Zhang**,[2] **and Zhenshuai Yu**[3]

[1]*School of Civil Engineering and Architecture, Zhejiang University of Science and Technology, Hangzhou 310023, China*
[2]*Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China*
[3]*Zhejiang Dahe Testing Co., Ltd., Hangzhou, China*

Correspondence should be addressed to Zehai Cheng; 103056@zust.edu.cn

Received 8 November 2022; Revised 22 December 2022; Accepted 27 December 2022; Published 14 January 2023

Academic Editor: Bingxiang Yuan

Aiming at the problem of anti-inrush of confined water in foundation pits considering the influence of engineering piles, a three-dimensional numerical analysis model of anti-inrush stability of deep foundation pits is established by using the finite element software ABAQUS, and the inrush failure mechanism and deformation behavior of the foundation pit bottom under the action of different confined water levels are analyzed. The effects of different pile lengths, pile spacing, waterproof layer thickness, and soil strength are studied, respectively, and the laws of pile foundation stress and soil deformation under the action of confined water are revealed. The results show that the existence of engineering piles has an obvious inhibitory effect on the stability of foundation pit confined water against inrush. By introducing the comprehensive correction coefficient of pile side friction, an analysis method for the anti-inrush stability of foundation pits considering the influence of engineering piles is proposed.

1. Introduction

In the construction process of deep foundation excavations with confined water, it is more likely to produce the phenomenon of outburst, flowing sand, or something similar to "boiling" water spraying sand [1]. In the design and construction of foundation excavations with confined water, we first analyze the anti-inrush stability of foundation excavations and then take certain measures to prevent foundation pits from destabilizing if they do not meet the requirements. How to accurately judge the anti-inrush stability of deep foundation pits with confined water requires the research on the internal mechanism and surge mode of foundation pit inrush.

At present, some scholars use numerical analysis methods to study the internal mechanism of foundation pit inrush. Gao et al. [2] obtained the relationship between the uplift deformation of the pit bottom and the confined water head by the finite difference method and proposed a calculation method for the critical water head of the foundation pit inrush. Ding and Wang [3, 4] put forward the concept of yield stress ratio and the judgment standard for foundation pit inrush based on the soil plasticity failure of the pit bottom. Sun and Zhou [5] summarised three failure modes of foundation pit inrush failure by means of model tests: water and sand inrush failure on the contact surface, overall jacking failure, and sand boiling failure on the surface of the waterproof layer. Zhang et al. used numerical methods to study the anti-inrush stability problem in inner bracing deep foundation pits [6]. Zhang et al. studied the effect of engineering piles on the rebound deformation of foundation pits [7]. Li et al. [8] presented a distinct lattice spring model for stability and collapse analysis of deep foundation pit excavation. Ng et al. [9]studied the performance of an existing piled raft and pile group due to adjacent multi-propped excavation. Yuan et al. [10, 11] analyzed the influence of groundwater depth on pile-soil mechanical properties and fractal characteristics under cyclic loading. For the deep foundation pit engineering using the reverse construction method or horizontal support, when the antisurge stability check is carried out, if the pressure balance method in the specification is adopted [12], it is obviously conservative and prone to the situation that the check calculation result does not match the actual project. Other methods include the homogeneous continuous beam (slab) analysis method [13, 14], the homogeneous continuum method [15], and so on. There are few studies considering the impact of engineering piles on the antisurge of foundation pit confined water. In fact, in order for the confined water to pour out from the bottom of the pit, it is necessary not only to overcome the self-weight of the soil in the aquiclude but also to overcome the cohesion and friction between the soil particles. For foundation pits with many engineering piles, the pullout resistance of the pile foundation should also be considered. In order to study the effect of engineering piles on the antisurge of the foundation pit, the finite element software package ABAQUS is used to establish a three-dimensional finite element analysis model of foundation pit inrush in pile group foundation in this article, considering different pile lengths, pile spacings, thickness of aquiclude, and soil strength as influencing factors, revealing the law of pile foundation stress and soil deformation under the action of confined water, by introducing the comprehensive correction coefficient of pile side friction resistance, proposing an analysis method of foundation pit antisurge stability.

2. Numerical Model of Anti-Inrush with Excavations

2.1. Calculation Assumptions. When using ABAQUS for finite element analysis in this paper, the following assumptions are made:

(1) The soil within the calculation range is a homogeneous, continuous, and isotropic elastic-plastic material with a horizontal distribution. The plastic stage follows the Mohr-Coulomb yield criterion;

(2) The change in soil stress caused by the construction of the enclosure structure and engineering piles before the excavation of the foundation pit is not considered;

(3) Both the enclosure structure and the engineering piles are assumed to be linearly elastic bodies.

2.2. Computational Model. The excavation depth of the foundation pit is 10 m, the boundary influence range of the calculation model is 4 times the excavation depth, the side length of the foundation pit is 16 m, and the engineering piles in the pit are arranged in a 5×5 rectangle. The type of pile foundation is bored cast-in-place pile, and the enclosure structure adopts an underground diaphragm wall and three reinforced concrete supports. The wall thickness is 0.8 m, and the geometry and load distribution of the foundation pit are symmetrical. Therefore, take 1/4 of the structure to establish a finite element analysis model; the thickness of the lower soil layer at the pile end is 8 m; the calculated model size is length 48 m, width 48 m, height 34 m; the finite element model and mesh division are shown in Figures 1 and 2.

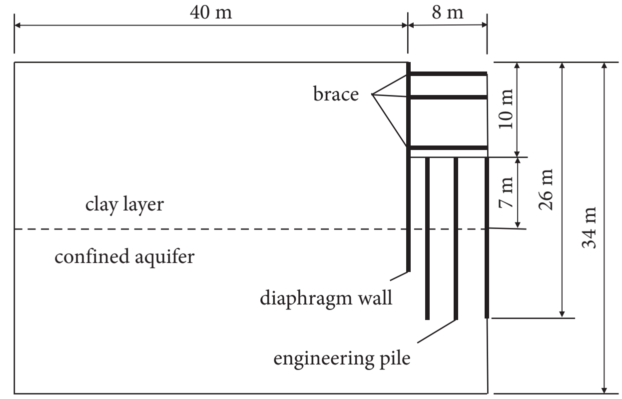

Figure 1: The profile of the 1/4 gushing model of the foundation pit.

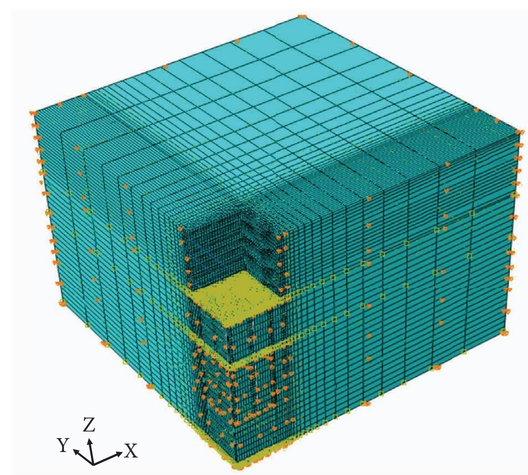

Figure 2: Meshes of the finite element model.

The surface of the model is a free-draining surface; the soil adopts a C3D8P three-dimensional eight-node pore pressure element; a C3D8R unit is used for the pile body and underground diaphragm wall; contact elements are set at the pile-soil contact surface; the Coulomb friction model is used; the friction coefficient is selected as $\mu = \tan(0.75\phi)$, where ϕ is the internal friction angle of the soil [12].

2.3. Calculated Parameters. The foundation pit envelope and the pile body are simulated by linear elastic materials, Elastic modulus $E = 28$ GPa, Poisson's ratio $v = 0.2$, physical and mechanical parameters of the soil are shown in Table 1. The geometric parameters of the model are shown in Table 2.

