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Research Article

Study on the Influence of Excavation of Superlarge and Ultra-Deep Foundation Pits on the Pile Foundation of Existing Viaducts

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The rapid development of urban above- and underground transportation has brought an increasing number of deep foundation pit projects that close to existing urban viaducts. Excavation of the deep foundation pit projects leads to soil movement around the pile foundation, which adversely affects the adjacent existing pile foundation and seriously threatens the operation safety of the adjacent existing viaduct. In this paper, the three-dimensional numerical model of foundation pit excavation, viaduct, and pile foundation was established by using the MIDAS GTS against the background of the basement foundation pit project in the new Guangzhou Baiyun Station comprehensive transportation hub building, production, and life complex, where the interaction between foundation pit excavation and viaduct pile foundation was simulated. The influence of various excavation-related factors and different parameters of the pile foundation on lateral displacements of the pile body adjacent to the existing pile foundation was analyzed. The variables controlled in the numerical model included the different excavation depths of the foundation pit, the distance between the excavation surface and the adjacent pile foundation, the spatial effect of different excavation sequences, the diameter of the pile that adjacent to the existing pile foundation, and the elastic modulus of the bored occlusal pile support structure. The results indicated that the lateral displacement of the pile body of the bridge pile foundation was significantly affected by the excavation of the deep foundation pit. The excavation depth exerted the greatest influence on the lateral displacement of the pile foundation, followed by the distance between the pile foundation and the excavation surface, the excavation sequence of the foundation pit, and the elastic modulus and the diameter of the bored occlusive pile support structure. Among them, the pile foundation located at the corner of the foundation pit was negligibly affected by these influencing factors. The findings in this study can provide valuable experiences for similar projects.

1. Introduction

In recent years, urban underground structure buildings are increasingly dense, and a growing number of deep foundation pit projects are inevitably in close proximity to pile foundations of existing structures, which have attracted attentions of many scholars to the safety of existing structures adjacent to deep foundation pit projects [1–13]. The unloading effect during excavation of foundation pit near pile foundations of the existing viaduct led to redistributions in displacement and stress fields of the surrounding soils, which consequently affected the load-bearing capacity of the viaduct pile foundations [14–16]. It also seriously contributed to the shear or puncture failure of the bridge pile foundations, affecting the stability of the bridge superstructure and ultimately threatening the operation safety of the viaduct.

Many studies have investigated the deformation of existing adjacent pile foundations caused by soil excavation with the numerical simulations, physical model tests, and on-site monitoring [17–20]. Poulos and Chen [21, 22] adopted centrifugal simulation tests and two-stage analysis methods of the finite element and boundary element to study the influence of excavation-induced lateral soil displacement on adjacent pile foundations, They examined influence of various factors on pile foundation response and proposed design charts to estimate the bending moment and deflection of pile foundations, which could provide reference for the construction of foundation pit engineering with adjacent existing pile foundation. Goh et al. [23] and Finno et al. [24] studied the effects of tunnel excavation on existing adjacent pile foundations through physical experiments. All of the above researchers have used planar assumptions to study the effects of pit excavation on adjacent piles, but it is essentially a three-dimensional problem. Ong et al. [25, 26] investigated the response of excavation to monopiles and piles by performing the centrifugal experiments, and they found that the main factors affecting the bending moment and lateral displacement of pile bodies after excavation were the distance between the pile foundation and the ground wall, as well as the availability of load-bearing constraint at the pile head. Although model tests can restore the stress field of real soil and the results are intuitive, the test process is complicated and expensive to prepare.

Compared with the experimental analysis and on-site monitoring analysis, the numerical simulations allow more accurate prediction of the pile foundation response and are more economical and reasonable in parameter analysis. Liyanapathirana and Nishanthan [27] developed numerical models to verify the centrifuge test results reported by Ong et al. [25] and studied the influence of foundation pit excavation on a single pile by comprehensively considering the excavation depth, undrained shear strength, pile diameter spring rate, vertical support spacing, and other factors. Shakeel and Ng [28] systematically analyzed the effects of excavation depth, pile length, pile distance, excavation position, support system stiffness, soil state, and permeability, as well as working load on the farm group by establishing a three-dimensional numerical model for the excavation of a floating pile group in foundation pit of the soft clay soil layer; it was obtained that the settlement of group piles was maximum when the distance between the group piles and the excavation surface of the foundation pit was 0.75 times of the excavation depth; on the contrary, the lateral displacement of the group piles was minimum at this time, and the lateral displacement of the group piles was maximum the closer it was to the ground-connecting wall side. Nishanthan et al. [29] employed finite element method to analyze the effect of excavation of deep foundation pit with or without support on the deflection of pile foundations with or without pile head constraints; the results show that in unsupported excavation of foundation pits, the existence of piles close to the excavation surface of foundation pits greatly reduces the deflection of foundation piles in group piles, which are far away from the excavation surface of foundation pits, and the deflection of foundation piles caused by foundation pits excavation can be reduced when group piles are setup with bearing platforms, and, on the contrary, when foundation pits are setup with support, the top of group piles, whether or not they are setup with bearing platforms, can't affect the effect of foundation piles excavated by foundation pits, except for the case where the depth of the excavation is very large.

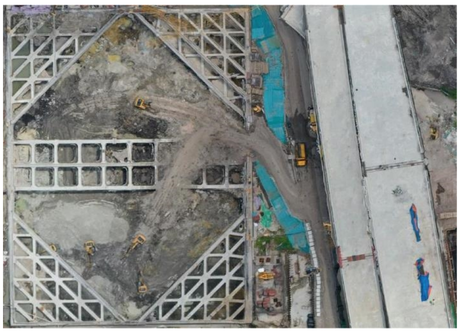


Figure 1: Top view of the foundation pit and viaduct of the production and living complex.

From the above, it can be seen that the parameter analysis of the current research is mostly based on the distance of pile foundation from the excavation surface of the pit, with or without pile head restraint, the number of piles and soil layer parameters, and the research considering the interaction of the spatial position of the close proximity close to the pile foundations and the pit is less; compared with the actual project, more attention is paid to the influence of the excavation sequence of the pit on the close proximity close to the pile foundations, so that it can provide more reference significance to the actual project. In addition, at present, the relevant research mainly adopts the model such as Moore Cullen, and the soil model is too simplified, and it can't sufficiently consider the interaction between soil and pile foundation under the condition of foundation pit excavation and unloading.

In this paper, with reference to the foundation pit of the production and life complex building of Guangzhou Baiyun Station and the comprehensive transportation hub of Guangzhou Baiyun (Tangxi) Station, the influence of the complex construction environment of the foundation pit on the pile foundation of the adjacent existing viaduct was studied. The reliability of the model was verified by the monitoring results of the horizontal displacement of the piles in the foundation pit of the production and living complex and the numerical simulation results. A 3D finite element model developed with the finite element software of MIDAS GTS NX was utilized to simulate the relationship between the foundation pit, and the existing bridge pile foundation, considering the length, pile diameter, the distance of the pile foundation from the foundation pit, and the top of the pile foundation has no bearing constraints, was qualitatively summarized, which provided necessary references for design, construction, and research of the similar engineering.

