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Research Article

Field Experimental Study on Mechanical Properties of Frame Support Structure Composed of Subway Foundation Pit Retaining Pile and Steel Strut Rigid Joint

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In order to study the advantages of frame support structure composed of rigid joint between steel strut and retaining pile in restraining the lateral displacement of retaining structure and maintaining the stability of foundation pit, foundation pit failure test was carried out. Compared with the traditional support structure, which can only bear pressure composed of steel strut and retaining pile lap joint, the variation characteristics of pile lateral displacement and support axial force of frame support structure under the influencing factors, such as weak stratum, pit side loading, groundwater level rise, and support drop, are studied. The test results show that, compared with the traditional steel strut, the pile-strut frame support structure can not only bear the compressive stress, but also the tensile stress caused by the lateral displacement of the top of the retaining pile outside the foundation pit. The overall stability is better, and the axial force distribution of each layer of support is more uniform so as to reduce the overall lateral displacement of the retaining pile. In the process of foundation pit collapse, the frame support structure will not have the problem of strut falling, which can maintain part of the support capacity, prolong the collapse time of retaining piles, strive for more escape time for front-line construction workers, and reduce the number of casualties.

1. Introduction

The urban subway foundation pit is a regular cuboid. As the excavation depth of the foundation pit increases gradually, the spatial effect caused by soil unloading increases significantly [1], resulting in a significant increase in the risk of foundation pit construction [2, 3]. There are two types of support commonly used in subway foundation pit: reinforced concrete support and steel support. The reinforced concrete brace is rigidly connected with the retaining structure to form a frame support structure, which can bear the tensile and compressive stress caused by the lateral displacement of the soil [4–6]. For instance, the stratum of Xinggang Street Station of Suzhou Metro Line 3 is dominated by soft clay, and the excavation depth of the foundation pit is 20 m. The monitoring data show that tensile stress generally occurs in the first layer of reinforced concrete support during the excavation, and the maximum tensile force is 3000 kN [7, 8]. The design depth of the foundation pit of Jianguo Road Station of Hangzhou Metro Line 5 is 25.6 m. The reinforced concrete brace has tensile stress, and the maximum tensile force is about 1500 kN [9]. The design depth of the foundation pit of an air shaft of a subway in Shanghai is 25.07 m, and the reinforced concrete brace has tension during construction [10, 11]. During the excavation of the foundation pit of the interchange station of Anhui Hefei Metro Line 4 and Line 7, the tensile stress of the reinforced concrete brace on the first floor was affected by the lateral movement of the top of the diaphragm wall outside the foundation pit [12].

However, the cast-in-situ concrete brace has some problems, such as slow strength growth, low construction efficiency, low reuse rate, waste of resources, and environmental pollution, which does not conform to the development trend of green and civilized construction. Compared with the reinforced concrete support, although the steel strut is fabricated and can quickly provide support force, it is connected with the retaining structure by "lap joint," which is weak and can only bear the axial compression stress. Once the deformation of the retaining structure is too large or the lateral displacement outside the foundation pit is too large, it will cause the loss of preloading axial force of the steel strut and increase the risk of foundation pit collapse accident and casualties caused by the falling of the steel strut [13–17], as shown in Figure 1. Some scholars have proposed to use hydraulic cylinder to compensate the axial force loss of steel strut, which is inappropriate to maintain the axial force stability of steel strut at the expense of surrounding soil deformation [18–20]. The function of the foundation pit supporting structure is to reduce the disturbance and deformation of the surrounding soil caused by the foundation pit excavation. It is necessary to protect not only the construction safety of the foundation pit, but also the structural safety and normal use of the surrounding buildings and structures, which requires that the surrounding soil do not produce large displacement in any direction. The axial force loss of steel strut caused by the displacement of retaining structure outside the foundation pit will be compensated by hydraulic cylinder, which will aggravate the lateral displacement of surrounding soil to a certain extent, which is unfavorable to the protection of surrounding buildings and structures.

Therefore, learning from the supporting mechanism of reinforced concrete bracing, changing the connection mode between steel strut and retaining structure into rigid joint to form a frame supporting structure may be more beneficial to control the deformation of foundation pit. Taking the support structure of steel strut + retaining pile as an example, through the large-scale outdoor model failure test, this paper analyzes the advantages of frame support structure in controlling the lateral displacement of retaining pile and balancing the axial force of support compared with the traditional form of steel strut. Because the model test cannot truly restore the spatial effect in the excavation process of foundation pit engineering, therefore, simulating the failure process of foundation pit collapse can significantly distinguish the advantages and disadvantages of the two support forms.