2.4. Treatment of Hydraulic Conditions. The program requires that a certain vertical reference water level y_{ref} (y-direction) be set for the cluster first and that its pore pressure be equal to the reference pressure value P_{ref}, below the reference water level, the pore pressure of the cluster increases linearly in proportion to the P_{inc}. A model for confined water action in a deep foundation pit can be established in two ways: by defining the confined aquifer group water table and by defining the pore pressure

Table 1: Physical and mechanical parameters of soils.

Soil layers	Dry density ρ_d (kg/m^3)	Elastic modulus E (MPa)	Poisson's ratio ν	Cohesion c (kPa)	Internal friction angle φ (°)	Void ratio e	Permeability coefficient k (m/s)
Clay	1500	6.8	0.35	14	16	1.3	3×10^{-9}
Sandy soil	1700	22.5	0.27	1.5	24.4	0.5	5×10^{-5}

Table 2: Geometrical parameters of the model.

Pile length L (m)	Pile diameter D (m)	Pile spacing nD (m)	Impervious bed thickness h (m)	Excavation depth H (m)	Excavation width B (m)	Total number of models
10, 16, 20	0.4, 0.5, 0.8	4D, 6D, 8D	5, 7, 9	10	16	7

distribution. Confined water pressure is loaded in stages; the initial pore pressure below the surface is the distribution of hydrostatic pressure. The water pressures at all levels on the top surface of the confined aquifer are 100 kPa, 120 kPa, and 142.46 kPa, thereafter increasing by 10%. The loading method of confined water is shown in Figure 3.

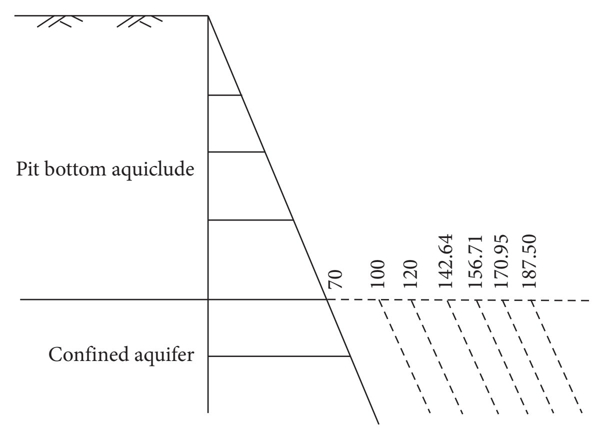

Figure 3: The loading mode of confined water (unit: kPa).

2.5. Verification of Numerical Simulation Results. In order to ensure the accuracy and reliability of the finite element numerical simulation calculation results, comparing the numerical simulation results with the laboratory model test results [16], the deformation law of the soil at the bottom of the pit is the same as that obtained from the indoor model test; the vertical displacement of soil at the center of the foundation pit changes with water pressure as shown in Figure 4; the error is less than 10%.

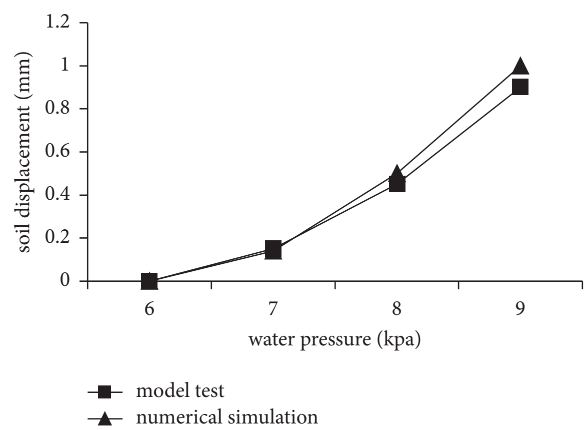

Figure 4: Variation of vertical displacement of soil at the center of pit bottom with water pressure.

3. Analysis of Calculation Results

3.1. Axial Force of Pile Analysis. The model calculation parameters are selected as pile length $L = 16$ m, pile diameter $D = 0.8$ m, pile spacing 4D, and water barrier thickness $h = 7$ m. The soil weight at the top of the confined aquifer is 142.46 kPa. After the excavation of the foundation pit is complete, increase the pressure of the confined water step by step according to the method shown in Figure 3 until the foundation pit is damaged by a sudden surge. Figure 5 shows the change of the axial force of the pile foundation (namely the central pile, the side pile, and the corner pile) at different positions of the foundation pit with the pressure of the confined water.

It can be seen from Figure 5 that each pile mainly bears the tensile force, showing a trend of increasing first and then decreasing, and the axial force at different positions of the pile body increases with the increase in confined water pressure. Due to the jacking action of the confined water, the aquiclude at the bottom of the pit is uplifted and deformed, the top of the confined aquifer rebounds due to the unloading effect, and the maximum axial force is located below the soil layer interface (the top surface of the confined water layer) 2~3 m. The relative displacement of the pile and soil at the center of the foundation pit is large. Under the same bearing water pressure, the relationship between the axial force of each pile body is: center pile > side pile > corner pile.

3.2. Skin Friction of Pile Distribution. With the loading of the confined water head, the side friction of the piles develops step by step; the variation of the side friction distribution of each pile with the confined water pressure is shown in Figure 6. The relative displacement of the pile and soil within the aquiclude is positive, and the pile side produces positive frictional resistance. According to the friction characteristics of the pile-soil interface, different relative displacements of piles and soil are closely related to the degree of pile side friction.

It can be seen from Figure 6 that the variation law of the side friction resistance of each pile is similar; the pile side frictional resistance develops step by step with the increase of the confined water head, the relative displacement of the pile and soil at the soil layer interface is the largest, and therefore, the positive frictional resistance of the upper part of the pile body reaches the maximum value, the lower part of the pile body is subject to negative frictional resistance, and there is no softening phenomenon. The lateral friction resistance of the pile is distributed in an inverse “S” shape; the neutral point gradually moves down with the increase of the bearing water pressure, and the range of the positive friction resistance gradually increases.