2. Project Overview

The new Guangzhou Baiyun Station comprehensive transportation hub building is located in the southern part of Baiyun District, Guangzhou, with a total construction area of ~453,000 m^2. Figures 1 and 2 illustrate the relative position relationship between the foundation pit and the viaduct of the production and life complex building. The foundation pit of

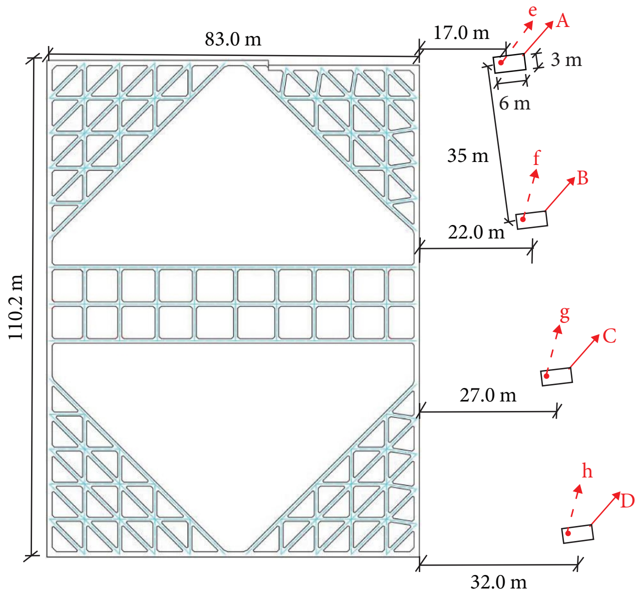


Figure 2: Floor plan of the foundation pit and viaduct bearing of the production and living complex building.

the production and living complex building is a three-story basement structure, with a regular rectangular outer edge. The north–south and east–west lengths are ~110.2 and 83.0 m, respectively, with a circumference of ~386.4 m and an area of ~9,146.6 m^2. The construction of the foundation pit of the production and life complex building adopted cut-and-cover method, and the enclosure employed a comprehensive support system combining the slope, drilling occlusive pile, and reinforced concrete inner support. The excavation depth of the main structure of the foundation pit was 17 m, and the length of the bored occlusal pile was 27 m. A set of support was setup from top to bottom of the foundation pit, and an 18-m long lattice column was installed. On the east side of the foundation pit, the viaduct on the west side of Chashen Avenue extended eastward to Tangchung South Street Viaduct. The centerline of the viaduct pier pile foundation was about 17.0–32.0 m from the centerline of the foundation pit enclosure. The viaduct utilized bored piles, and the pile length and diameter are 35 and 1.4 m, respectively. Field monitoring on horizontal displacements of the bored occlusal pile support structure along the depth direction was carried out to understand the horizontal deformation of the supporting structure. Then, the field monitoring results were compared with the numerical simulation results to verify the rationality of the developed numerical model.

3. Numerical Simulation

3.1. Constitutive Model. For meeting the engineering demands, as well as convenience and practicality, the modified Mohr–Coulomb model was chosen to describe the stress–strain behaviors of the soil in numerical simulation of the construction stage of the foundation pit. The modified Mohr–Coulomb model, a composite of nonlinear elasticity and plasticity, can fully consider shear and compression deformations and is suitable for clay simulation. Therefore, this constitutive model was used for simulation, in which the unevenness of the soil layer and the occurrence of individual lens bodies were ignored and the soil mass was simplified into layered soil. The numerical model assumed that the support structure and other components were isotropic materials. The effect of water level was not considered in the simulations, and also the influence of excavation time and space on the calculation results was not considered in the analysis process.

3.2. Engineering Geology. On the basis of the relevant geological survey data and drilling results, the surface cover layers of the site were the artificial fill layer and alluvium of the quaternary, and the lower bedrock was the marl and limestone of the Permian Qixia Formation. The soil layers from top to bottom in the influencing range were mainly the mixed fill soil, silty clay, fully weathered marl, and moderately weathered marl, and the thickness of each soil layer can be calculated according to the elevation displayed in the soil profile. The typical profile, as shown in Figure 3, was adopted to represent the soil layer distribution in the foundation pit area of the production and living complex building. The detailed soil parameters determined by on-site and laboratory tests are shown in Table 1.

3.3. Model Establishment. To avoid boundary effects from affecting the numerical results, the boundary influencing width and depth from excavation boundary in the model was considered to be ~three to five and two to four times of the excavation depth of the foundation pit. The 3D numerical model of the foundation pit and viaduct, as shown in Figure 4, was established using the finite element software MIDAS GTS NX, and the length, width, and height of the model were 340, 160, and 70 m, respectively. Figure 5 illustrates the schematic diagram of bored occlusal piles, concrete supports, crown beams, lattice columns, and bridge pile foundations. Since the bored occlusal piles were subjected to lateral pressures from the soil and concrete support after excavation of the foundation pit, they were simulated with 2D unit plate and elastic constitutive model, in order to improve the calculation accuracy of the model. The internal support, crown beam, and pile foundation were simulated with linear beam elements, and the piers and piles were automatically coupled with the soils. The numerical model sets boundary constraints and considered only the self-weight stress effect, in which the torsional constraints were applied to the lattice columns and bridge pile foundations. The bridge pile foundation adopts interface unit and pile end unit to simulate the interaction with soil body in the actual construction process, and the soil body and other models adopt hexahedral solid unit, with a total number of 143,053 units and 101,182 nodes. The numerical model did not consider the effects of groundwater, soil consolidation, and creep.

3.4. Calculation of Load Steps. The simulated excavation of the foundation pit consisted of eight steps. For the initial stress field in the site before excavation, the changes in the soil stress field due to the construction of the viaduct should be considered. Therefore, it is necessary to simulate the

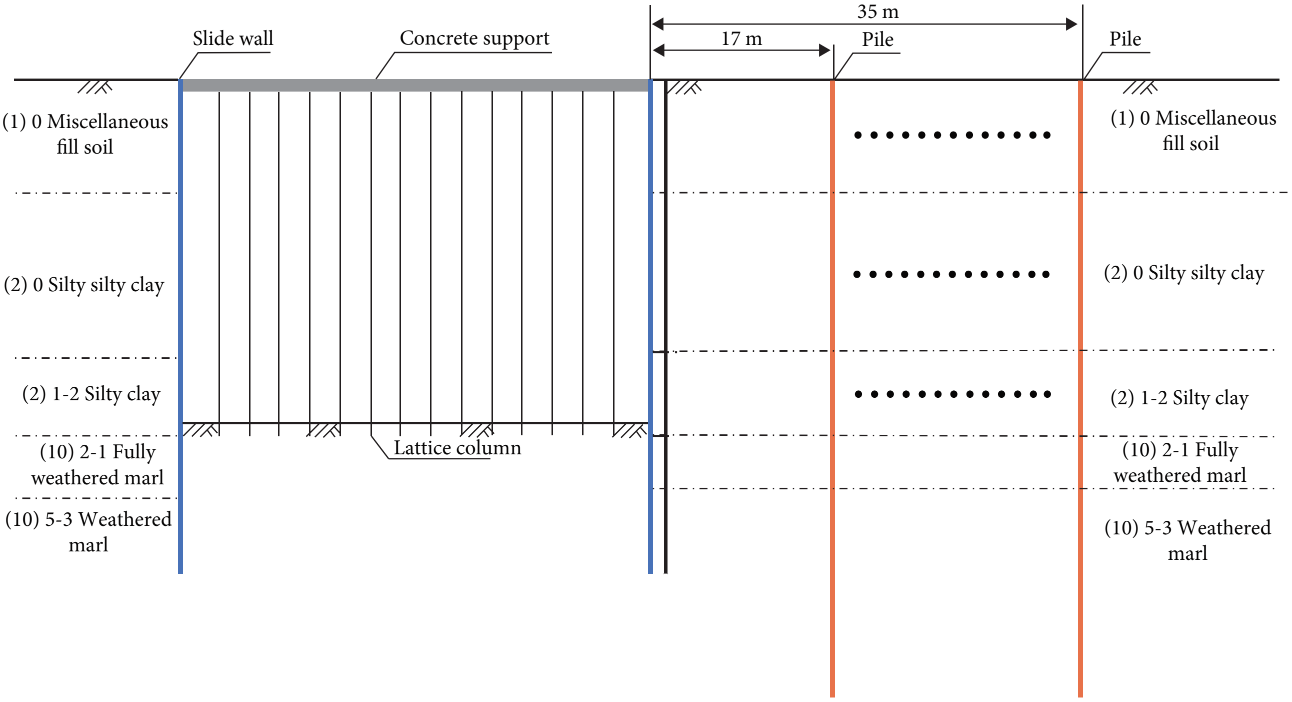


Figure 3: The typical profile represents the soil layer distribution in the foundation pit area of the production and living complex building.