2. Design of Foundation Pit Failure Experiment

2.1. Test Purpose. Taking the traditional steel strut as the control group and the frame support structure with rigid joint between pile and strut as the experimental group, set four working conditions: soft soil layer, pit side loading, groundwater level rise, and support fall, from foundation pit excavation to foundation pit collapse and failure, and analyze the variation characteristics of pile's lateral displacement and strut's stress under the two support forms.

2.2. Test Foundation Pit Design. The test site is located at a site in Mafang Village, Shunyi District, Beijing, China. The size of the test foundation pit is 8 m long, 2 m wide, and 4 m high. The working condition simulation is carried out in the west area of the foundation pit. In order to simulate the weak stratum conditions, an earth pit with a length of 8 m, width of 4 m, and depth of 3 m is excavated in the west of the foundation pit in advance, and the fine sand with a depth of 1.5 m and the undisturbed soil with a depth of 1.5 m are backfilled successively. From top to bottom, the stratum is composed of 1.5 m backfill, 1.5 m fine sand layer, and undisturbed sand gravel layer below. On the west side of the foundation pit, three working conditions are simulated in chronological order: pit side loading, groundwater level rise, and partial support fall. Under the condition of rising groundwater level, the pipeline needs to be embedded in the west of the foundation pit. Backfilling shall be carried out together with the layout of embedded pipelines and monitoring instruments.

Figure 1: Foundation pit collapse.

2.3. Layout of Monitoring Points. The main monitoring items of the test are support axial force and pile lateral displacement. The monitoring instruments include fixed inclinometer, earth pressure gauge, pore water pressure gauge, steel plate gauge, and automatic collection box. The measuring points are arranged in the area of the replacement fill layer of the foundation pit. Due to the rapid collapse process of the foundation pit, HD cameras are set up on the north and south sides of the foundation pit for recording, as shown in Figure 2.

2.4. Design of Foundation Pit Support Structure

2.4.1. Installation of Retaining Pile. The retaining pile has a diameter of 170 mm, a length of 6 m, and a spacing of 60 cm. The main reinforcement of the pile is 20 m in diameter. The embedded steel plate is welded at the position of the main reinforcement facing the waist beam of the foundation pit to facilitate the installation of the waist beam. The construction process of retaining pile is shown in Figure 3.

2.4.2. Embedding of Inclinometer. The fixed inclinometer developed by golden civil engineering company is used to monitor the lateral displacement of piles. Two inclinometer monitoring holes are set in the test, and one measuring point is arranged every 1 m in each monitoring hole, with a total of three measuring points. First, install three inclinometers in parallel on the ground, point the high guide wheel to the

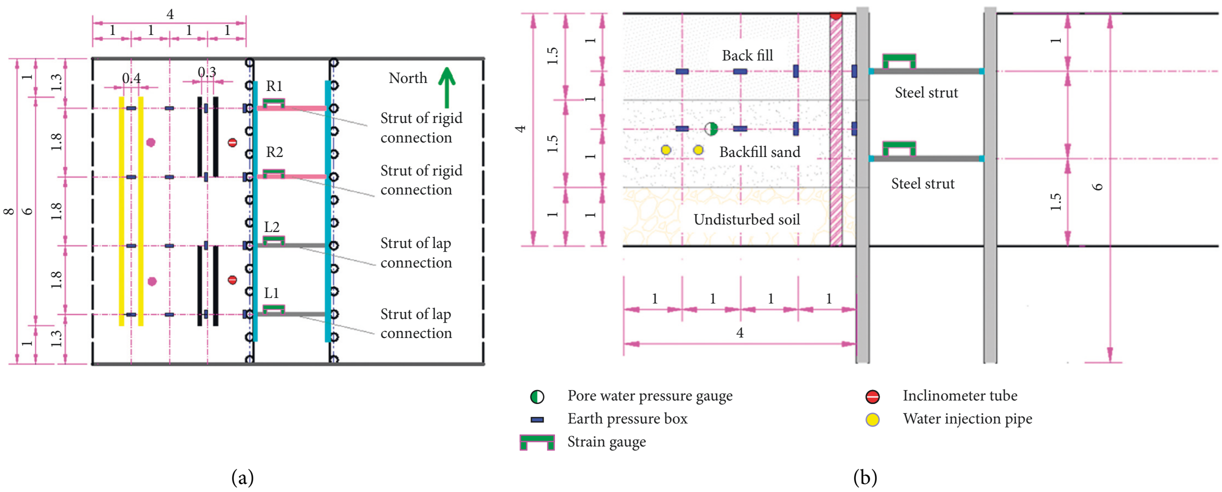


Figure 2: Layout of measuring points of foundation pit. (a) Vertical view. (b) Profile.

