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Research Article

Deformation Characteristics of a Deep Subway Foundation Pit in Hard Rock Strata under a Delayed Supporting Condition

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In this investigation, deformations of a deep foundation pit in hard rock strata, respectively, under delayed and in-time supporting schemes of one-layer transverse reinforced concrete bracings at the top of the foundation pit, one-layer steel bracings at a depth of 8 m, and one-layer prestressed anchorages at a depth of 22.5 m during excavation were characterized according to lateral deformations of the foundation pit, settlements of the surrounding ground, and axial forces of the steel bracings according to numerical calculations and on-site monitoring. Numerical calculation results showed that the maximum lateral deformations of the foundation pit and settlements of the surrounding ground were, respectively, 10.34 mm and 8.49 mm at an excavation depth of 31 m, which were obviously larger than those under in-time supporting. Meanwhile, under delayed supporting conditions, lateral deformations of the foundation pit and settlements of the surrounding ground were far less than the allowed values, respectively, being 0.3% and 0.15% of the excavation depth, required in the Chinese standard of GB50007-2011, indicating that the foundation pit under delayed supporting conditions had good stability. Therefore, when excavating deep foundation pits in hard rock strata, proper delayed supporting schemes could be considered so that strengths of the surrounding hard rocks could be utilized to the fullest, and at the same time, more spaces for excavation could be freed up, and construction duration and construction costs could thus be lowered.

1. Introduction

To alleviate transportation stresses, many cities in China have been developing subway systems during the last five years [1, 2]. Subway stations are one of the most important parts of subway systems, the construction of which is closely related to foundation pit excavation. Excavation techniques and supporting schemes for the foundation pit should not only consider the geological conditions but also the adjacent existing buildings, structures, and transportations [3–5].

During excavation process, stresses of surrounding soil strata are redistributed, and certain pressures are thus acted on enclosure structures of the foundation pit, thus leading to lateral deformations of the foundation pit and settlements of the surrounding ground [6]. Excessive lateral deformations and settlements will cause instability of the foundation pit, which poses a great threat to the safety of the foundation pit during excavation process [7]. Therefore, stability of the foundation pit during excavations should be carefully analyzed before constructions based on the deformation characteristics of the foundation pit [8].

In order to analyze the stability of the foundation pit, deformations of the foundation pit are usually characterized based on empirical and numerical analyses [9]. Many researchers have investigated deformations of foundation pits during excavation based on empirical analysis methods, and some new empirical analysis methods are thus proposed corresponding to a certain geological condition, such as an improved MSD method for foundation pit in soil strata and a Gaussian-type empirical formulation for foundation pit in soil-rock composite strata [10, 11]. Though empirical analysis methods are precise in terms of analyzing deformations of a foundation pit, the corresponding analysis processes are usually of low efficiency. Therefore, numerical analysis tools, such as FlAC^{3D}, Midas GTS NX, and PLAXIS3D, are usually adopted to calculate stresses and deformations of the foundation pits to be excavated for the purpose of increasing analysis efficiency meanwhile assuring the analysis accuracy [12–15].

At present, most numerical investigations are focused on deformations of foundation pit in soil strata or soil-rock composite strata [16–19]. Unlike foundation pit in soil strata or soil-rock composite strata, foundation pit in hard rock strata has good stability if the same supporting schemes for foundation pits in soil strata or soil-rock composite strata are adopted, which is because the surrounding rocks of the foundation pit in hard rock strata have certain strengths and antideformation abilities [20]. However, considering the antideformation ability of the surrounding rocks with certain strengths, the supporting schemes and techniques for foundation pit excavations in soil strata or soil-rock strata are not practical for those in hard rock strata, which is because such supporting schemes and techniques may lead to narrow working spaces, oversupport, waste of resources, and an increase in the construction period. Therefore, in terms of foundation pit excavations in hard rock strata, how to utilize strengths of the surrounding rocks while at the same time assuring the safety of the foundation pit during excavation is of great importance to lower costs and shorten the construction duration of the foundation pit.

In this investigation, a supporting scheme of one-layer transverse reinforced concrete bracings at the foundation pit top, one-layer steel bracings at an excavation depth of 8 m, and one-layer prestressed anchorages at an excavation depth of 22.5 m was adopted to support a deep foundation pit in hard rock strata for constructing a transfer subway station in Xuzhou, China. Deformations of the foundation pit under both in-time and delayed supporting conditions were, respectively, characterized based on lateral deformations of the deep foundation pit, settlements of the surrounding ground, and axial forces of the steel bracings, according to numerical calculations. Then, deformations of the foundation pit under on-site monitoring as well as under the condition of in-time supporting were compared to those under the condition of delayed supporting to demonstrate the suitability of delayed supporting for practical foundation pit excavation in hard rock strata.

2. Engineering Background

2.1. Project Introduction. The deep foundation pit for constructing the subway transfer station was located at the intersection of Sanhuannan Road and Jiefang Road in Xuzhou City, Jiangsu Province, China, as shown in Figure 1. The deep foundation pit consisted of a three-underground-floor standard section and a four-local-floor transfer section. The total length of the foundation pit was 217.5 m, the width of the standard section was 21.5 m, and the excavation depth was 24 m at the standard section and 31 m at the transfer section.

Geological conditions of the foundation pit are illustrated in Table 1. According to Table 1, geological conditions of the foundation pit within 0 to 8 m along the excavation depth were miscellaneous fill, strong and medium weathered limestones, and those within 8 m to 18 m along excavation depth were marl and limestone. Geological conditions of the foundation pit at 18 m or higher excavation depth were mainly weak weathered limestones, as illustrated in Table 1. Therefore, excavation of the foundation pit was mainly in hard rock strata.