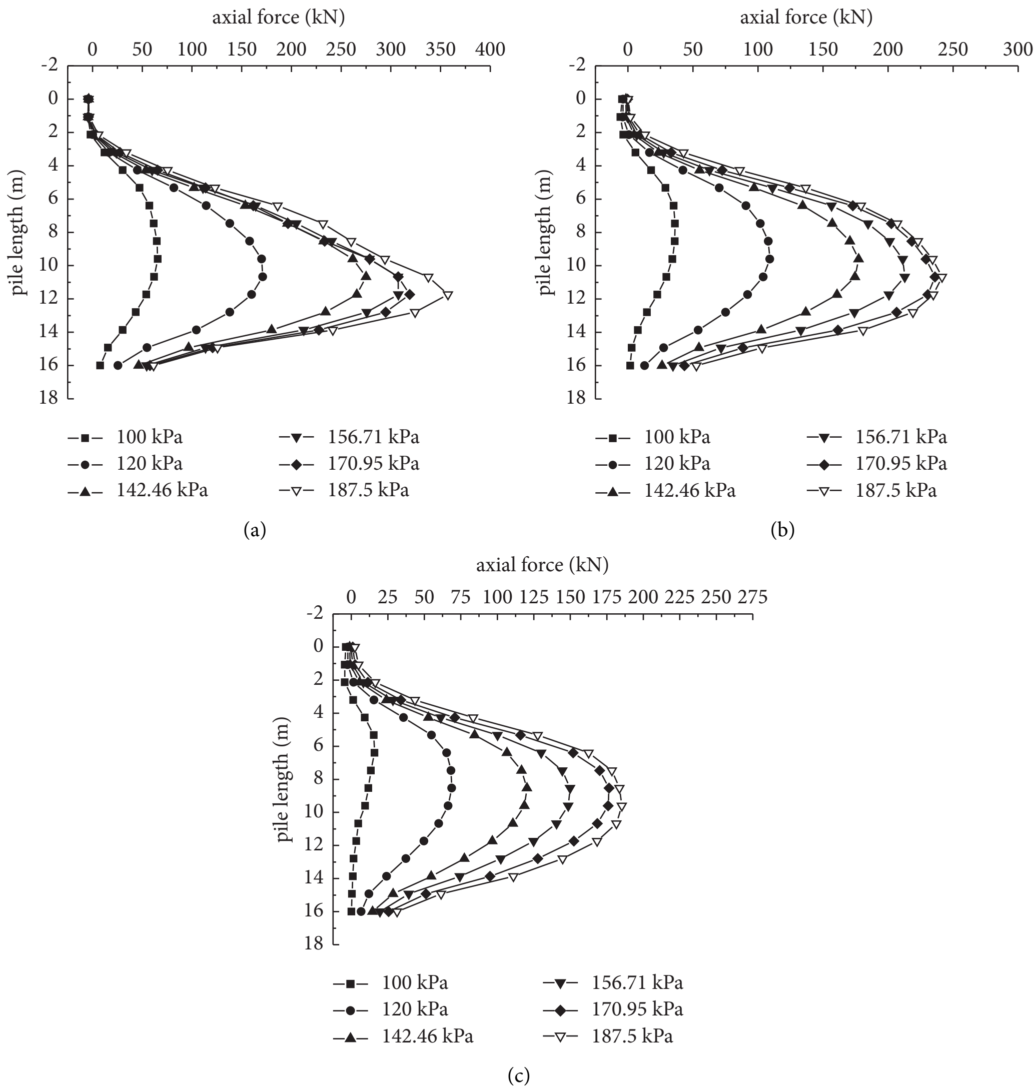

Figure 5: Distribution of axial force of piles at different positions. (a) Central pile, (b) side pile, and (c) corner pile.

Under the same confined water head pressure, the relative displacement of the pile and soil at the center of the foundation pit is the largest, the side friction resistance of the center pile is the largest, and the corner pile is the smallest. However, in the range of 0~3 m at the top of the aquiclude, the side friction resistance of each pile is distributed in a triangle, and the size is basically the same. It shows that the soil deformation at the bottom of the aquiclude is obvious, and the relative displacement of the pile and soil is large. Since the development of the pile side friction is related to the physical and mechanical properties of the soil around the pile, the negative friction at the bottom of the pile body does not reach the limit friction.

3.3. Deformation Analysis. After the excavation of the foundation pit, the soil rebounded due to unloading, and the maximum rebound amount was 96 mm. The soil deformation is uniform and symmetrical, and the deformation and displacement curve of the soil at the bottom of the pit during the loading stage are shown in Figure 7.

The soil deformation curve in the figure is parabolic; due to the constraints between the soil and the underground diaphragm wall, the deformation at the center of the foundation pit is larger than that at the edge of the foundation pit, and uplift deformation of the soil increases with the increase of the confined water pressure. It can be seen from the figure that for every 10% increase in the confined water pressure, the maximum deformation growth rate is about 6%, and the maximum uplift of the soil is 14.8 cm when the final foundation pit is damaged by inrush. The distribution of the soil plastic zone is shown in Figure 8. It can be seen from the figure that the plastic zone is mainly generated at the contact surface of the pile and soil and is distributed within a certain waterproof layer above the soil layer interface. The plastic zone of the pile-soil contact

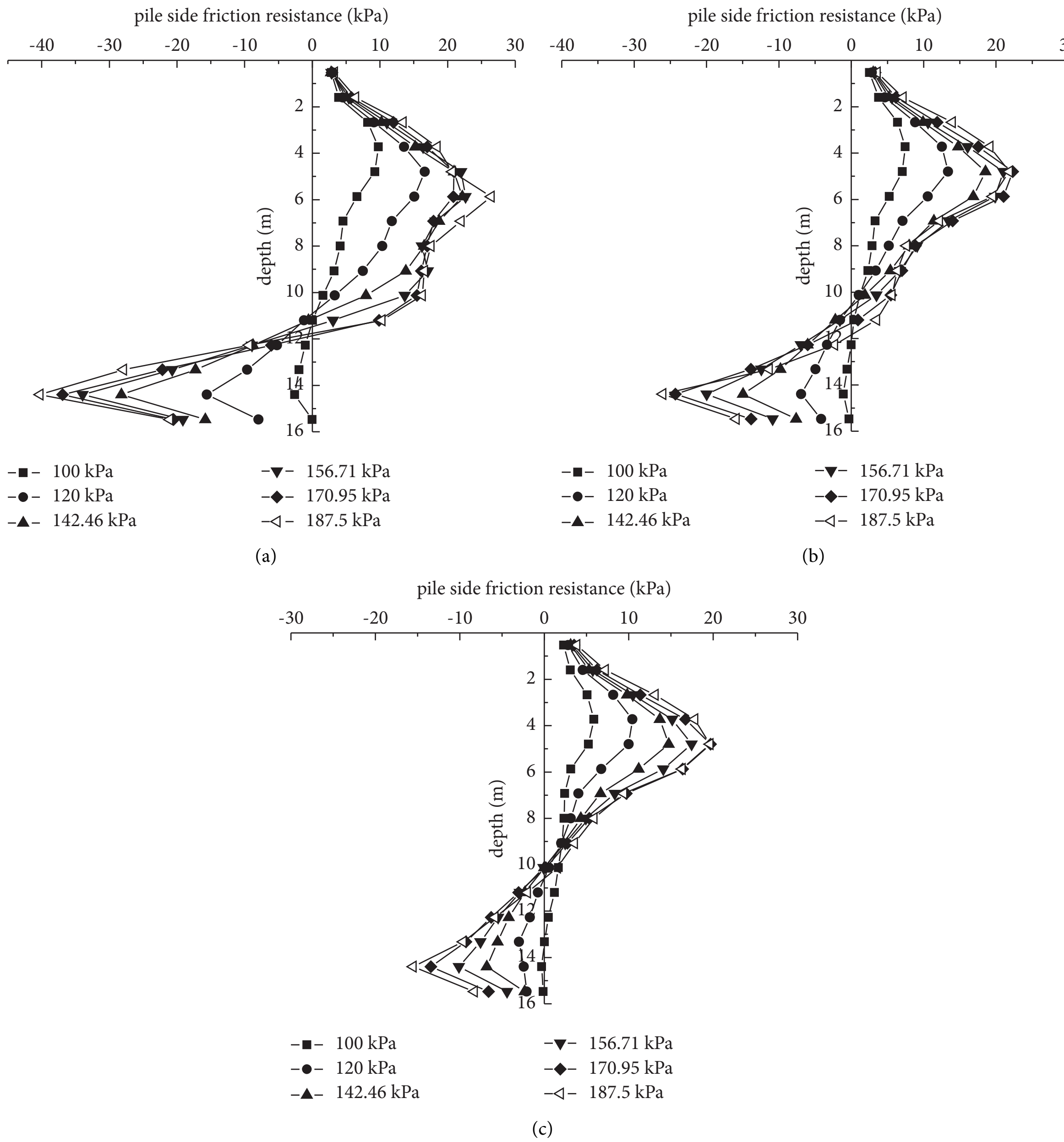

FIGURE 6: Distribution of skin friction of piles at different positions. (a) Central pile, (b) side pile, and (c) corner pile.

surface at the center of the foundation pit is larger, and the plastic zone gradually develops upward from the soil layer interface with the increase in water pressure.