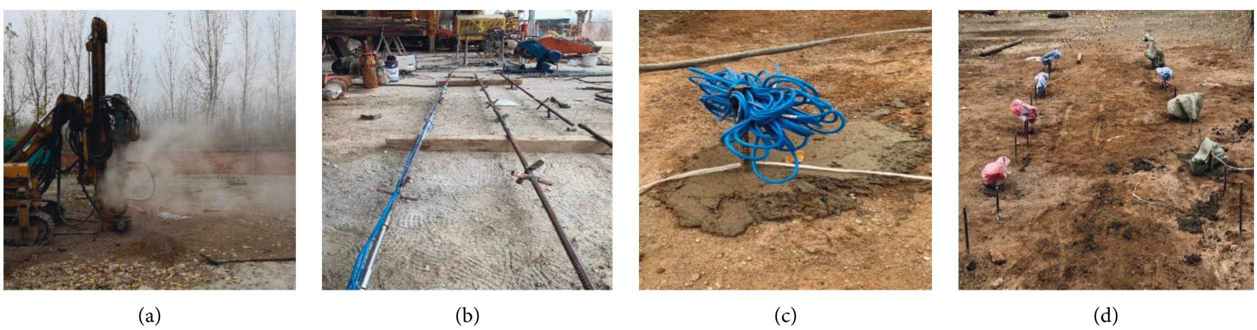


Figure 3: Construction of pile. (a) Drilling hole. (b) Assembly process of main reinforcement. (c) Grouting of retaining pile. (d) Completion of pile construction.

foundation pit, slowly lower it into the buried inclinometer pipe, and record the corresponding data line number of each measuring point, as shown in Figure 4.

2.4.3. Crown Beam Design. L5 angle steel with a length of 7.5 m is used as the crown beam frame and erected on both sides of the reserved reinforcement at the pile top. It is surrounded by wooden boards, poured with cement, troweled, and covered with plastic film for maintenance.

2.4.4. Waist Beam Design. The waist beam adopts a section size of (height × width × thickness) 10 cm × 10 cm × 2 mm square steel pipe. When the foundation pit is excavated to the inner support position, chisel out the embedded steel plate and weld the waist beam. The bottom of the waist beam is welded with (length × width) 10 cm × 5 cm thin steel plate, which represents the bracket. Cement mortar shall be poured into the gap between the retaining pile and the waist beam to make it close.

2.4.5. Steel Strut Design. The cross section size is (height × width × thickness) 4.5 cm × 4.5 cm × 2 mm square steel pipe simulated steel strut. Its horizontal spacing is 1.8 m, four supports are installed in the horizontal direction, and two layers of steel struts are set at −1 m and −2.5 m, respectively, in the vertical direction. The strut that can only bear the axial compressive stress is installed on the south half of the foundation pit, the steel strut is overlapped between the two brackets, and the gap between the steel strut and the waist beam is filled with a wooden wedge. The strut that can bear axial compressive stress and tensile stress is installed on the north half of the foundation pit, and the steel strut is welded with the waist beam to realize rigid joint. The supporting structure is shown in Figure 5.

Figure 4: Burying the inclinometer.

Figure 5: Supporting structure.

2.4.6. Installation of Steel Plate Gauge. JTM-V5000G steel plate gauge developed by Jincivil Engineering Company is used to measure the strut axial force. After the strut installation is completed, install the steel plate gauge. The strain on the steel strut surface measured by the steel plate gauge is converted to obtain the support axial force. According to the engineering monitoring experience, the bending moment at one-third of the steel strut is 0, and the monitoring results will not be affected by the bending moment. Therefore, weld and install the steel plate gauge at one-third of the length of each steel strut, and record the instrument number, as shown in Figure 6.

2.4.7. Monitoring Record and Data Processing. The process of foundation pit collapse takes a short time, and the manual collection of various monitoring data is slow and has poor accuracy. Therefore, all monitoring data are stored, recorded, and processed in the automatic collection box developed by Golden Civil Engineering Company, as shown in Figure 7.