2.2. Supporting Scheme of the Foundation Pit

2.2.1. Supporting Elements. During the excavation processes of the foundation pit, both vertical and transverse supports are needed to ensure the stability of the foundation pit. In this investigation, drilled grouting piles were adopted as vertical supports for the purpose of resisting surrounding soil pressures and underground hydraulic pressures during excavation. The diameter of the drilled grouting piles was 1000 mm. The pile interval was 1000 mm at the standard section and 500 mm at the transfer section. Transverse supports of the foundation pit include reinforced concrete bracings at a depth of 0.5 m, steel bracings at a depth of 8 m, and prestressed anchorages at a depth of 22.5 m, as illustrated in Figure 2. The foundation pit was excavated sectionally layer by layer. Once when the drilled grouting piles were set, excavation of the foundation pit began.

2.2.2. Supporting Scheme

(1) In-Time Supporting. In order to investigate the setting time of transverse supporting elements on stability of the deep foundation pit, an in-time supporting scheme and a delayed supporting scheme were, respectively, considered in this investigation. In terms of the in-time supporting scheme, reinforced concrete bracings, steel bracings, and prestressed anchorages were set when the excavation depth was 0.5 m below the corresponding predetermined positions.

(2) Delayed Supporting. With regard to the delayed supporting scheme, the transverse supporting elements were set when the foundation pit was excavated to the places where the next transverse supporting elements were located, which was that reinforced concrete bracings were set when the foundation was excavated to the position corresponding to the steel bracings and that steel bracings were set when the foundation pit was excavated to the positions corresponding to the prestressed anchorages.

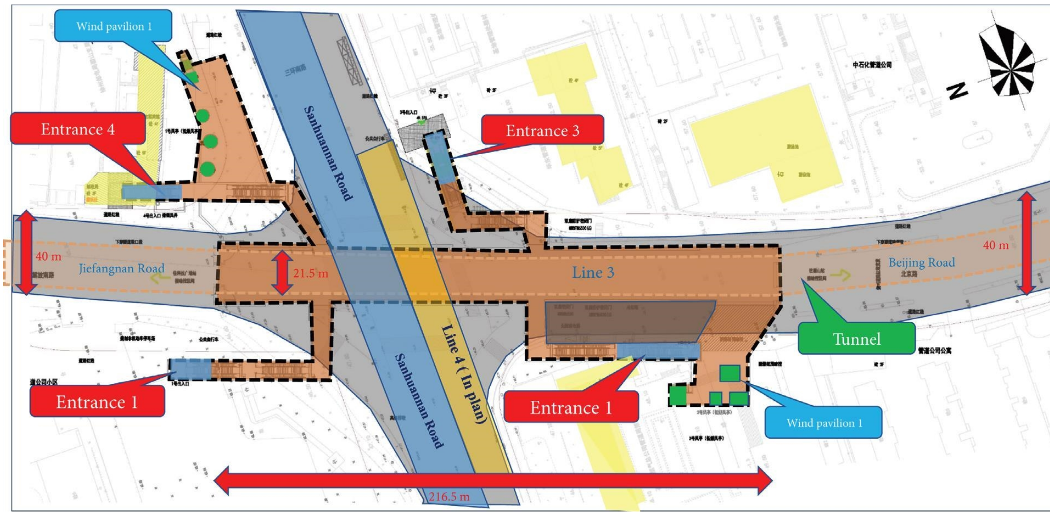

Figure 1: Location of the deep foundation pit.

Table 1: Geological conditions of the foundation pit.

Geotechnical stratum	Depth (m)	Unit weight (kN/m^3)	Elastics modulus (MPa)	Cohesion (kPa)	Internal friction angle (°)	Poisson's ratio
Miscellaneous soil	0~2	16.5	40	25	5.5	0.3
Strong weathered limestone	2~3	19.5	70	45	8	0.3
Medium weathered limestone	3~8	20.3	70	45	8.2	0.2
Marl	8~15	25	110	25	9.5	0.2
Limestone	15~18	25	110	25	10	0.2
Weak weathered limestone	>18	27.5	1150	150	13.5	0.15

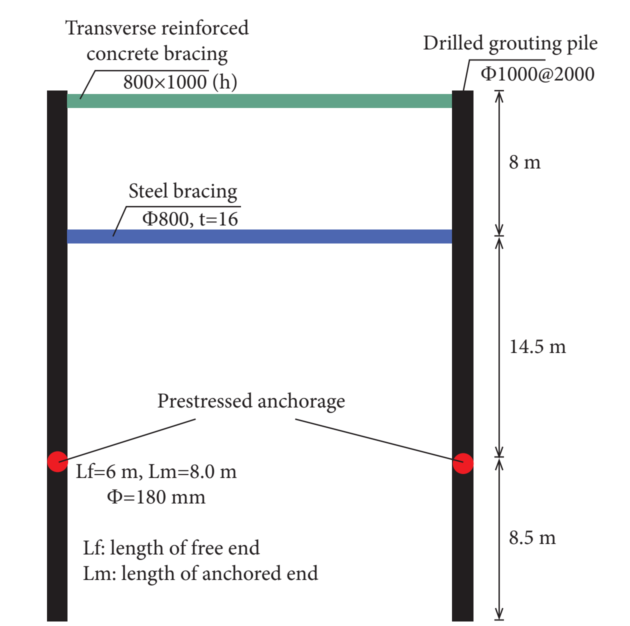

Figure 2: Supporting scheme of the deep foundation pit (note that h in Figure 2 refers to the height of the reinforced concrete bracings, and t in Figure 2 refers to the thickness of the steel bracings).

3. Numerical Simulation Schemes

3.1. Geometrical Dimensions of the Simulation Model. In order to accurately simulate settlements of the surrounding ground and lateral deformations of the foundation pit, a full-scale simulation model of the foundation pit was established based on FLAC^{3D}. The simulation model included the foundation pit and a potential influential area. Considering influential areas during the foundation excavation process and the boundary conditions, the surrounding ground was set to be four to five times of the excavation depth. Therefore, the simulation model in this investigation had a length, width, and height of 379 m, 189 m, and 75 m, as illustrated in Figure 3.