3.4. Analysis of the Influence of Different Factors

3.4.1. Influence of Pile Length. In order to study the effect of pile length on the antisurge capacity of the foundation pit, the pile lengths are respectively 10 m, 16 m, and 20 m, the pile diameter D is 0.8 m, the pile spacing is $4D$, the thickness of the water barrier is 7 m, and the soil strength parameters are listed in Table 1. The change of the axial force of each pile under the action of a certain confined water pressure is shown in Figure 9. It can be seen that with the increase of the pile length, the position of the maximum axial force of each pile moves downward, indicating that the embedded and fixed effect of the confined aquifer on the engineering pile is more obvious after the increase of the pile length. The confining water pressures when the foundation pit inrush fails are 177.4 kPa, 187.5 kPa, and 187.7 kPa, respectively. It can be seen that the increase of the pile length can effectively improve the antisurge capacity of the foundation pit; the axial force of the central pile is greater than that of the side piles and the corner piles; when the lateral friction resistance of the soil body in the aquiclude at the bottom of the pit reaches the limit, increasing the pile length is very limited in improving the antisurge ability of the foundation pit; the exertion of the lateral friction resistance of the pile has a depth effect.

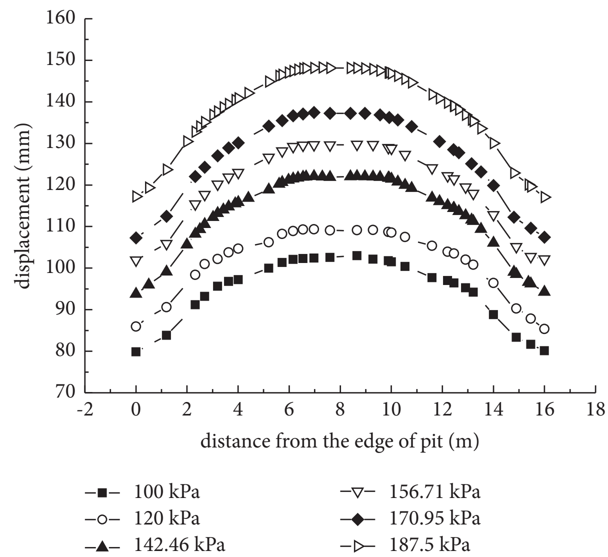

Figure 7: The deformation curve of the bottom soil.

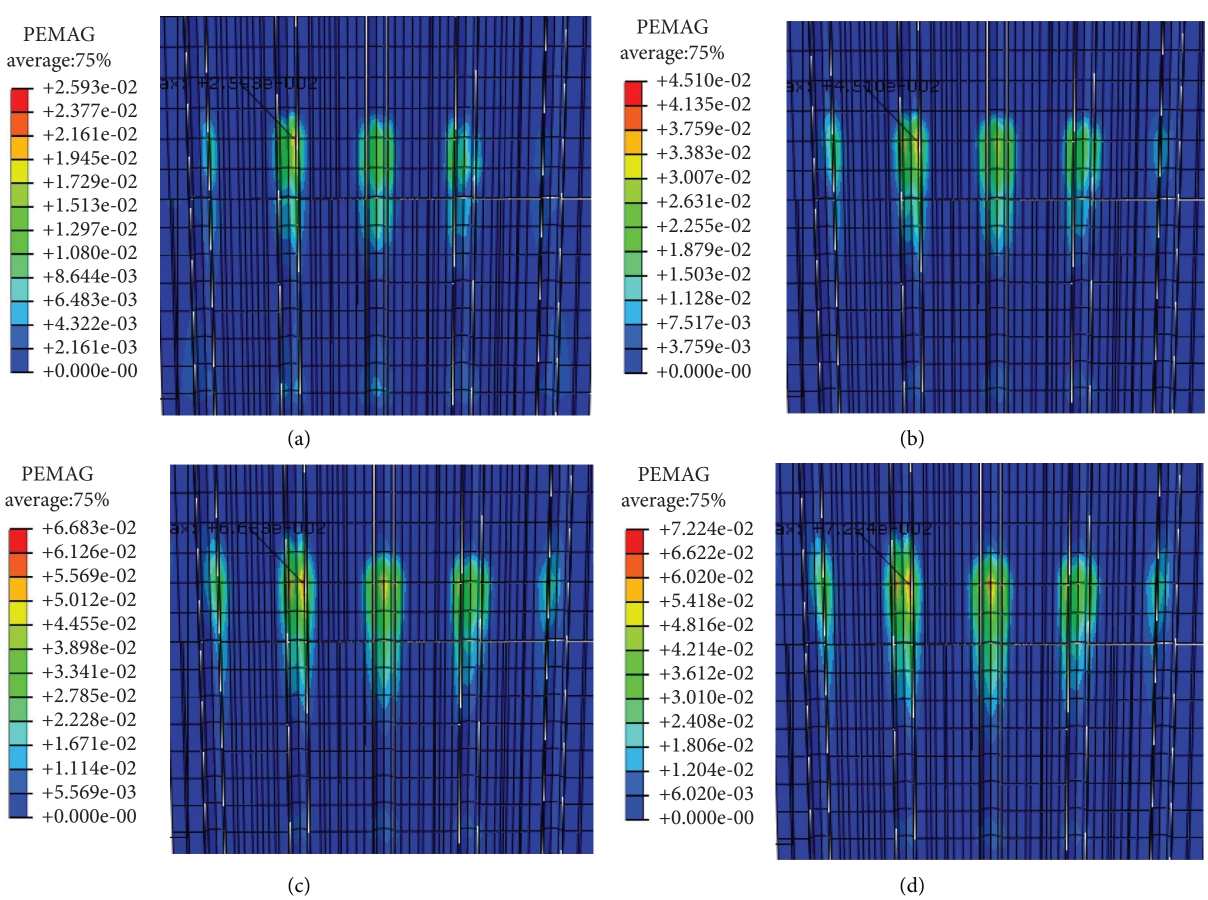

Figure 8: Distribution of the plastic zone under different confined water pressure: (a) confined water pressure $P = 142.46$ kPa; (b) confined water pressure $P = 156.71$ kPa; (c) confined water pressure $P = 170.95$ kPa; (d) confined water pressure $P = 187.50$ kPa.

When the confined water pressure is $P = 170.95$ kPa, the uplift deformation of the soil at the bottom of the pit with different pile lengths is shown in Figure 10. It can be seen that the soil uplift when the pile length is $L = 10$ m is significantly greater than that when $L = 16$ and 20 m; the maximum value reaches 44 mm, which are 14.3% and 19.6% larger than those when $L = 16$ and 20 m, respectively. With the increase in pile length, the uplift amount of soil