Table 1: Soil parameters.

Soil	ν	γ (kN/m^3)	ρ (g/m^3)	c (kPa)	φ (°)
(1) 0 Miscellaneous fill soil	0.3	19.0	1.9	6.8	12
(2) 0 Silty silty clay	0.3	16.8	1.68	8	6
(2) 1-2 Silty clay	0.3	17.3	1.9	26.25	9.21
(10) 2-1 Fully weathered marl	0.25	23.0	1.89	44.2	24.6
(10) 5-3 Weathered marl	0.2	26.8	2.59	300	30

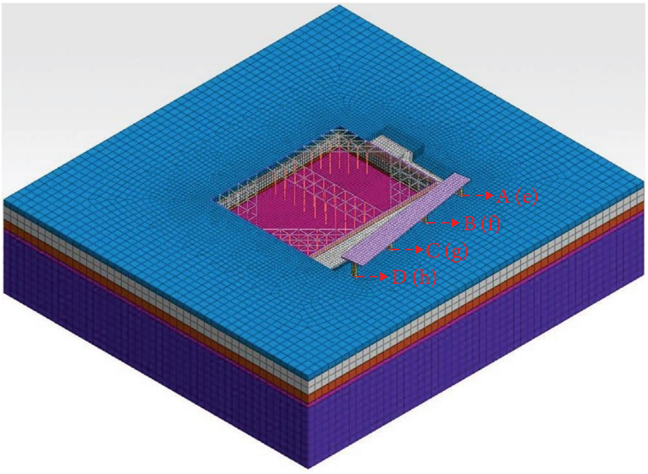


Figure 4: Schematic diagram of the overall model.

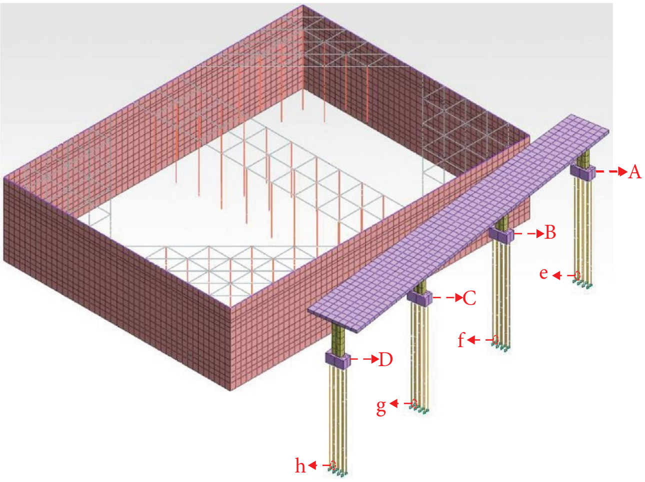


Figure 5: Schematic diagram of the supporting structure and the pile foundation model of the viaduct.

construction process of the viaduct with considering the self-weight stress field of the soils. As the viaduct was built before the excavation of the foundation pit, the displacement of the viaduct structure was cleared in the model after the bridge construction was completed, and only the effect of excavation of the foundation pit on pile foundation was considered. The detailed analysis conditions are shown in Table 2.

TABLE 2: Construction steps.

Excavation stage no.	Description
1	Initial in situ stress analysis and self-weight load application
2	Viaduct structure construction
3	Displacement clearance
4	Drilled occlusal pile construction
5	Crown beam construction, inner support and lattice column construction, and the first stage of the foundation pit excavation to the elevation of −5 m
6	The second stage of the foundation pit was excavated to an elevation of −8 m
7	The third stage of the foundation pit was excavated to an elevation of −12.5 m
8	The fourth stage of the foundation pit was excavated to an elevation of −17 m

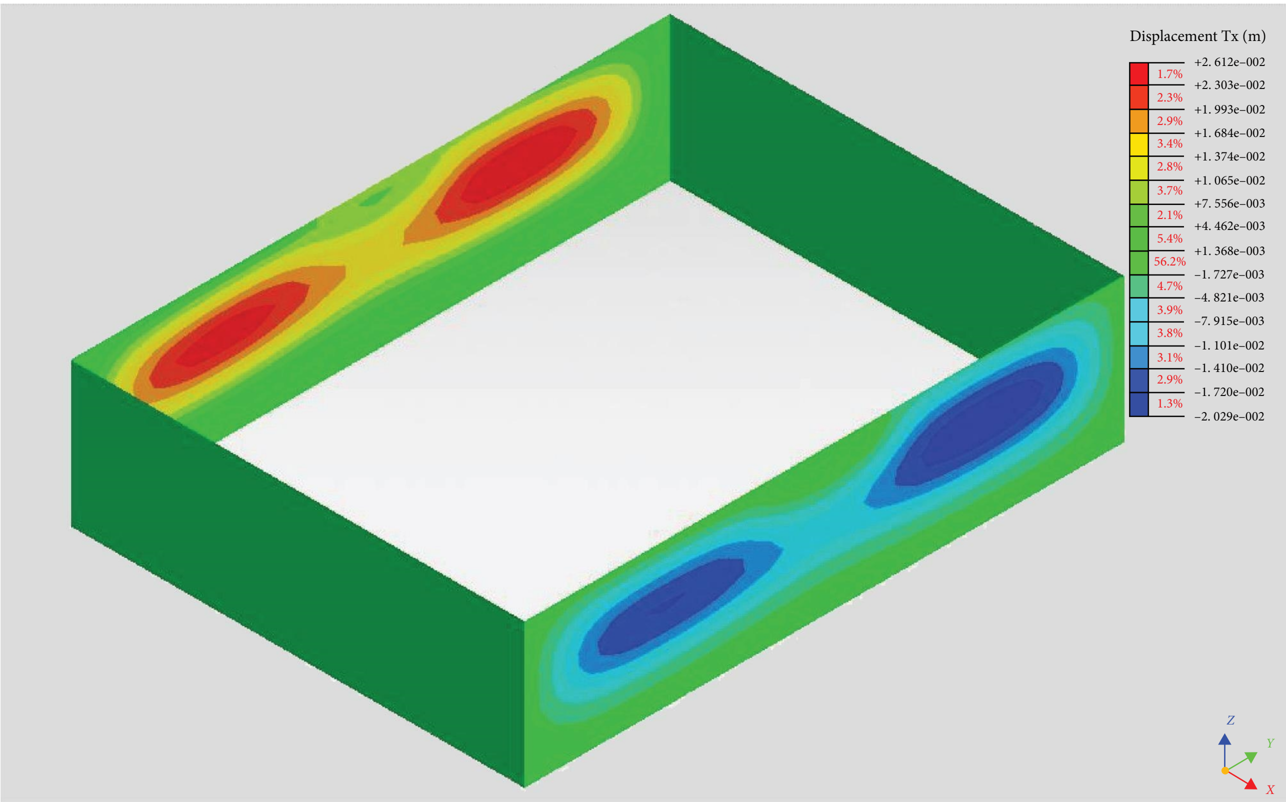


FIGURE 6: Horizontal displacement deformation cloud in the *X* direction of the bored occlusal pile envelope.