3.2. Boundary Conditions. Boundary conditions of the simulation model are shown in Figure 4. Sides, bottom, and top of the simulation model are, respectively, with a slip, fixed, and free boundary conditions. During the excavation process, there was a temporary road around the foundation pit. Meanwhile, Sanhuannan Road and Jiefang Road are main traffic roads, and traffic gridlocks usually occur at rush hours. Therefore, additional external forces exist near the foundation pit, which cannot be neglected. As a result, in the

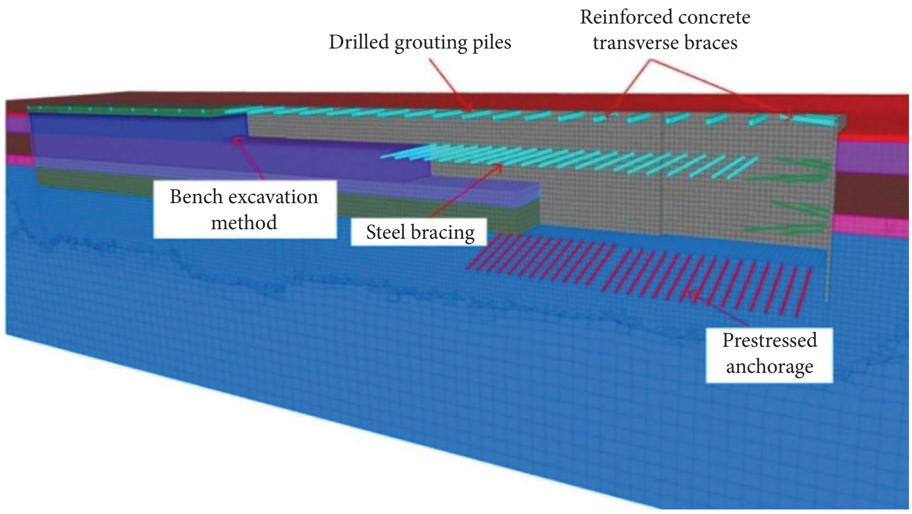

Figure 3: Simulation model of the foundation pit.

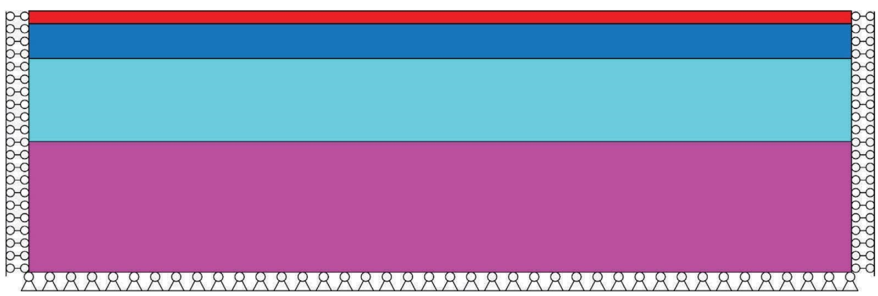

Figure 4: Boundary conditions of the simulation model.

simulation model, a simplified vertical uniform load with a value of 20 kPa was applied to surroundings of the foundation pit based on traffic statistics.

3.3. Properties of the Supports for Simulation Calculations

3.3.1. Drilled Grouting Piles and Transverse Reinforced Concrete Bracings. Drilled grouting piles and transverse reinforced concrete bracings were made from concrete, and considering properties of concrete are close to those of rocks, the Mohr-Coulomb constitutive model was adopted to simulate drilled grouting piles and transverse reinforced concrete bracings. Density, elastic modulus, and cohesion of both drilled grouting piles and transverse bracings were, respectively, 2500 kg/m^3, 31.5 MPa, and 20 MPa. Internal friction angle and Poisson's ratio were, respectively, 18° and 0.25. Physical and mechanical parameters of drilled grouting piles and transverse reinforced concrete bracings are illustrated in Table 2.

3.3.2. Steel Bracings. For steel bracings, the corresponding elastics modulus and Poisson's ratio were 200 GPa and 0.3, respectively. The section area of the steel bracings was 0.0394 m^2. In the simulation model, beam units were used to simulate steel bracings, and the corresponding parameters for numerical calculation are illustrated in Table 3.

3.3.3. Prestressed Anchorages. In terms of prestressed anchorages, the corresponding prestressed force and elastics modulus were 200 kN and 200 GPa. Unanchored and anchorage lengths of the prestressed anchorages were 6 m and 8 m, respectively. In the simulation model, cable units were utilized to simulate prestressed anchorage, and the corresponding parameters for calculation are illustrated in Table 4.

3.4. Criteria for Evaluating Stability of the Foundation Pit. Deformations of the foundation pit are strictly required in the Chinese standard of Code for Design of Building Foundation (GB50007-2011). According to environmental protection requirements and complexity of surrounding structures or utilities, deformations of the supporting structures and settlements of the surrounding ground should not exceed 0.3% and 0.15% of the excavation depth. Besides, some other parameters, such as stresses or deformations of the supporting elements, could also reflect deformation characteristics of the foundation pit. Therefore, in this investigation, the stability of the foundation pit under different in-time supporting schemes could be analyzed according to lateral deformations of the foundation pit, settlements of the surrounding ground, and stress of the steel bracings as well as top displacements of the drilled grouting piles.

Table 2: Physical and mechanical parameters of drilled grouting piles and transverse reinforced concrete bracings.

Supporting types	Density (kg/m^3)	Elastic modulus (GPa)	Cohesion (MPa)	Internal friction angle (°)	Tensile strength (MPa)	Poisson's ratio
Drilled grouting piles	2500	31.5	20	18	3	0.25
Reinforced concrete bracings	2500	31.5	20	18	3	0.25

Table 3: Beam unit parameters of steel bracings.

Elastic modulus (GPa)	Section area (m^2)	Z-axial inertia moment (m^3)	Y-axial inertial moment (m^3)	Polar inertia moment (m^3)	Poisson's ratio
200	0.0394	0.003	0.003	0	0.3

Table 4: Cable unit parameters of prestressed anchorages.