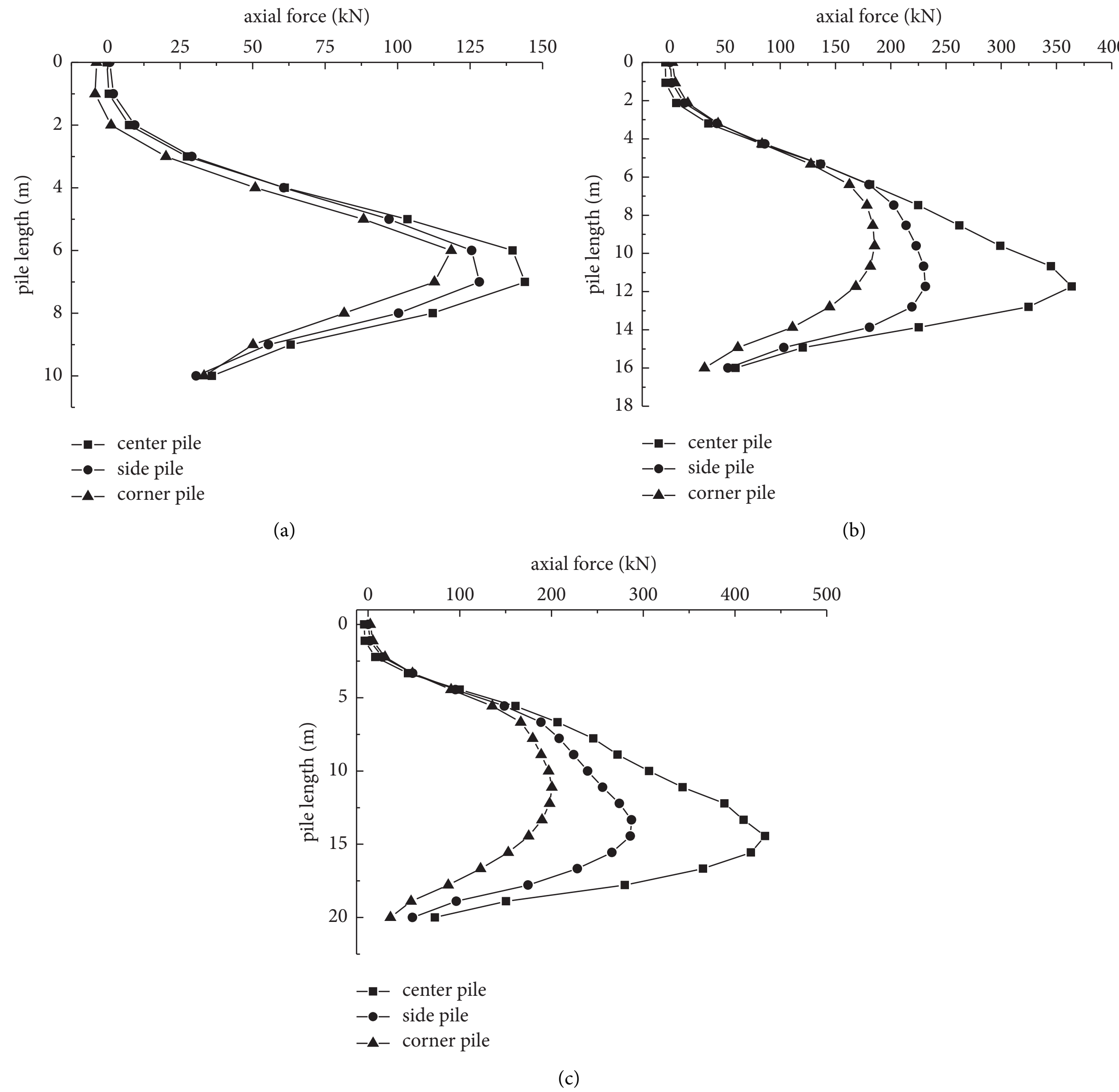

Figure 9: Axial force of the pile under different pile lengths. (a) L = 10 m and $P = 177.4$ kPa axial force diagram of the pile; (b) $L = 16$ m and $P = 187.5$ kPa axial force diagram of the pile; (c) $L = 20$ m and $P = 187.7$ kPa axial force diagram of the pile.

displacement gradually decreases, and the maximum soil displacement at $L = 16$ and 20 m differs by 4.6%. It can be seen that the increase in pile length has a significant inhibitory effect on soil uplift deformation.

3.4.2. Influence of Pile Spacing. The pile spacing is 4*D*, 6*D*, and 8*D*, respectively (*D* is the pile diameter), and the model parameters are: the pile length is 16 m, the pile diameter is 0.8 m, 0.5 m, and 0.4 m, the thickness of the water barrier is 7 m, and the pile group is 5×5 arranged distribution. The calculation results show that under the condition of different pile spacing, the antisurge ability of the foundation pit is different, the pile spacing increases, the antisurge ability of the foundation pit gradually weakens, and the confined water pressures of the foundation pit are 187.5 kPa, 175.6 kPa, and 171.8 kPa, respectively, when the foundation pit is damaged. Figures 11 and 12 show the axial force and pile side friction distribution of each pile in the foundation pit when the confined water pressure is 170.95 kPa.

It can be seen from Figure 11 that the distribution of axial force for each pile is similar for different pile spacings. Under the same bearing water pressure, the axial force of the lower part of each pile gradually decreases with the increase in pile spacing, and the axial force changes in the range of the aquiclude are similar. It can be seen from Figure 12 that the upper part of the pile body is subject to positive frictional resistance, and the positive frictional resistance of each pile within the range of the clay layer is distributed in a triangle within the range of 3-4 m below the bottom of the pit to the top surface of the confined aquifer, the lower part of the pile body is subject to negative frictional resistance. With the increase of pile spacing, relative displacement of pile and soil increases, resulting in greater pile side friction, but the

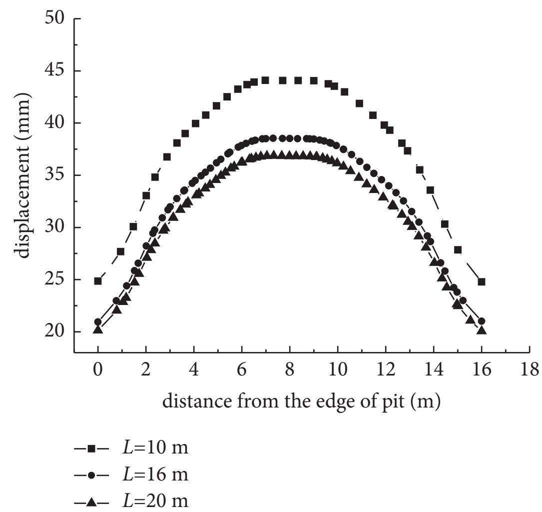

FIGURE 10: Deformation of pit bottom soil under different pile lengths.

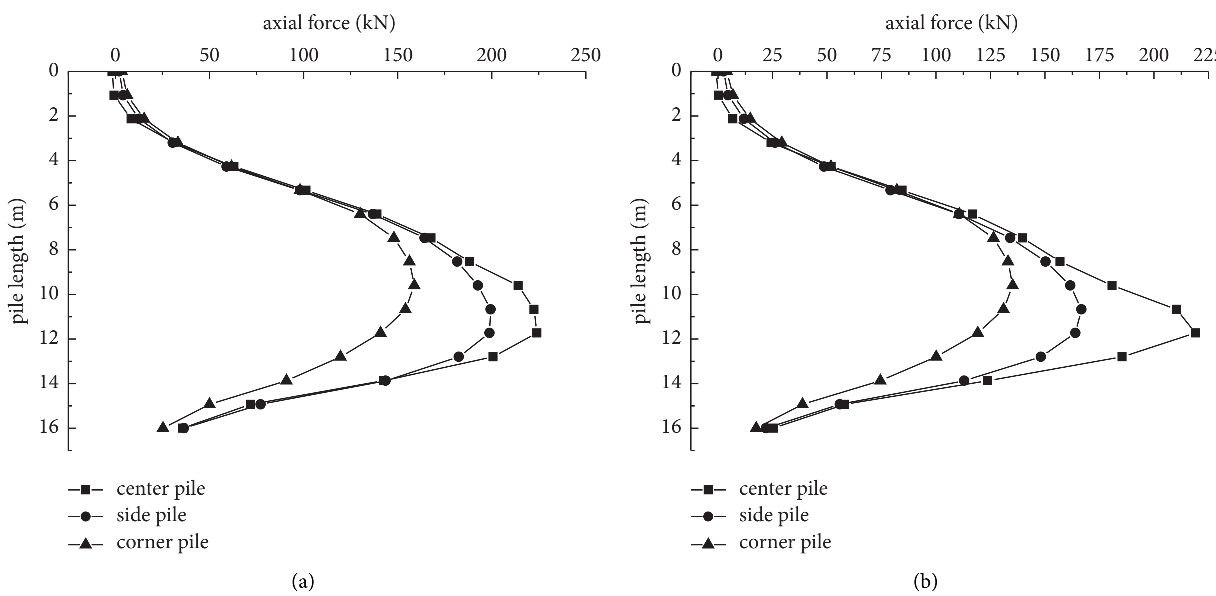

FIGURE 11: Axial force of pile shaft under different pile spacing. (a) Pile spacing 6*D* and (b) pile spacing 8*D*.

increase of pile spacing reduces reinforcement effect of the engineering piles on soil at the bottom of pit, antisurge capacity of foundation pit does not increase significantly. The results show that the critical water pressure of the foundation pit inrush at 8*D* is 171.8 kPa, which is only 21% higher than that of the pileless foundation pit.