3.5. Analysis of Numerical Simulation Results

3.5.1. Horizontal Displacement Analysis of Bored Occlusal Pile Envelope. The displacement and stress fields of the surrounding soil would also change during the excavation of the foundation pit of the XingBaoLou, and subsequently horizontal deformation of the bored occlusal pile enclosure structure would occur. Figure 6 illustrates the horizontal displacement cloud diagrams of the bored occlusal pile enclosure structure. It demonstrates that the lateral displacement of the envelope on both sides in the *X* direction is asymmetrical, and the horizontal displacement change of the right envelope is smaller than the horizontal displacement change of the left envelope; this is due to the fact that the soil around the envelope near the pile foundation side of the viaduct was graded. As shown in Figure 6, the positive direction of the *X*-axis was plotted from left to right, and the negative sign indicated the opposite reverse, i.e., the ground wall is deformed toward the inside of the foundation pit. Figure 7 presents the monitoring and numerical simulation results of the lateral displacements of the ungraded side of the ground wall and the side away from the bridge. The red dashed circle represents the inclinometer tube and is buried at the central position of the pit enclosure structure; because of the long time of pit excavation and construction, the lateral displacement of the pit enclosure structure is monitored at a frequency of 1 time/day, and the horizontal displacement of the enclosure structure is up to 21.2 mm as of the completion of pit excavation. It is

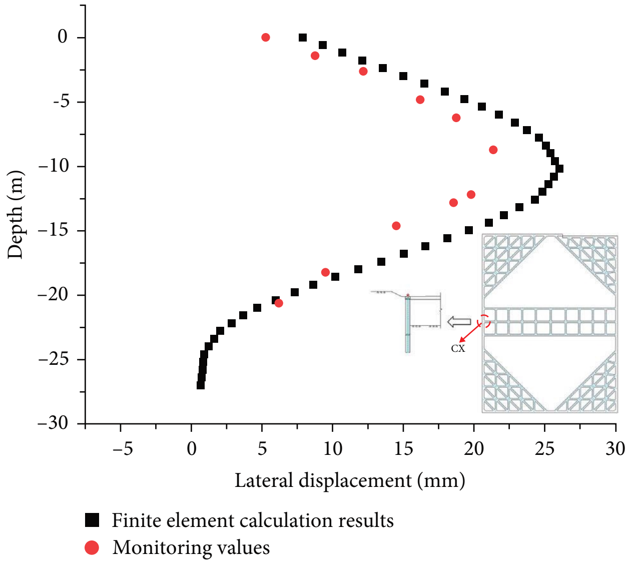


Figure 7: Comparison of on-site monitoring and numerical results of CX enclosure structure at monitoring points.

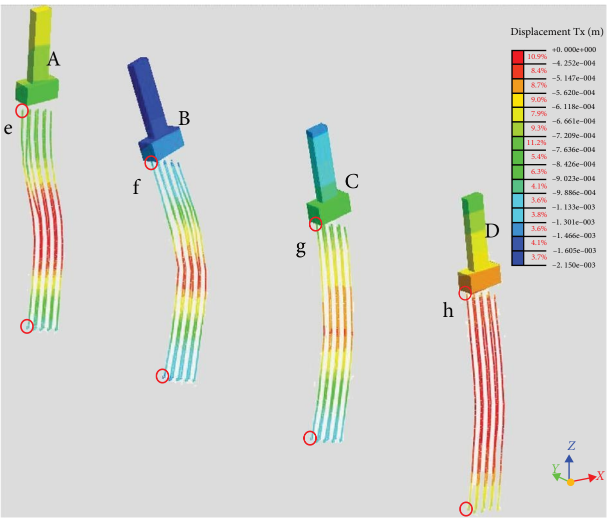


Figure 8: Horizontal deformation cloud diagrams of viaduct pile.

demonstrated that the two results matched well, in which the maximum values of the monitoring and numerical results were 21.2 and 26.1 mm, respectively, and the numerical results were close to the monitoring values. Therefore, numerical simulation can effectively predict the deformation of the enclosure structure and bridge pile foundation during the construction of the deep foundation pit, so as to guide the on-site construction.

3.5.2. Analysis of Horizontal Displacement of Viaduct Pile Foundation by Excavation. During the excavation of the foundation pit of the production and life complex building, the displacement and stress fields of the surrounding soil would also change. The displacement cloud diagrams, as shown in Figure 8, confirmed that the four piers and pile foundations of the viaducts labeled A, B, C, and D all generated lateral horizontal displacements toward the foundation pit. The displacement cloud diagrams of pile, as shown in Figure 8, demonstrated that the displacements of the four pile foundations e, f, g, and h marked with red circles were the same, as shown in Figure 9, Also, they were the same as the displacements of the side of the foundation pit. The four piles labeled e, f, g, and h were situated at different locations, and their lateral displacements varied considerably. The lateral displacements of the pile f were the largest because it was situated in the middle of the foundation pit and was closest to the excavation surface of the foundation pit. The lateral displacement of g, e, and h piles decreased sequentially. Although the pile e was very close to the foundation pit, it was located at the corner of the foundation pit and was constrained by the corner, and the damage range of the soil caused by the foundation pit excavation in the corner was much smaller than that of the soil in other areas of the foundation pit. Therefore, the lateral displacement of the pile e is less than the lateral displacement of the pile body of f, g, and h. Figure 9 presents the variations of the lateral displacement of the four pile foundations of e, f, g, and h when the excavation depths were 5, 8, 12.5, and 17 m, respectively. It can be seen that the lateral displacements and bending moments of the pile body increased with the increasing excavation depths.

4. Parametric Analysis

4.1. Influence of Different Distance of Pile Foundation from the Excavation Surface of the Foundation Pit. The soil parameters and envelope parameters were kept constant in the model, where the pile diameter and length of the existing pile foundation were 1.4 and 35 m, respectively. Figure 10 presents the overall lateral displacements of pile body of existing pile foundation, when the excavation depth of the foundation pit was 17 m. The distances between the existing pile foundation and the excavation surface of the foundation pit were 2, 7, 12, 17, and 22 m, respectively. It can be observed that the larger the distance between the pile body and the excavation surface of the foundation pit, the smaller the overall lateral displacement of the adjacent pile foundation. The lateral displacements of the four piles were f > g > e > h, as the order of distance from the excavation surface of the foundation pit was arranged in the order of h > g > f > e. The pile of e was located at the corner of the foundation pit, and the pit angle effect led to the lateral displacements less than those of piles f and g.

4.2. Influence of Different Excavation Sequences. Different excavation sequences of the soil in the foundation pit gave rise to different displacement and stress fields in the surrounding soil, which resulted in varying lateral displacement effects on the adjacent pile foundation. As shown in Figure 11, the soil in the foundation pit was divided into four zones that identified as 1, 2, 3, and 4. Figure 11 illustrates seven different excavation sequences: the effects of integral excavation;