Prestressed force (kN)	Elastic modulus (GPa)	Section area (m^2)	Unanchored length (m)	Anchorage length (m)	Bond stiffness (MPa)	Grouting perimeter (m)
200	200	0.002	6	8	27.5	0.565

Meanwhile, in order to demonstrate the suitability of the delayed supporting scheme in practical foundation pit excavation, lateral deformations of the foundation pit and settlements of the surrounding ground, as well as axial forces of the steel bracings, were also monitored on-site during the excavation process. On-site monitoring points of axial forces, lateral deformations, and settlements are illustrated in Figure 5.

4. Results and Discussion

4.1. Total Settlements of the Surrounding Ground after Excavation. After the foundation pit was completely excavated, settlements of the surrounding ground under the condition of the delayed supporting scheme are illustrated in Figure 6. It can be seen from Figure 6 that the space effect of the long and narrow foundation pit was obvious. Meanwhile, settlements of the surrounding ground mainly occurred at both sides of the foundation pit, and the corresponding influential areas during the excavation process were within one time of the excavation width. Settlements at both ends of the foundation pit mainly occurred at 5 m to 10 m away from the foundation pit and were relatively lower compared to those occurring at both sides of the foundation pit.

Moreover, settlements of the surrounding ground were sectionally distributed along the length direction of the foundation pit, which was because the foundation pit was sectionally excavated layer by layer. Therefore, the numbers of maximum settlement were in accord with those of excavation segments. Furthermore, settlements at the east side of the foundation pit were relatively larger than those at the west side, which was due to additional loads at the east side of the foundation pit closely adjacent to a municipal road. A maximum settlement of 12 mm occurred at the transfer section of the foundation pit during the excavation process, which indicated that focus should be paid to the deformations of the foundation pit at the transfer section. Therefore, the following discussions were focused on analyses of settlements in the surrounding ground, lateral displacements of the foundation pit, and axial forces of the steel bracings at the transfer section.

4.2. Settlements of the Surrounding Ground at Different Excavation Depths

4.2.1. Under In-Time Supporting Condition. Settlements of the surrounding ground at the transfer section of the foundation pit at different excavation depths are illustrated in Figure 7. For the in-time supporting scheme, the maximum settlements corresponding to each excavation depth were, respectively, −0.04 m, −2.00 m, −6.57 mm, and −6.57 mm, which were all within the allowed values required in the Chinese standard of GB50007-2011. And the corresponding influential areas were 3 m, 17 m, 22 m, and 22 m away from the foundation pit. Moreover, according to Figure 7(d), when excavation depth was 31 m, the maximum settlement of the surrounding ground under the in-time supporting scheme was basically equal to that obtained according to on-site monitoring, indicating that the numerical simulation was precise in terms of the calculation of the deformations of the foundation pit.

4.2.2. Under Delayed Supporting Condition. For the delayed supporting scheme, when the excavation depth of the foundation pit was 8 m, 15 m, 24 m, and 31 m, the maximum settlements were, respectively, −1.16 mm, −6.27 mm, −8.13 mm, and −8.49 mm, which were all within the allowed values required in the Chinese standard of GB50007-2011. Meanwhile, the corresponding influential areas at each excavation depth were 17 m, 25 m, 27 m, and 28 m away from the foundation pit. Besides, the maximum settlement of the surrounding ground at an excavation depth of 31 was relatively larger than that obtained according to on-site monitoring.

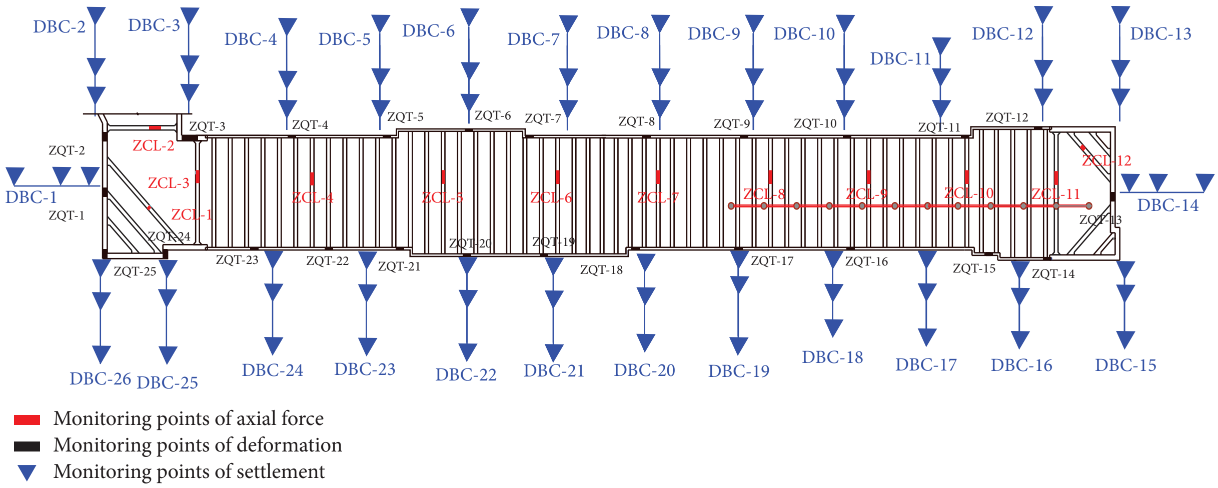

Figure 5: On-site monitoring positions of axial forces, displacements, and settlements.