Figure 13 shows the soil uplift displacement of the foundation pit with different pile spacings when the confined water pressure is 170.95 kPa. Under the same condition of confined water pressure, pile spacing is different, and soil uplift displacement is also different. When pile spacing is 4*D*, uplift displacement is the smallest, and the maximum displacement is about 38 mm, which is 11.9% and 19.3% lower than that of 6*D* and 8*D*, respectively. Since engineering piles in the foundation pit can play a certain role in strengthening the soil at the bottom of the pit, the soil at the bottom of the pit is subject to downward friction. In the antisurge stability analysis of the foundation pit, not only the weight of the soil but also the negative friction force of the pile on the soil and the cohesion of the soil should be considered. It can be found that the smaller the pile spacing, the larger the pile-soil contact area, the better the reinforcement effect, and the smaller the soil uplift displacement.

3.4.3. Influence of the Thickness of Aquiclude. Figure 14 shows the relationship between soil uplift displacement and confined water pressure for different aquiclude thicknesses ($h = 5$ m, 7 m, and 9 m), and the results show that uplift displacement of soil increases with the increase in confined water pressure, all of which are parabolic. Under the same water pressure, the larger the thickness of the aquiclude, the smaller the soil uplift displacement. The foundation pit with aquiclude thickness of $h = 5$ m only

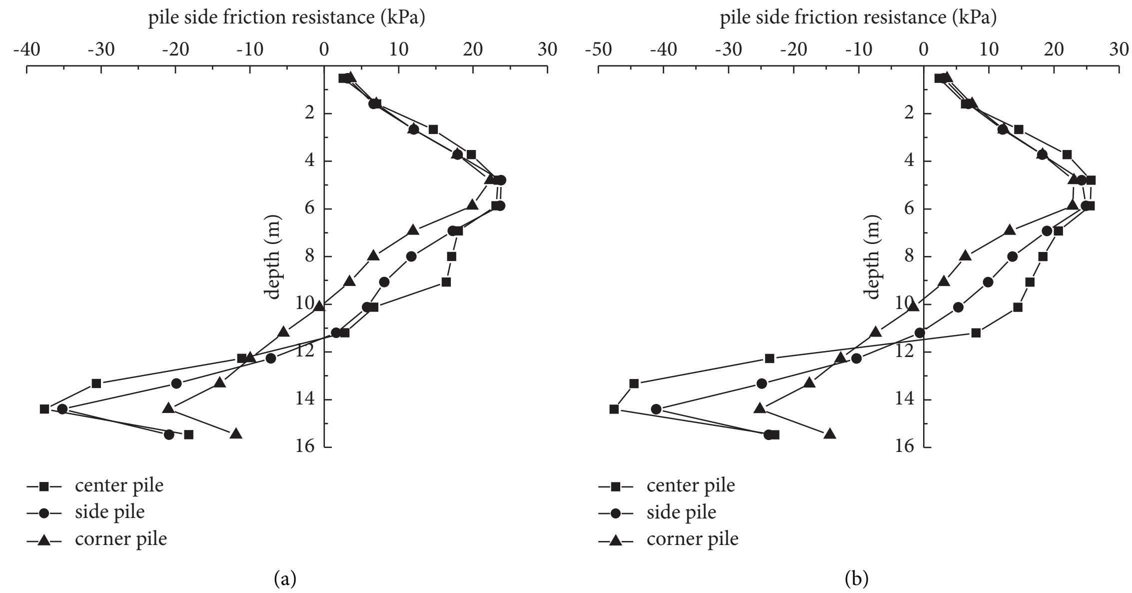

Figure 12: Distribution of pile side friction under different pile spacing. (a) Pile spacing 6*D* and (b) pile spacing 8*D*.

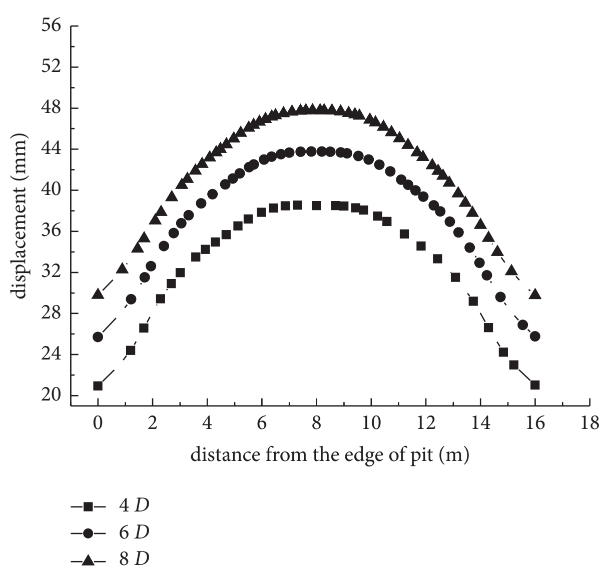

Figure 13: Uplift displacement of soil under different pile spacing.

suffers sudden surge failure when the confined water pressure is 129.4 kPa; when $h = 7$ m and 9 m, the confining water pressures of the foundation pit for sudden surge failure are 187.6 kPa and 242.1 kPa, so that increasing the thickness of the aquiclude can improve the antisurge ability of the foundation pit. In engineering, grouting at the bottom of the pit is often used to increase the thickness of the aquiclude, which is one of the most effective measures to resist a sudden surge. If the thickness of the water-retaining layer at the bottom of the pit is 5 m after the excavation of the foundation pit is completed, the maximum confined water pressure is 129 kPa, and the maximum uplift displacement of soil is 30 mm, by increasing the minimum thickness of foundation pit floor to 7 m by the grouting method, foundation pit will not suffer from inrush damage, and the maximum uplift displacement of soil is reduced to 17 mm, the anti-inrush capacity of foundation pit is improved.

3.4.4. Influence of Soil Strength. The soil weight and shear strength of the aquiclude at the bottom of the pit are one of the factors that affect the stability of the foundation pit inrush. The use of triaxial cement mixing piles or high-pressure rotary jetting piles to reinforce soil at the bottom of the pit can effectively increase the strength of the soil and improve the antisurge capacity of the foundation pit. It is assumed that the soil at the bottom of the pit is reinforced with three-axis cement mixing piles; the cement content of materials used is 15%; the water-cement ratio is 0.5; and the physical and mechanical parameters of the cement-soil mixture after the reinforcement of the pit bottom are shown in Table 3.