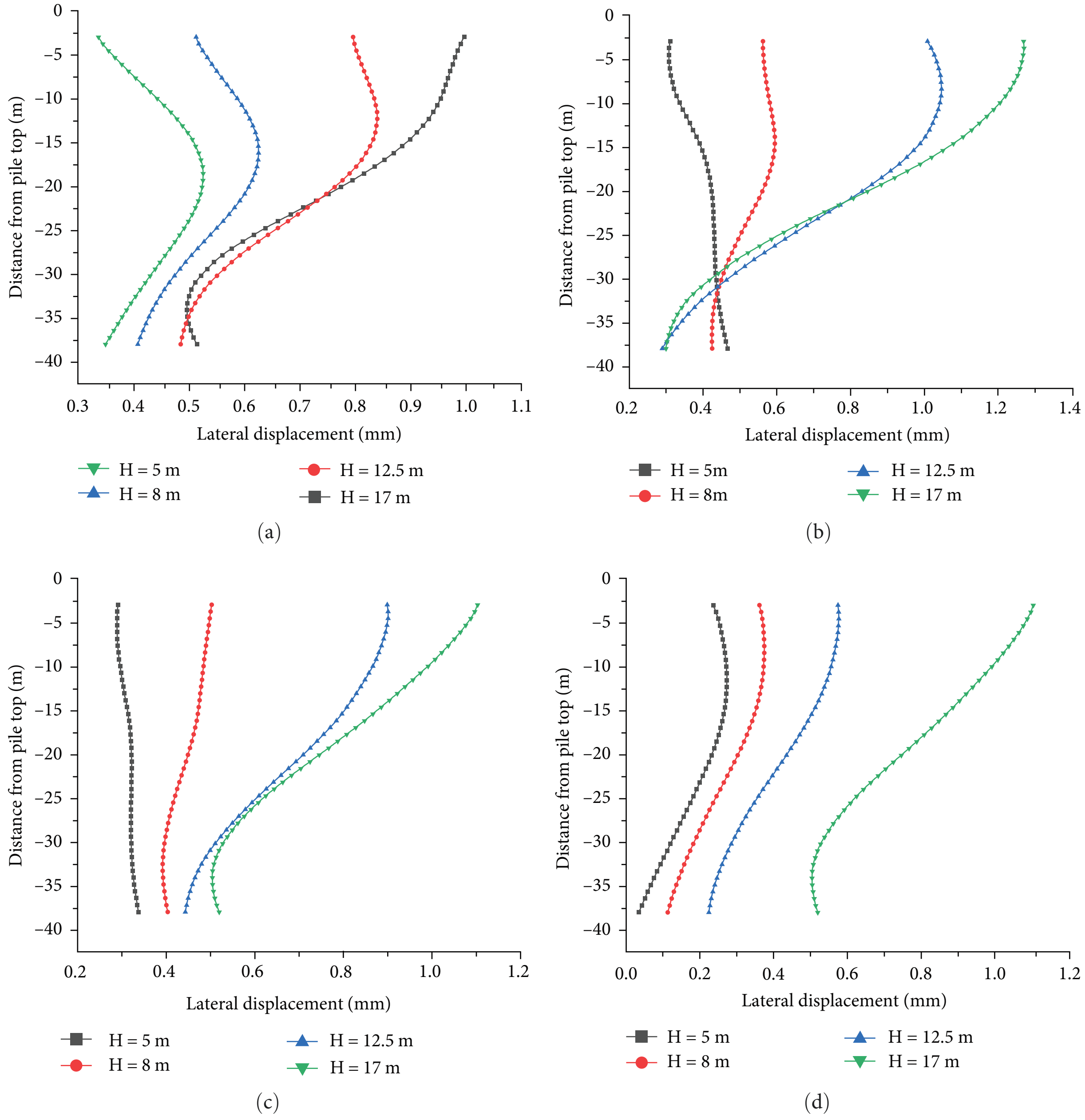
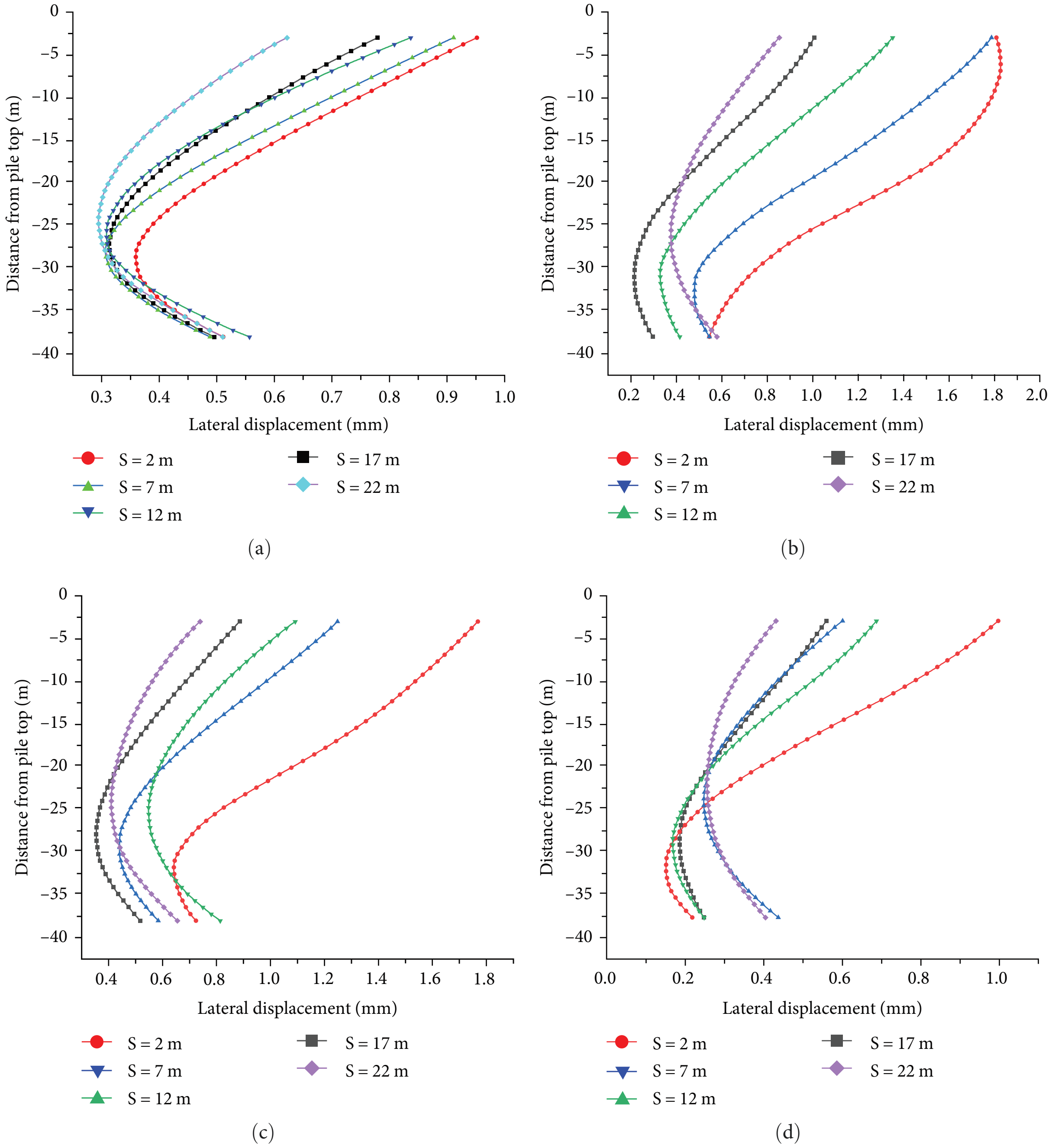


Figure 9: Diagram of the change of pile displacement of different piles with the increase of excavation depth (the letters a, b, c, and d represent piles e, f, g, and h, as shown in Figure 8, respectively).

1 → 2 → 3 → 4; 1 → 3 → 2 → 4; (3, 4) → (1, 2); (3, 2) → (1, 4); (1, 4) → (2, 3); and (1, 2) → (3, 4) on the lateral displacement of existing pile foundations. It indicates that the lateral displacements of the pile e, f, g, and h under the overall excavation sequences of (3, 2) → (1, 4); (1, 4) → (2, 3) along the long side of the foundation pit were greater than that under the overall excavation sequences of 1 → 2 → 3 → 4; 1 → 3 → 2 → 4; (3, 4) → (1, 2); (1, 2) → (3, 4) along the short side direction of the foundation pit. The sequence of pit excavation in this paper suggests to excavate along the direction of the short side of the pit, according to this way of excavation can reduce the impact of pit excavation on the adjacent existing pile foundation, but in the actual project, the sequence of pit excavation can be chosen to be perpendicular to the pile foundation or existing building immediately adjacent to the pit of a side of the direction of the direction of the excavation, which can reduce the impact of pit excavation on the surrounding environment.