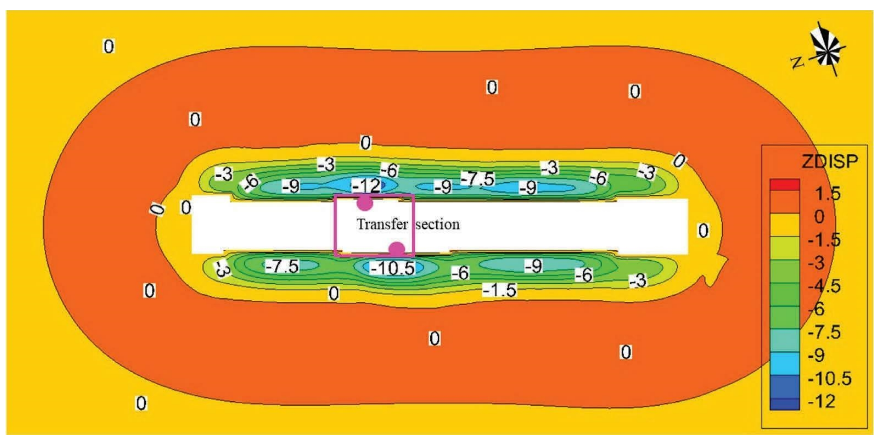

Figure 6: Settlements of the surrounding ground when the foundation pit was completely excavated.

For the delayed supporting scheme, transverse reinforced concrete bracings were set when the foundation was excavated to the positions where the steel bracings were set, and the steel bracings were set when the foundation pit was excavated to the positions where the prestressed anchorages were set, during which period the surrounding rocks of the excavated foundation pit gradually deformed. Therefore, settlements and influential areas of the surrounding ground during excavations under delayed supporting condition were always higher than those under an in-time supporting scheme.

According to the above analyses, it can be obtained that settlements of the surrounding ground gradually increased and influential areas of the surrounding ground during the excavation process also increased under both delayed and in-time supporting schemes when excavation depth gradually increased. However, settlements of the surrounding ground during the excavation process under delayed supporting and the corresponding influential areas were always larger than those under in-time supporting for a fixed excavation depth, but the corresponding maximum settlement did not exceed the allowed value required in the Chinese standard of GB50007-2011, indicating that foundation pit in hard rock strata had good stability during excavation when a delayed supporting scheme was adopted.

4.3. Lateral Deformations of the Foundation Pit at Different Excavation Depths

4.3.1. Under In-Time Supporting Condition. Lateral deformations of the foundation pit at the transfer section at different excavation depths are illustrated in Figure 8. For in-time supporting scheme, when the foundation pit was, respectively, excavated to a depth of 8 m, 15 m, 24 m, and 31 m, maximum lateral deformations based on numerical simulations were, respectively, 0.016 mm, 2.3 mm, 6.75 mm, and 8.16 mm, which were also did not exceed the allowed deformation values required in the Chinese standard of GB50007-2011. Meanwhile, lateral deformations of the foundation pit were gradually increased with increasing

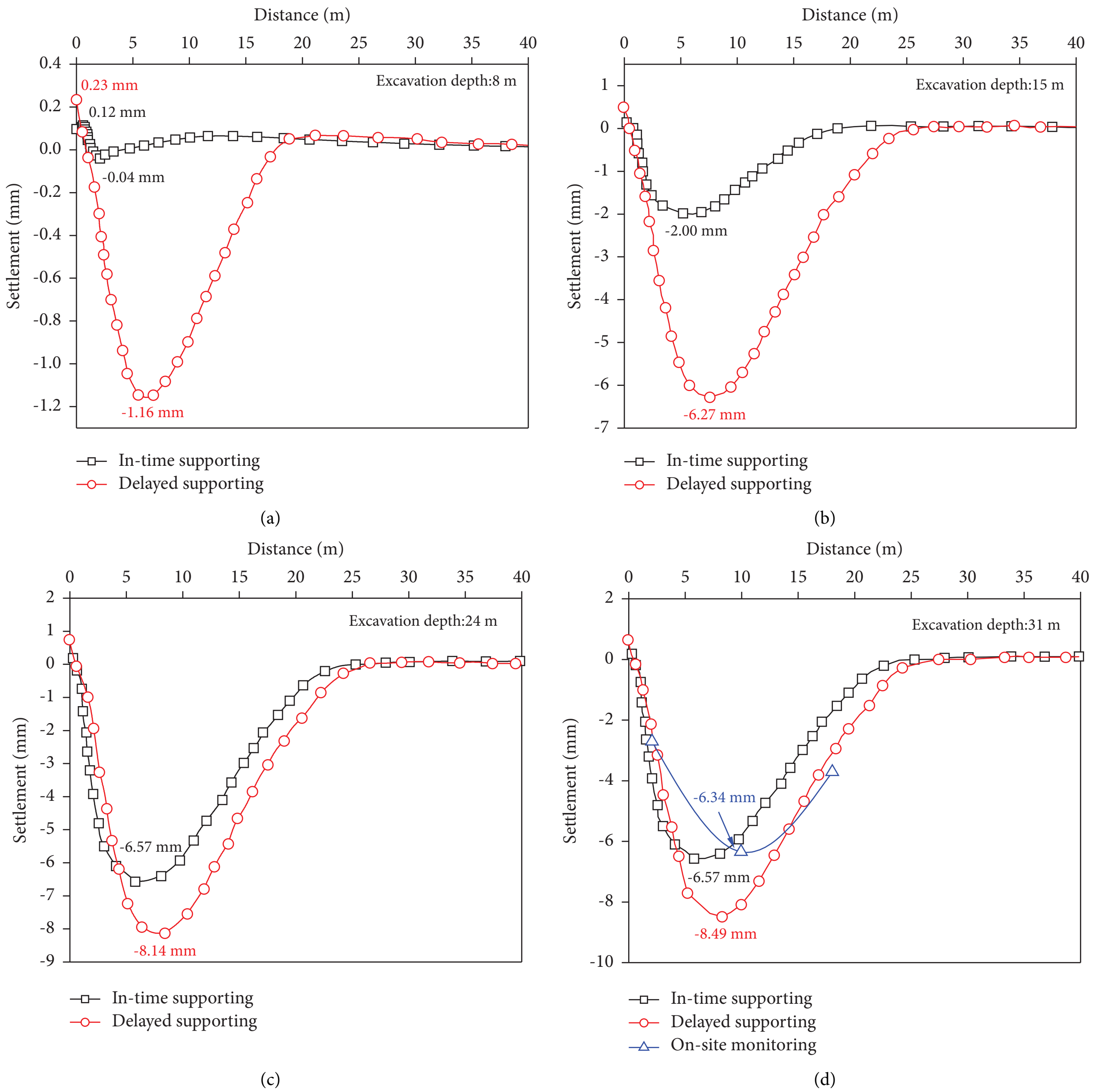

FIGURE 7: Settlements of the surrounding ground at different excavation depths. (a) Excavation depth: 8 m. (b) Excavation depth: 15 m. (c) Excavation depth: 24 m. (d) Excavation depth: 31 m.

excavation depth under an in-time supporting condition, which presented a P shape when excavation depth was higher than 8 m.