Figure 15 shows the limit value of the side friction resistance of the pile before and after the reinforcement of the pit bottom soil. After the soil at the bottom of the pit is reinforced, the limit value of the side friction resistance of the central pile is 8 times higher than that before the reinforcement, the friction resistance at the interface of the soil layer is the largest, the position of the neutral point is moved up, the antisurge capacity of the foundation pit is obviously improved, and the confined water pressure of the foundation pit at the time of inrush failure is 340.57 kPa, which is 163% higher than that before reinforcement. Figure 16 shows the uplift deformation of soil at the bottom of the pit after reinforcement. It can be seen that the uplift displacement of soil at the bottom of the pit is significantly reduced due to the increase in the shear strength of the soil after reinforcement.

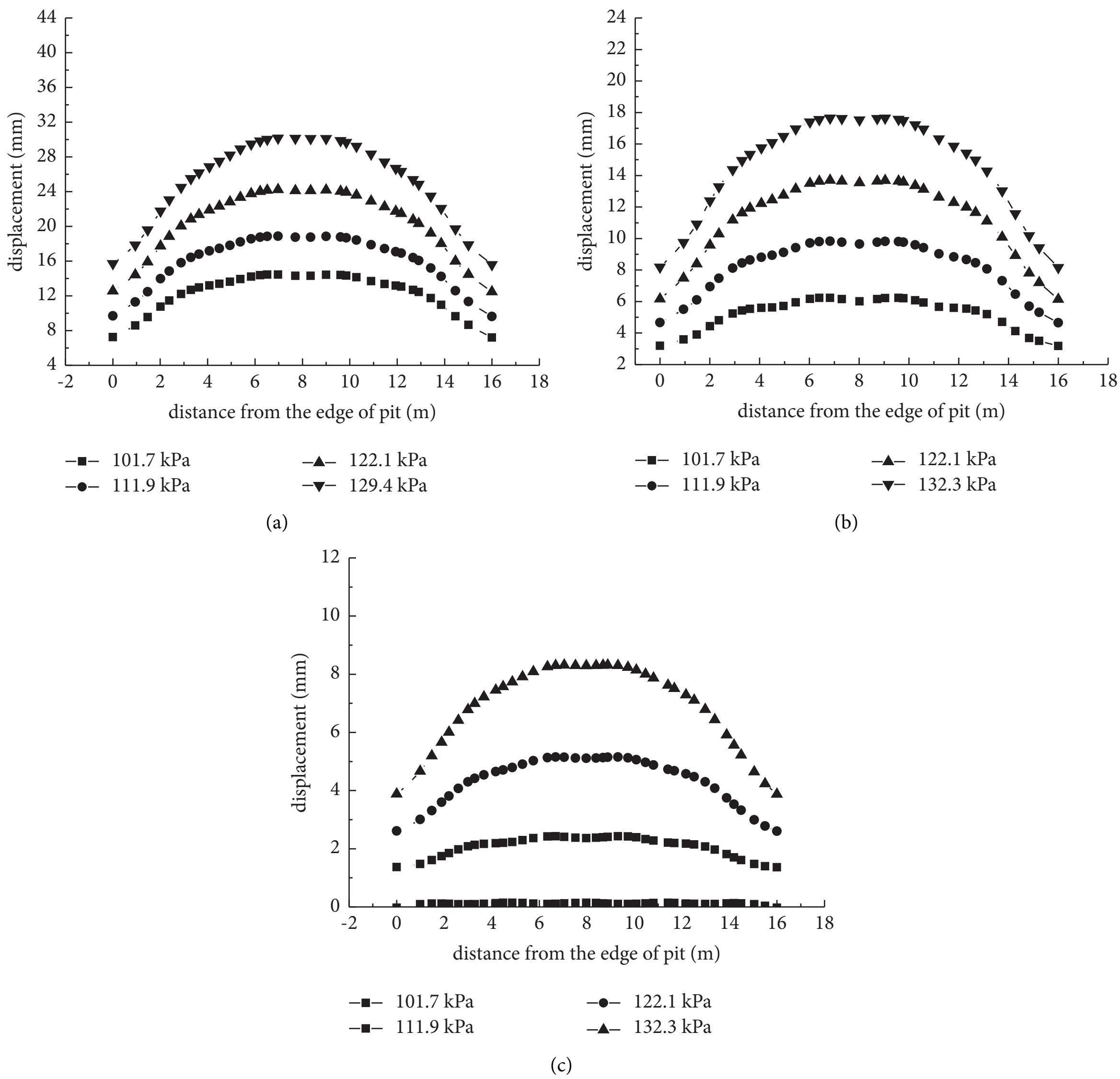

Figure 14: Uplift displacement of soil mass with different thicknesses of the water-resisting layer. (a) $h = 5$ m, (b) $h = 7$ m, and (c) $h = 9$ m.

Table 3: Physical and mechanical parameters of soil-cement.

Volumetric weight γ (kN/m^3)	Elastic modulus E (MPa)	Poisson's ratio (ν)	Cohesion (c)	Friction angle (ϕ)
19	120	0.1	235	38.7

4. Revised Analysis Method of Foundation Pit Antisurge Stability

The above finite element analysis shows that the engineering piles have a certain contribution to the anti-inrush of the foundation pit's confined water. Therefore, the effect of side friction resistance on engineering piles and soil strength can be considered. Compared with the pressure balance method, considering the soil nailing effect of engineering piles can reduce the water level drawdown of pressure-relief wells and save on the cost of water treatment. Establish a foundation pit antisurge analysis model and propose the foundation pit's antisurge safety factor discriminant formula. The antisurge safety factor K of foundation pit considering the influence of engineering piles is defined as

$$K = \frac{W + u\beta \cdot Q_{sk} h}{p_w S}, \quad (1)$$

where W—soil weight; u—pile perimeter; h—aquiclude thickness; β—comprehensive correction coefficient of pile lateral frictional resistance; S—foundation pit bottom area; Q_{sk}—standard value of ultimate lateral resistance of piles within aquiclude range; p_w—confined water pressure.

According to the finite element analysis, the comprehensive correction coefficient β of pile side friction resistance

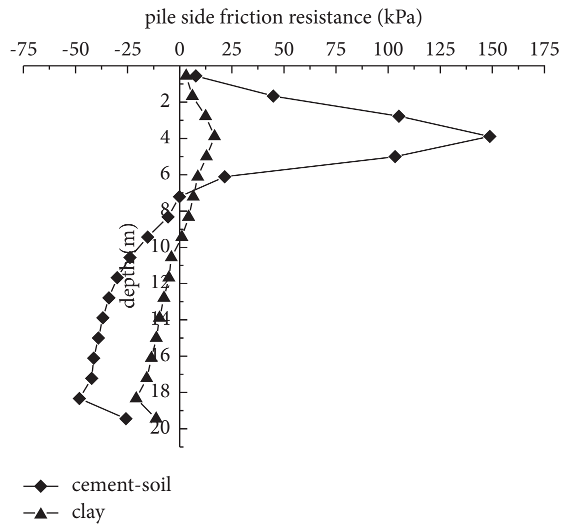

FIGURE 15: Comparison of ultimate frictional resistance of the central pile before and after soil reinforcement.