4.3. The Influence of Different Pile Diameters. The lateral displacement of the existing pile foundation adjacent to the excavation surface of the foundation pit was related to the diameter and cross-sectional area of the pile body. In this numerical scenery, the diameters of the existing pile



(a)

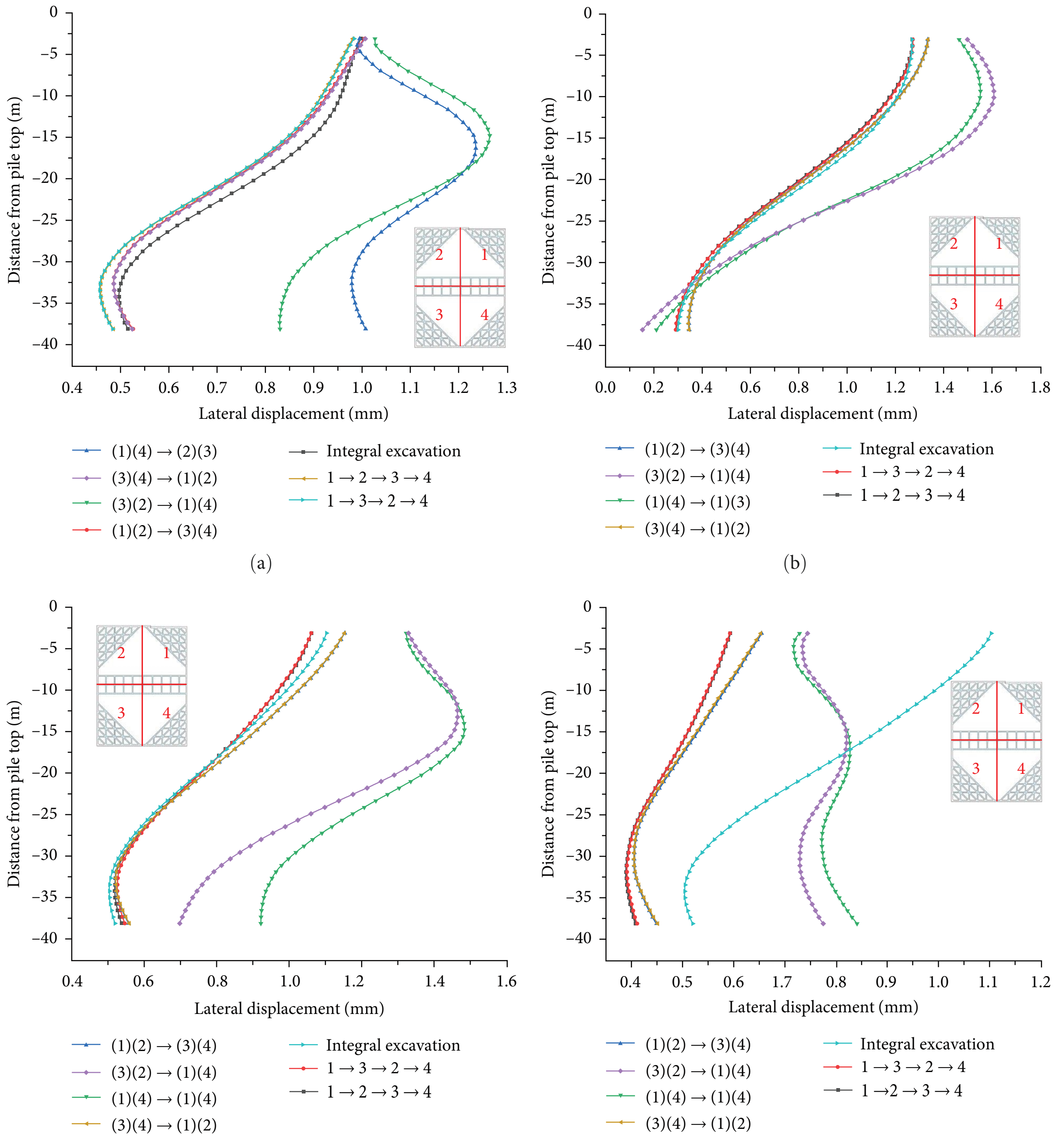
(b)

(c)

(d)

FIGURE 10: Influence of different distances of pile foundation from excavation surface of foundation pit on the overall lateral displacement of pile body of existing pile foundation (the letters a, b, c, and d represent piles e, f, g, and h, as shown in Figure 8, respectively).

foundation were 0.8, 1, 1.1, 1.2, and 1.4 m, respectively, and the soil parameters and envelope parameters were kept constant. The excavation depth of the foundation pit was 17 m, while the pile diameter and length were 1.4 and 35 m, respectively. Figure 12 shows the lateral displacement change diagrams of the four piles e, f, g, and h with different diameters of pile foundations. It can be seen that the larger the diameter of the existing pile foundation, the smaller the lateral displacement of the pile foundation. The lateral displacements of the four piles e, f, g, and h were f > g > e > h, as the sizes of the four piles were h > g > f > e. The pile body of e was located at the corner of the foundation pit, and the pit angle effect led to the lateral displacements less than those of piles f and g. It can be seen that by increasing the pile base of the pile foundation, it has a certain effect on limiting the lateral displacement of the pile body, but it is not obvious, because the increase of the pile diameter of the pile foundation is not obvious for the improvement of the overall bending stiffness of the extra long pile; so in the actual project, increasing the pile diameter of the pile foundation is not an effective

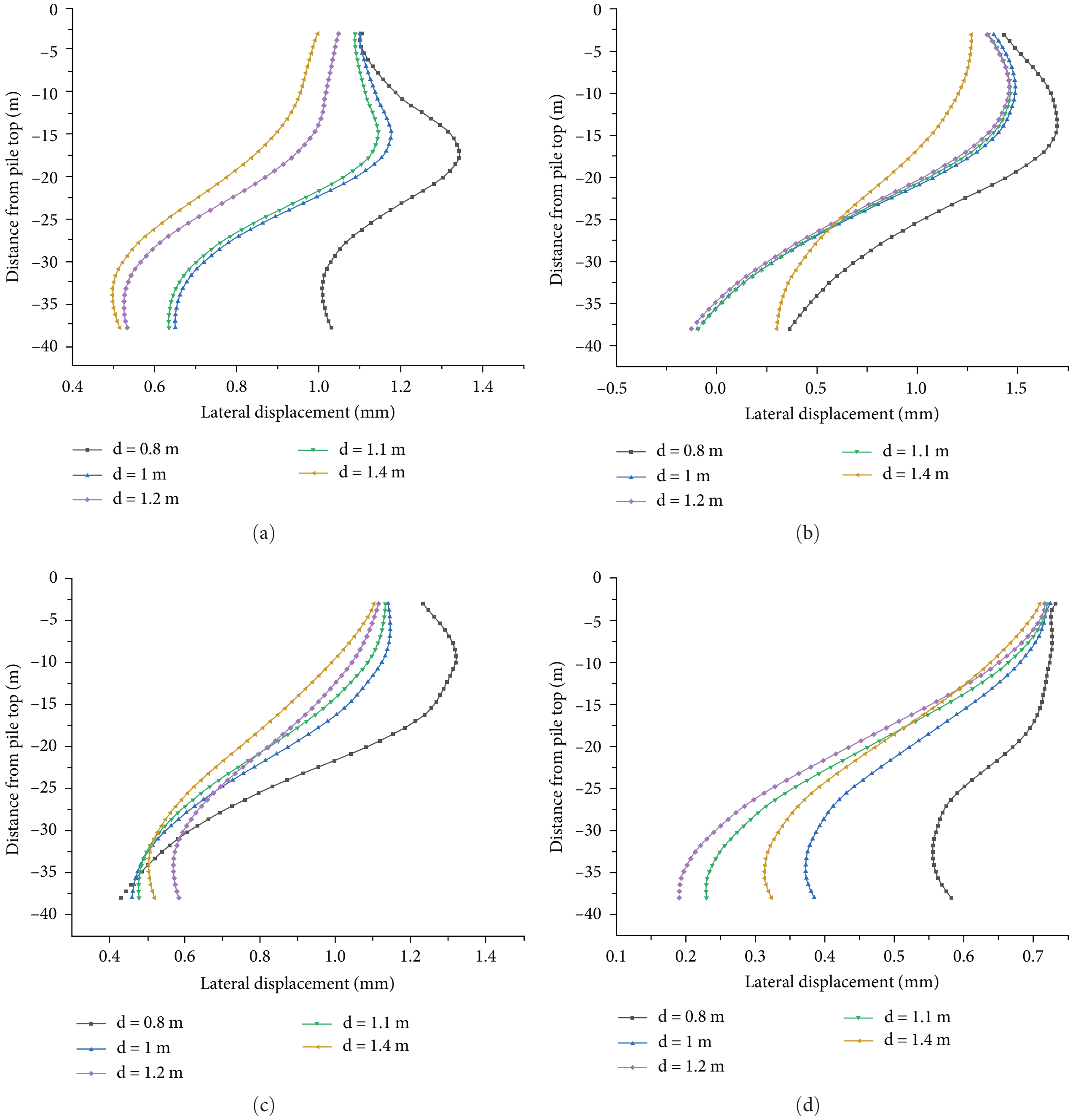


(a) (b) (c) (d)

Figure 11: Influence of different excavation sequences on the lateral displacement of the overall pile body of the existing pile foundation (the letters a, b, c, and d represent piles e, f, g, and h, as shown in Figure 8, respectively).

method to solve the problem of the pile foundation with the lateral displacement becoming larger.