4.3.2. Under Delayed Supporting Condition. For the delayed supporting scheme, when the foundation pit was, respectively, excavated to a depth of 8 m, 16 m, 24 m, and 31 m, the maximum lateral deformations of the foundation pit were, respectively, 1.46 mm, 6.4 mm, 10.02 mm, and 10.34 mm, which were also within the allowed deformation values required in Chinese standard of GB50007-2011. Meanwhile, lateral deformations of the foundation pit also increased with increasing excavation under the delayed supporting condition, which also presented a P shape along the excavation depth.

Furthermore, increments in lateral deformations of the foundation pit were not obvious, and locations where maximum lateral deformation occurred were basically unchanged when excavation depth increased from 24 m to 31 m, which was because excavation of the foundation pit was mainly in the limestone strata that had relatively high strengths, good stability, and strong antideformation ability. Therefore, with increasing excavation depth, lateral deformations of the foundation pit were basically stable.

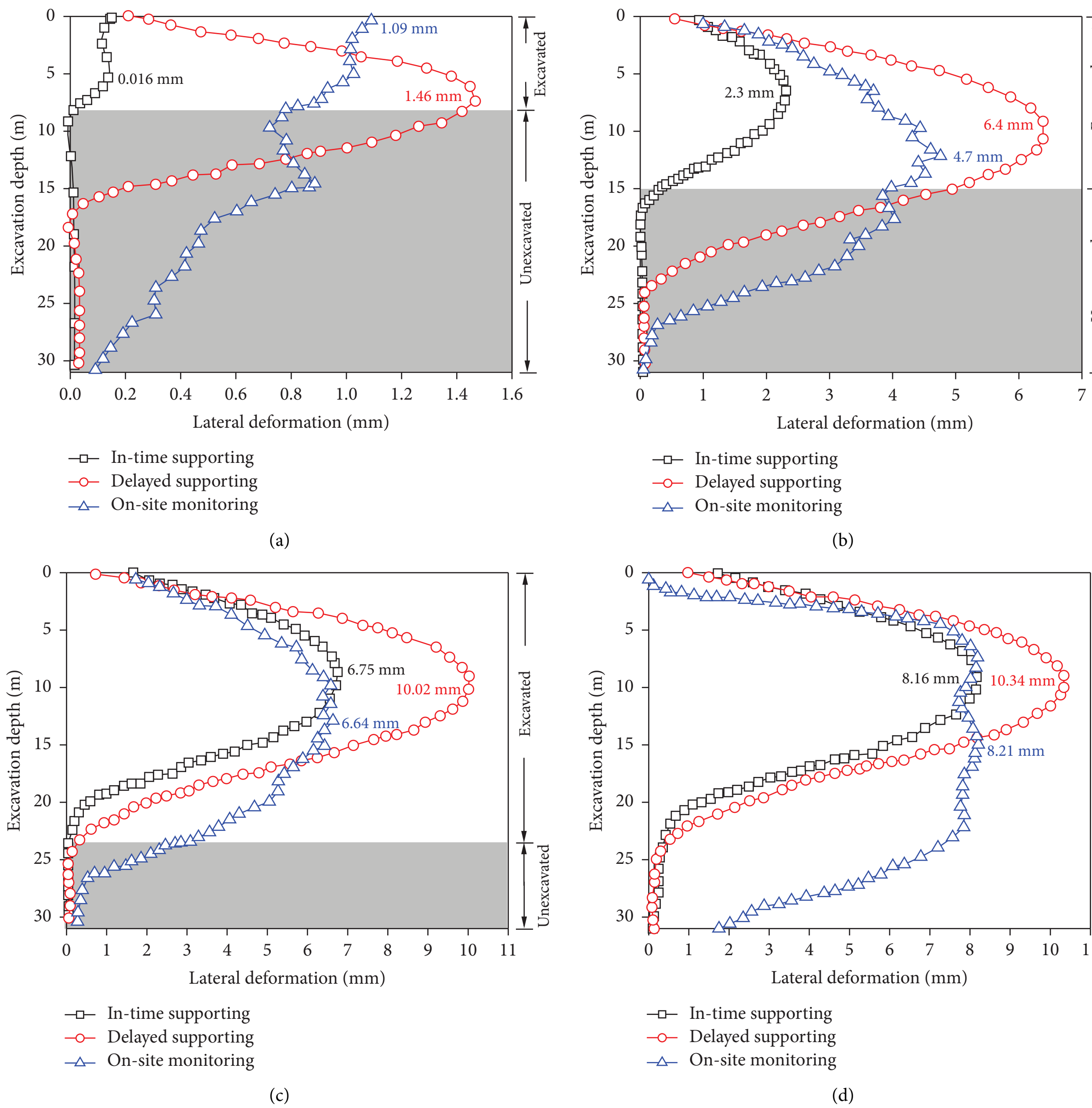

Figure 8: Lateral deformations of the foundation pit at different excavation depths. (a) Excavation depth: 8 m. (b) Excavation depth: 15 m. (c) Excavation depth: 24 m. (d) Excavation depth: 31 m.