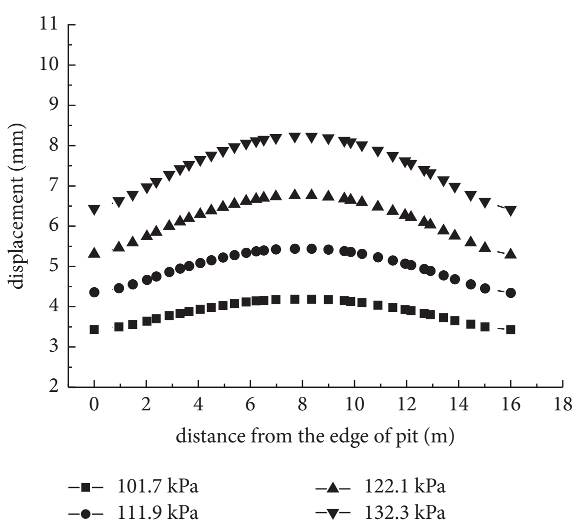

FIGURE 16: Soil heave displacement after pit bottom reinforcement.

is mainly related to the thickness of the water barrier and strength of the soil; the comprehensive correction coefficient β of pile side friction resistance ranges from 0.65 to 0.8; the larger the thickness of the water-repellent layer and the higher the soil strength, the smaller the value of β, and the larger the value otherwise.

Considering the inhibitory effect of engineering piles, assuming that the confined water pressure and soil weight balance, the critical thickness h_{cr} of the aquiclude at the bottom of the pit can be obtained as

$$h_{cr} = \frac{(K-1)\gamma_{sat}S - u\beta \cdot c_{uu}}{u\beta \cdot \gamma' \tan \phi_{uu}}, \tag{2}$$

where c_{uu} is unconsolidated undrained cohesion of soil mass, ϕ_{uu} is unconsolidated undrained internal friction angle. The safety antisurge stability and safety check shall be carried out before the excavation of the foundation pit so that the minimum thickness of the water-retaining layer at the bottom of the pit is $h \geq h_{cr}$, so that the foundation pit will not be damaged by a sudden surge, otherwise, decompression and dewatering measures should be taken.

5. Conclusion

This paper studies the anti-inrush mechanism of foundation pits, considering the soil nailing effect of engineering piles using ABAQUS finite element software. The effects of different pile length, pile spacing, soil strength, and other factors on the antisurge capacity of foundation pits are investigated. Consequently, a revised analysis method for foundation pit antisurge stability is put forward. The main conclusions are as follows:

(1) Under the action of confined water, the engineering piles in the foundation pit are mainly affected by axial tensile force, and the internal force of each pile foundation is quite different. Before the inrush failure of the foundation pit, the relationship of the axial force is center pile > side pile > corner pile, and the maximum value is located near the top surface of the confined aquifer. The pile body is subject to positive frictional resistance within the range of aquiclude, and it develops step by step with the increase of water pressure. The side friction resistance of piles at different positions increases step by step with water pressure, and they are all distributed in an "S" shape. The positions of neutral points of the central pile and side piles gradually move down; the positive friction resistance of the central pile is the highest. The soil plastic zone is generated at the contact surface of the pile and soil and is mainly distributed in a certain waterproof layer above the soil layer interface. The plastic zone gradually develops upward from the soil layer interface with the increase in water pressure.

(2) Under the action of confined water, the uplift displacement curves of soil at the bottom of the foundation pit are all parabolic. The deformation at the center is the largest, compared with the soft soil foundation pit without a pile under confined water. Accordingly, the existence of an engineering pile has an obvious inhibitory effect on the uplift deformation of soil at the bottom of the pit.

(3) With an increase in pile length, the uplift bearing capacity of an engineering pile gradually increases. Increasing pile length can improve the anti-surge capacity of the foundation pit, but the exertion of pile side friction has a depth effect. The occurrence of foundation pit inrush is also related to pile spacing, the thickness of the water barrier, and the strength of the soil. In the case of a certain number of piles, the smaller the pile spacing or the greater the thickness and strength of the water-repellent layer, the smaller the uplift deformation of the soil mass.

(4) The comprehensive correction coefficient of ultimate friction resistance on the pile side is introduced, and

the calculation formula of the antisurge safety coefficient of the foundation pit considering the influence of engineering piles is proposed. The correction coefficient β is approximately 0.65~0.80, which can be specified by the water barrier thickness, pile spacing, and soil strength [16].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Natural Science Foundation of Zhejiang Province (grant no. LY18E080015) and Science and technology plan project of Zhejiang Provincial Department of Water Resources (RB2026).

References

[1] C. L. Ding, "Summary of study on calculation method of inrushing for confined water foundation pit in soft area," *Chinese Journal of Underground Space and Engineering*, vol. 3, no. 2, pp. 333–338, 2007.

[2] G. Y. Gao, J. L. Chai, X. L. Zhang, and Q. S. Jin, "Critical water head determination of water gushing in foundation pit based on three-dimensional numerical analysis," *Rock and Soil Mechanics*, vol. 33, no. S1, pp. 251–256, 2012.

[3] C. L. Ding and D. F. Wang, "A study on calculation model for piping in foundation pit with confined underground water based on plastic failure," *Engineering Mechanics*, vol. 24, no. 11, pp. 126–131, 2007.

[4] C. L. Ding, "A study on calculation model of inrushing for foundation pit of semipervious aquiclude with confined water in soft soil area," *Engineering Mechanics*, vol. 25, no. 10, pp. 194–199, 2008.

[5] Y. Y. Sun and S. H. Zhou, "Mode and mechanism of bursting in foundation pit based on centrifugal model test," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 12, pp. 2551–2557, 2010.

[6] F. Zhang, J. P. Li, and C. A. Sun, "Numerical simulation technology for hydraulic heave stability of deep braced excavation under confined water," *Chinese Journal of Underground Space and Engineering*, vol. 13, no. 4, pp. 1100–1105, 2017.

[7] X. Zhang, S. Y. Liu, K. Wu, G. J. Cai, and T. S. Lu, "Numerical analysis of influences of engineering piles on rebound deformation of foundation pit," *Chinese Journal of Geotechnical Engineering*, vol. 43, no. 2, pp. 11–14, 2021.

[8] Z. Li, G. F. Zhao, X. Deng, J. B. Zhu, and Q. B. Zhang, "Further development of distinct lattice spring model for stability and collapse analysis of deep foundation pit excavation," *Computers and Geotechnics*, vol. 144, Article ID 104619, 2022.

[9] C. W. W. Ng, M. Shakeel, J. Wei, and S. Lin, "Performance of existing piled raft and pile group due to adjacent multi-propped excavation: 3D centrifuge and numerical modeling," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 147, no. 4, Article ID 4021012, 2021.

[10] B. X. Yuan, W. J. Chen, J. Zhao et al., "Addition of alkaline solutions and fibers for the reinforcement of kaolinite-containing granite residual soil," *Applied Clay Science*, vol. 228, Article ID 106644, 2022.

[11] B. X. Yuan, Z. H. Li, W. J. Chen et al., "Influence of groundwater depth on pile–soil mechanical properties and fractal characteristics under cyclic loading," *Fractal and Fractional*, vol. 6, no. 4, p. 198, 2022.

[12] National Standard Of The People'S Republic Of China, *GB50007-2011Code for Design of Building Foundations*, China Building and Building Press, Beijing, China, 2011.

[13] Y. R. Liang, "Analysis of gushing in a strip pit of foundations," *Chinese Journal of Geotechnical Engineering*, vol. 18, no. 1, pp. 75–79, 1996.

[14] S. C. Ma, Y. S. Zou, and Y.-S. Wang, "Calculation on the critical thickness of the layer of soil against water pressure of pit," *Building Structure*, vol. 30, no. 11, pp. 44–46, 2000.

[15] S. L. Tan, "Analyses of abrupt gush problem of soil and water based on strength of soil body in building foundation pit," *Journal of China University of Geosciences: Earth Science*, vol. 27, no. 2, pp. 209–211, 2002.

[16] Z. H. Cheng, Z. S. Yu, W. F. Jin, and Z. Y. Song, "Model test study of foundation pit inrush considering the influence of pile foundation," *Bulletin of Science and Technology*, vol. 34, no. 8, pp. 206–210, 2018.