4.4. Influence of Different Elastic Modulus of Drilled Occlusal Pile Support Structures. In this numerical scenery, the elastic moduli of bored occlusal pile were 5, 20, 30, and 40 MPa, as well as the diameter and length of the pile were 1.4 and 35 m, respectively. Figure 13 shows the lateral displacement change cloud diagrams of the four piles a, b, c, and d under different elastic modulus of the bored occlusal pile support structure at an excavation depth of 17 m. It indicates that the larger the elastic modulus of the bored occlusal pile, the smaller the lateral displacement of the adjacent pile foundation. When the elastic moduli of the bored occlusal pile were 20, 30, and



(a)

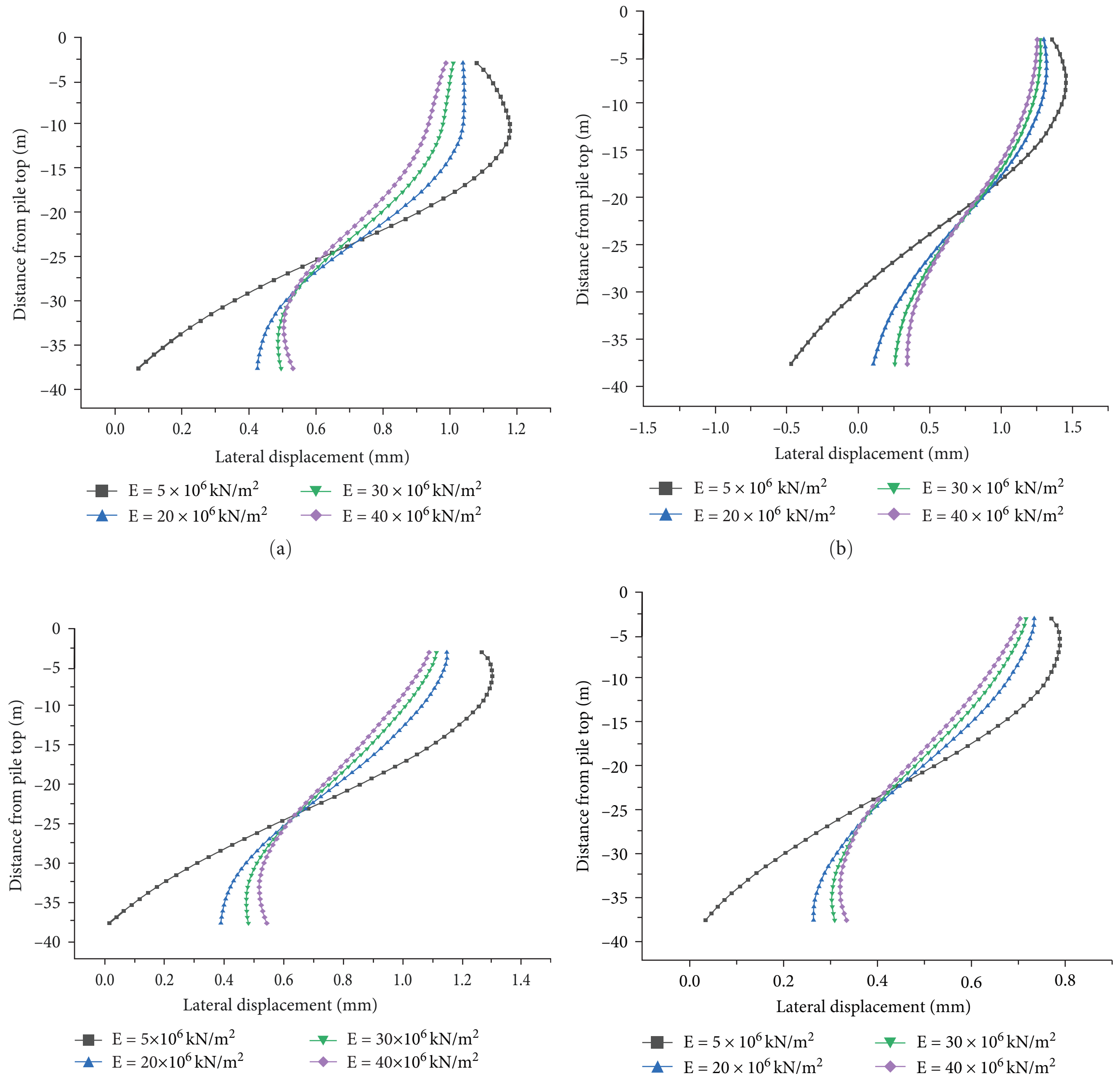
(b)

(c)

(d)

Figure 12: Influence diagram of different pile diameters on the lateral displacement of the overall pile body of the existing pile foundation (the letters a, b, c, and d represent piles e, f, g, and h, as shown in Figure 8, respectively).

40 MPa, the lateral displacements of the adjacent e, f, g, and h foundations were similar, and they were all less than that when the elastic modulus of the bored occlusal pile was 10 MPa. Also, the lateral displacements of the four piles were f > g > e > h because the order of distance from the excavation surface of the foundation pit was arranged in the order of h > g > f > e. The pile body of e was located at the corner of the foundation pit, and the pit angle effect led to the lateral displacements less than those of piles f and g. It can be seen that changing the modulus of elasticity of the drilled and bitten pile support structure has a very small effect on the lateral displacement of the pile foundation; this is because the soil excavation unloads, the bottom of the foundation pit rises, and when the stiffness of the drilled and bitten pile support structure is large, the displacement of the soil on the side of the drilled and bitten pile support structure to the foundation pit decreases, and the soil on the side of the bridge pile foundation; the amount of the displacement to the foundation pit increases, resulting in the deflection of the bridge pile foundation to the direction of the foundation pit increases, but the amount of change is very small.



(a) (b) (c) (d)

Figure 13: Effect of different elastic modulus of drilled occlusal pile support structures on the lateral displacement of the overall pile body of existing pile foundation (the letters a, b, c, and d represent piles e, f, g, and h, as shown in Figure 8, respectively).

5. Conclusion

In this paper, with reference to the foundation pit project of Guangzhou Baiyun Station Engineering Production and Life Complex Building and Guangzhou Baiyun (Tangxi) Station Comprehensive Transportation Hub, the finite element 3D numerical model of the deep foundation pit excavation, support structure, and viaduct was established by using MIDAS GTS NX, and then the influence of foundation pit excavation on the adjacent existing pile foundation was analyzed. The variation characteristics of adjacent excavation and horizontal displacement were studied, and the main conclusions are given as follows:

(1) The horizontal displacements and bending moments generated by the existing pile foundation increased with the increasing excavation depth.

(2) The horizontal displacements generated by the adjacent existing pile foundation varied with the changes of the elastic modulus of the bored occlusal pile support structure. The smaller the elastic modulus of the bored occlusal pile support structure, the greater the influence

of the adjacent existing pile foundation and the larger the displacement of the adjacent existing pile foundation. On the contrary, the larger the elastic modulus of the bored occlusal pile support structure, the smaller the influence of the adjacent existing pile foundation.