4.3.3. On-Site Monitoring. For on-site monitoring, when the excavation depth was 8 m, the maximum lateral deformation of the foundation pit was 1.09 mm at the top of the drilled grouting piles, which was attributed to the unsetting of the transverse reinforced concrete bracings leading to the formation of cantilever structures at the tops of the drilled grouting piles. With the increasing excavation depth of 16 m, lateral deformations of the upper part of the foundation pit were restrained by transverse reinforced concrete bracings. Deformations of the foundation pit, therefore, present a D-type. When the foundation pit was excavated at a depth of 24 m and 31 m, lateral deformations at the bottom part of the foundation pit also presented a D-type, which resulted from the unsetting of the prestressed anchorages.

Therefore, according to the above analyses, it can be concluded that lateral deformations of the foundation pit under both in-time and delayed supporting schemes gradually increased with increasing excavation depths. Moreover, lateral deformations of the foundation pit with delayed supporting were obviously increased compared to those under in-time supporting condition, which was because

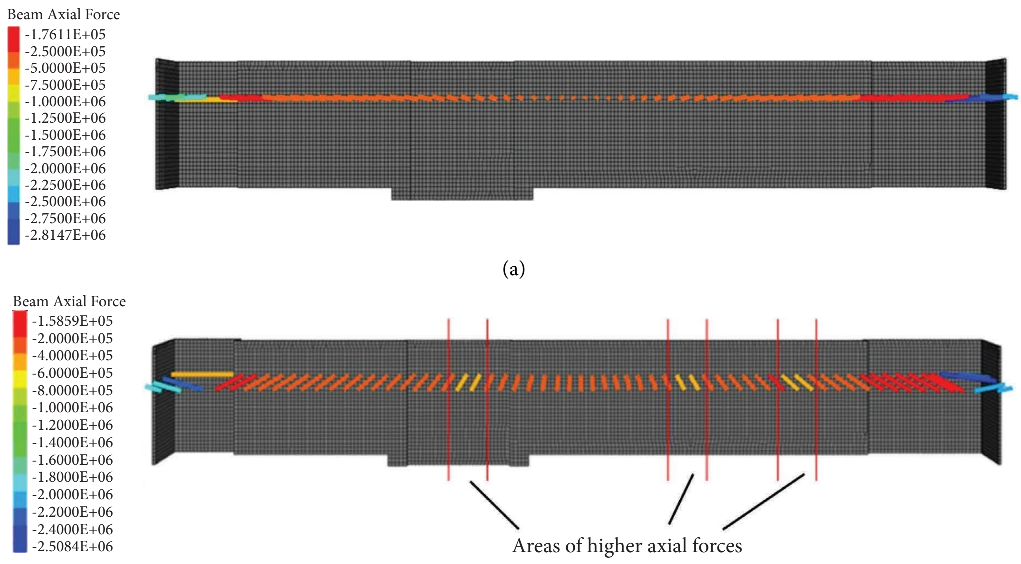

Figure 9: Axial forces of the steel bracings at the transfer section. (a) In-time supporting. (b) Delayed supporting.

delayed supporting of the foundation pit led to proper deformations of the surrounding rocks and thus resulted in increased lateral deformations of the foundation pit.

4.4. Axial Forces of the Steel Bracings at the Transfer Section. Axial forces of the steel bracings at the transfer section are illustrated in Figure 9. It can be obtained from Figure 9(a) that the maximum axial forces of the steel bracings under delayed supporting condition were basically lower than those under in-time supporting conditions. For the delayed supporting scheme, supporting elements at the upper layer were set when the foundation pit was excavated to the place where supporting elements at the lower layer were located, during which period the surrounding rocks deformed properly and the stresses of the surrounding rocks were redistributed. Consequently, when the supporting schemes were set, the forces applied to the supporting elements were reduced. Therefore, axial forces of the steel bracings under delayed supporting conditions were relatively lower compared to those under delayed supporting conditions.

Meanwhile, for the delayed supporting scheme, three obvious higher axial forces of the steel bracings, which occurred at the excavation ends of the three different excavation sections, were observed along the length direction of the foundation pit, as shown in Figure 9(b). During the excavation process, due to delayed supporting of the foundation pit, the surrounding rocks of the foundation pit deformed, and the stresses of the surrounding rocks were thus redistributed. However, when the foundation pit was excavated to the ends of each section, supports were set once the excavation was finished, indicating that there was not enough time for surrounding rocks of the foundation pit to deform and to redistribute stresses. Therefore, the axial forces of the steel bracings at the ends of the excavation sections were relatively higher, and those at other positions of the foundation pit were relatively smaller, which further indicated that delayed support could fully utilize strengths of the surrounding rocks.

5. Conclusions

In this investigation, deformations of a deep foundation pit in hard rock strata under delayed and in-time supporting conditions were characterized according to lateral deformations of the foundation pit and settlements of the surrounding ground, as well as axial forces of the steel bracings based on numerical simulations. Meanwhile, deformations of the foundation pit according to on-site monitoring were compared with those obtained based on numerical calculations to demonstrate that delayed support could assure the safety of foundation pit in hard rock strata during the excavation process. According to simulation calculation results, conclusions can be drawn as follows:

(1) With increasing excavation depth, settlements of the surrounding ground gradually increased. During foundation excavation, settlements of the surrounding ground and the corresponding influential areas under delayed supporting conditions were obviously larger than those under in-time supporting condition. Settlements at the transfer section of the foundation pit were relatively larger than those at the standard section.

(2) Lateral deformations at the transfer section of the foundation pit gradually increased with increasing excavation depths. Though lateral deformations of the foundation pit under delayed supporting conditions were significantly larger than those under in-time supporting, the maximum lateral deformations

were far less than the allowed values required in the Chinese standard of Code for the Design of Building Foundation (GB50007-2011).

(3) Under delayed supporting conditions, lateral deformations and settlements obtained according to on-site monitoring were smaller than those obtained according to numerical simulations. Delayed support of one-layer transverse reinforced concrete bracings, one-layer steel bracings, and one-layer prestressed anchorages was effective in terms of controlling deformations of the deep foundation pit in hard rock strata.