(3) The influence of excavation sequence on the lateral displacement of adjacent existing pile foundation was also very obvious, and the influence of the excavation sequence along the long side of the foundation pit on the lateral displacement of the adjacent existing pile foundation was greater than that of the overall excavation and the excavation sequence along the short side of the foundation pit. The lateral displacement of pile foundation located at corner of the foundation pit was less affected by excavation sequence, while influence of diameter of the pile foundation and elastic modulus of the bored occlusal pile support structure on the lateral displacement was almost negligible.

(4) The influence of excavation sequence on the lateral displacement of adjacent existing pile foundation was also very obvious, and influence of excavation sequence along the long side of the foundation pit on the lateral displacement of the adjacent existing pile foundation was greater than that of the overall excavation and excavation sequence along the short side of the foundation pit. The lateral displacement of pile foundation located at the corner of the foundation pit was less affected by the excavation sequence, and influence of the diameter of the pile foundation and the elastic modulus of the bored occlusal pile support structure was almost negligible.

(5) When the diameter of the existing pile foundation was greater than 1 m, the overall lateral displacement of the pile body was affected slightly; when the diameter of the pile foundation was less than 0.8 m, the overall lateral displacement of the pile body was affected significantly.

Data Availability

Data will be made available by the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] B. Liu, D.-W. Zhang, C. Yang, and Q.-B. Zhang, "Long-term performance of metro tunnels induced by adjacent large deep excavation and protective measures in Nanjing silty clay," *Tunnelling and Underground Space Technology*, vol. 95, Article ID 103147, 2020.

[2] S. L. Shen, H. N. Wu, Y. J. Cui, and Z. Y. Yin, "Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai," *Tunnelling and Underground Space Technology*, vol. 40, pp. 309–323, 2014.

[3] J. Shi, J. Wei, C. W. W. Ng, and H. Lu, "Stress transfer mechanisms and settlement of a floating pile due to adjacent multi-propped deep excavation in dry sand," *Computers and Geotechnics*, vol. 116, Article ID 103216, 2019.

[4] C. W. W. Ng, M. Shakeel, J. Wei, and S. Lin, "Performance of existing piled raft and pile group due to adjacent multipropped excavation: 3D centrifuge and numerical modeling," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 147, no. 4, pp. 110–112, 2021.

[5] P. Zhou, H. Zhou, H. Liu, X. Li, X. Ding, and Z. Wang, "Analysis of lateral response of existing single pile caused by penetration of adjacent pile in undrained clay," *Computers and Geotechnics*, vol. 126, Article ID 103736, 2020.

[6] F. Taiyari, M. Kharghani, and M. Hajihassani, "Optimal design of pile wall retaining system during deep excavation using swarm intelligence technique," *Structures*, vol. 28, pp. 1991–1999, 2020.

[7] J. Liu, C. Shi, C. Cao, M. Lei, and Z. Wang, "Improved analytical method for pile response due to foundation pit excavation," *Computers and Geotechnics*, vol. 123, Article ID 103609, 2020.

[8] Z. Zhang, M. Huang, C. Zhang, K. Jiang, and M. Lu, "Time-domain analyses for pile deformation induced by adjacent excavation considering influences of viscoelastic mechanism," *Tunnelling and Underground Space Technology*, vol. 85, pp. 392–405, 2019.

[9] F. Castelli, "Discussion of "behavior of pile groups subject to excavation-induced soil movement in very soft clay" by D. E. L. Ong, C. F. Leung, and Y. K. Chow," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 137, no. 1, pp. 110–112, 2011.

[10] H.-F. Shan, S.-H. He, Y.-H. Lu, and W.-J. Jiang, "Case study and numerical simulation of excavation beneath existing buildings," *Advances in Civil Engineering*, vol. 2020, Article ID 8817339, 14 pages, 2020.

[11] M.-Y. Zhang, J.-X. Ma, S.-J. Yang, Y.-H. Wang, X.-Y. Bai, and S.-X. Sun, "Experimental study on bending moment of double-row steel pipe piles in foundation excavation," *Advances in Civil Engineering*, vol. 2020, Article ID 8882713, 8 pages, 2020.

[12] H. Wei, "Influence of foundation pit excavation and precipitation on settlement of surrounding buildings," *Advances in Civil Engineering*, vol. 2021, Article ID 6638868, 9 pages, 2021.

[13] C. Lu and L. Huang, "Study on the effect of foundation pit excavation on the deformation of adjacent shield tunnel," *Advances in Civil Engineering*, vol. 2022, Article ID 8441758, 9 pages, 2022.

[14] C. W. W. Ng, J. Q. Wei, H. Poulos, and H. L. Liu, "Effects of multipropped excavation on an adjacent floating pile," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 143, no. 7, Article ID 04017021, 2017.

[15] Y.-Y. Liang, N.-W. Liu, F. Yu, X.-N. Gong, and Y.-T. Chen, "Prediction of response of existing building piles to adjacent

deep excavation in soft clay," *Advances in Civil Engineering*, vol. 2019, Article ID 8914708, 11 pages, 2019.

[16] Y. Chen, F. Lu, A. Namdar, and J. Cai, "Working mechanism of pile group with different pile spacing in dense sand," *Advances in Civil Engineering*, vol. 2019, Article ID 5376594, 16 pages, 2019.

[17] R. J. Finno, J. T. Blackburn, and J. F. Roboski, "Three-dimensional effects for supported excavations in clay," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 1, pp. 30–36, 2007.

[18] R. J. Finno, L. G. Arboleda-Monsalve, and F. Sarabia, "Observed performance of the one museum park west excavation," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 141, no. 1, Article ID 04014078, 2015.

[19] T. Schwamb and K. Soga, "Numerical modelling of a deep circular excavation at Abbey Mills in London," *Géotechnique*, vol. 65, no. 7, pp. 604–619, 2015.

[20] Y. P. Dong, H. J. Burd, and G. T. Houlsby, "Finite-element analysis of a deep excavation case history," *Géotechnique*, vol. 66, no. 1, pp. 1–15, 2016.

[21] H. G. Poulos and L. T. Chen, "Pile response due to unsupported excavation-induced lateral soil movement," *Canadian Geotechnical Journal*, vol. 33, no. 4, pp. 670–677, 1996.

[22] H. G. Poulos and L. T. Chen, "Pile response due to excavation-induced lateral soil movement," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 123, no. 2, pp. 94–99, 1997.

[23] A. T. C. Goh, K. S. Wong, C. I. Teh, and D. Wen, "Pile response adjacent to braced excavation," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 129, no. 4, pp. 383–386, 2003.

[24] R. J. Finno, S. A. Lawrence, N. F. Allawh, and I. S. Harahap, "Analysis of performance of pile groups adjacent to deep excavation," *Journal of Geotechnical Engineering*, vol. 117, no. 6, pp. 934–955, 1991.

[25] D. E. Ong, C. E. Leung, and Y. K. Chow, "Pile behavior due to excavation-induced soil movement in clay. I: stable wall," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 132, no. 1, pp. 36–44, 2006.

[26] D. E. L. Ong, C. F. Leung, and Y. K. Chow, "Behavior of pile groups subject to excavation-induced soil movement in very soft clay," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 135, no. 10, pp. 1462–1474, 2009.

[27] D. S. Liyanapathirana and R. Nishanthan, "Influence of deep excavation induced ground movements on adjacent piles," *Tunnelling and Underground Space Technology*, vol. 52, pp. 168–181, 2016.

[28] M. Shakeel and C. W. W. Ng, "Settlement and load transfer mechanism of a pile group adjacent to a deep excavation in soft clay," *Computers and Geotechnics*, vol. 96, pp. 55–72, 2018.

[29] R. Nishanthan, D. S. Liyanapathirana, and C. J. Leo, "Shielding effect in pile groups adjacent to deep unbraced and braced excavations," *International Journal of Geotechnical Engineering*, pp. 1–13, 2016.