(4) By adopting a delayed supporting scheme, the strengths of the surrounding rocks could be used to the fullest, during which period acceptable deformations of the surrounding rocks occurred and the stresses of the surrounding rocks were thus redistributed. Consequently, the axial forces of the steel bracings were reduced compared to those under in-time support. By adopting a delayed supporting scheme, not only can the safety of the foundation pit during the excavation process be assured but also more construction spaces are freed up for construction equipment, and construction duration could, therefore, be reduced.

Data Availability

No underlying data were collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] R. Z. Liang, T. D. Xia, M. S. Huang, and C. G. Lin, "Simplified analytical method for evaluating the effects of adjacent excavation on shield tunnel considering the shearing effect," *Computers and Geotechnics*, vol. 81, pp. 167–187, 2017.

[2] D. Q. Song, Z. Chen, L. H. Dong, G. J. Tang, K. L. Zhang, and H. Wang, "Monitoring analysis of influence of extra large complex deep foundation pit on adjacent environment a case study of Zhengzhou City China," *Geomatics, Natural Hazards and Risk*, vol. 11, no. 1, pp. 2036–2057, 2020.

[3] Y. Wang, Y. J. Zhang, M. F. Li, Y. Qi, and T. H. Ma, "A numerical investigation of the deformation mechanism of a large metro station foundation pit under the influence of hydromechanical processes," *Geofluids*, vol. 2021, Article ID 5536137, 16 pages, 2021.

[4] H. G. Di, H. J. Guo, S. H. Zhou, J. M. Chen, and L. Wen, "Investigation of the axial force compensation and deformation control effect of servo steel struts in a deep foundation pit excavation in soft clay," *Advances in Civil Engineering*, vol. 2019, Article ID 5476354, 16 pages, 2019.

[5] J. H. Yang and D. Y. Kong, "Deformation of deep and large foundation pit in soft soil of Fuzhou subway," *Arabian Journal of Geosciences*, vol. 13, no. 36, pp. 1–10, 2020.

[6] Z. Q. Li, "Displacement monitoring during the excavation and support of deep foundation pit in complex environment," *Advances in Civil Engineering*, vol. 2021, Article ID 5715306, 7 pages, 2021.

[7] Y. Wang and F. Zhang, "Effects of pit-bottom-soil reinforcement on the deformation of subway deep foundation pits based on an improved model," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 2661311, 8 pages, 2022.

[8] J. P. Zhao, Z. S. Tan, R. S. Yu, Z. L. Li, X. R. Zhang, and P. C. Zhu, "Deformation responses of the foundation pit construction of the urban metro station: a case study in Xiamen," *Tunnelling and Underground Space Technology*, vol. 128, Article ID 104662, 2022.

[9] D. X. Ren, C. Kang, H. H. Liu, Y. Li, and J. L. Wang, "Characteristics of a large-scale deep foundation pit excavated by the central-island technique in chengdu soft clay," *KSCE Journal of Civil Engineering*, vol. 26, no. 6, pp. 2610–2623, 2022.

[10] J. F. Zhang, J. J. Chen, J. H. Wang, and Y. F. Zhu, "Prediction of tunnel displacement induced by adjacent excavation in soft soil," *Tunnelling and Underground Space Technology*, vol. 36, pp. 24–33, 2013.

[11] G. Lei and X. N. Gong, "Analysis of lateral displacement law of deep foundation pit support in soft soil based on improved MSD method," *Advances in Civil Engineering*, vol. 2021, Article ID 5550214, 15 pages, 2021.

[12] Y. S. Sun and Z. M. Li, "Analysis of deep foundation pit pile-anchor supporting system based on FLAC3D," *Geofluids*, vol. 2022, Article ID 1699292, 19 pages, 2022.

[13] S. H. Ye, Z. F. Zhao, and D. Q. Wang, "Deformation analysis and safety assessment of existing metro tunnels affected by excavation of a foundation pit," *Underground Space*, vol. 6, no. 4, pp. 421–431, 2021.

[14] R. P. Chen, F. Y. Meng, Z. C. Li, Y. H. Ye, and J. N. Ye, "Investigation of response of metro tunnels due to adjacent large excavation and protective measures in soft soils," *Tunnelling and Underground Space Technology*, vol. 58, pp. 224–235, 2016.

[15] T. Yang, S. Y. Xiong, S. L. Liu, Y. Liu, H. Zhao, and Y. W. Li, "Numerical analysis of the influence of deep foundation pit construction on adjacent subway stations in soft soil areas," *Advances in Civil Engineering*, vol. 2022, Article ID 6071868, 14 pages, 2022.

[16] J. Cui and S. Shen, "Innovative excavation and support techniques for deep large foundations in soft ground," *Proceedings of the Institution of Civil Engineers-Civil Engineering*, vol. 172, 2018.

[17] Y. Mei, L. Wang, D. B. Zhou, and L. Y. Fu, "Displacement characteristics of a deep excavation in Hangzhou soft clay," *Advances in Civil Engineering*, vol. 2022, Article ID 5469471, 16 pages, 2022.

[18] G. C. Li, Q. M. Li, J. Wang, J. M. Dong, and Q. Sun, "The deformation characteristics of a 40-m-Deep excavation

supported by a suspended diaphragm wall in rock and soil composite ground," *KSCE Journal of Civil Engineering*, vol. 26, no. 3, pp. 1040–1050, 2022.
[19] Z. H. Qin, Z. Tao, Z. C. Chen et al., "Deformation analysis and prediction of foundation pit in soil-rock composite stratum," *Frontiers in Physics*, vol. 9, 2022.
[20] Y. S. Shen, P. Wang, M. P. Li, and Q. W. Mei, "Application of subway foundation pit engineering risk assessment: a case study of qingdao rock area, China," *KSCE Journal of Civil Engineering*, vol. 23, no. 11, pp. 4621–4630, 2019.