2.5. Simulation of Test Conditions. The whole test process simulates three working conditions from foundation pit excavation to foundation pit collapse:

(1) Pit side stacking: at 1 m to the west of the foundation pit, the spoil shall be taken and bagged, and an earth pile of 8 m long, 2 m wide, and 1.5 m high shall be stacked.
(2) Underground water pipe leakage: water injection pipeline and gas pipeline shall be embedded in the soil replacement area of foundation pit, and the embedding work shall be completed together with formation replacement. The water injection pipe is made of two round steel pipes with a length of 6 m, a diameter of 10 cm, and a wall thickness of 2.5 mm. Multiple water outlet holes are arranged on the pipe wall, and the end is connected with the surface water pump through plastic hose.
(3) Support falling: use the mechanical arm of the drilling rig to remove the traditional compression steel strut and rigid joint steel strut in the middle of the foundation pit from top to bottom, and observe the whole process of foundation pit damage. The whole working condition simulation process is shown in Figure 8. The whole test process is shown in Table 1.

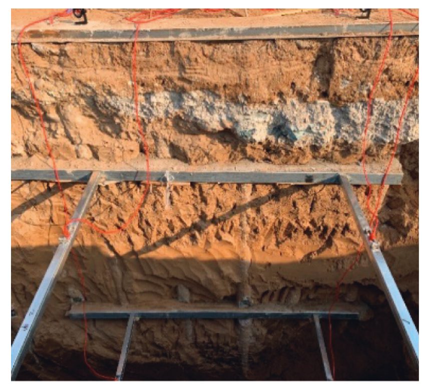


Figure 6: Installation of strain gauge.

Figure 7: Data acquisition instrument.

3. Analysis of Test Results

3.1. Analysis of Lateral Displacement of Foundation Pit. Extract the inclinometer data at different time nodes from the completion of foundation pit excavation to the removal of support, and obtain the variation curve of foundation pit lateral displacement under each test condition under the two support structures, as shown in Figures 9 and 10.

(a) (b)

Figure 8: Simulation of test conditions. (a) Pit side loading. (b) Strut falling.

Table 1: Statistics of key time nodes in the experiment.

Time node		Experimental phase
December 25th	11 : 56	Excavate the first layer of soil
	15 : 13	Install the first layer of steel strut
	15 : 35	Excavate the second layer of soil
	17 : 28	Install the second layer of steel strut
	17 : 57	Excavation to the bottom of foundation pit
December 26th	16 : 00 to 18 : 00	First loading
December 27th	9 : 00 to 13 : 00	Second loading
	15 : 00	Connect the water pipe to the water pump and start water injection
	15 : 45	End of water injection
	16 : 15	Start removing the inner strut
	16 : 19	Strut removal completed

It can be seen from the figure that after 12 : 00 on the 25th the foundation pit began to be excavated, and the lateral displacement of the retaining pile increased rapidly, showing a "belly-shaped" deformation law with the largest displacement in the middle and small displacement at the top and bottom. As of 8 : 00 on the 26th, that is, 12 hours after the completion of foundation pit excavation and support, the corresponding horizontal displacement values of the three measuring points of −1 m, −2 m, and −3 m of retaining pile connected by lap joint are −4.08 mm, −34.32 mm, and −26.65 mm, and the corresponding horizontal displacement values of retaining pile connected by rigid joint are −0.44 mm, −29.77 mm, and −27.05 mm. It can be seen that the frame support structure composed of steel strut and steel pipe pile rigid joint is more favorable to reduce the lateral displacement of foundation pit. After 8 : 00 on the 26th, the process simulation of pit side loading, groundwater injection, and support removal was carried out. It can be seen from Figures 10 and 11 that, under the two support structures, the top of steel pipe pile has lateral displacement outside the foundation pit, and the lateral displacement of the top of steel pipe pile connected by lap joint to the outside of the foundation pit is much greater than that of steel pipe pile connected by rigid joint, indicating that the frame support structure is conducive to reducing the lateral displacement of the top of retaining pile to the outside of the foundation pit.

Figure 11 shows the time evolution law of lateral displacement of retaining piles at the same depth under two kinds of support structures. It can be seen from Figure 11 and Table 2 that the horizontal displacement of all measuring points shows an approximate linear growth trend after the first and second pit side loading, but during the second loading, the position of −1 m depth of lap connected retaining pile begins to produce a displacement trend outside the foundation pit.

The lateral displacement of retaining pile increases rapidly after the leakage of underground water pipe, which is due to the intrusion of groundwater, which changes the physical properties of soil and reduces the cohesion c and friction angle φ. It makes the self-stability of soft soil near the pit worse. The lateral displacement of the retaining pile with lap joint at −1 m depth is +7.18 mm and that of the retaining pile with rigid joint is +2.58 mm, indicating that the frame support structure has a better effect on controlling the lateral displacement of the top of the retaining pile outside the foundation pit. At the depth of −2 m and −3 m, the lateral displacement of the lap joint retaining pile is −44.57 mm and

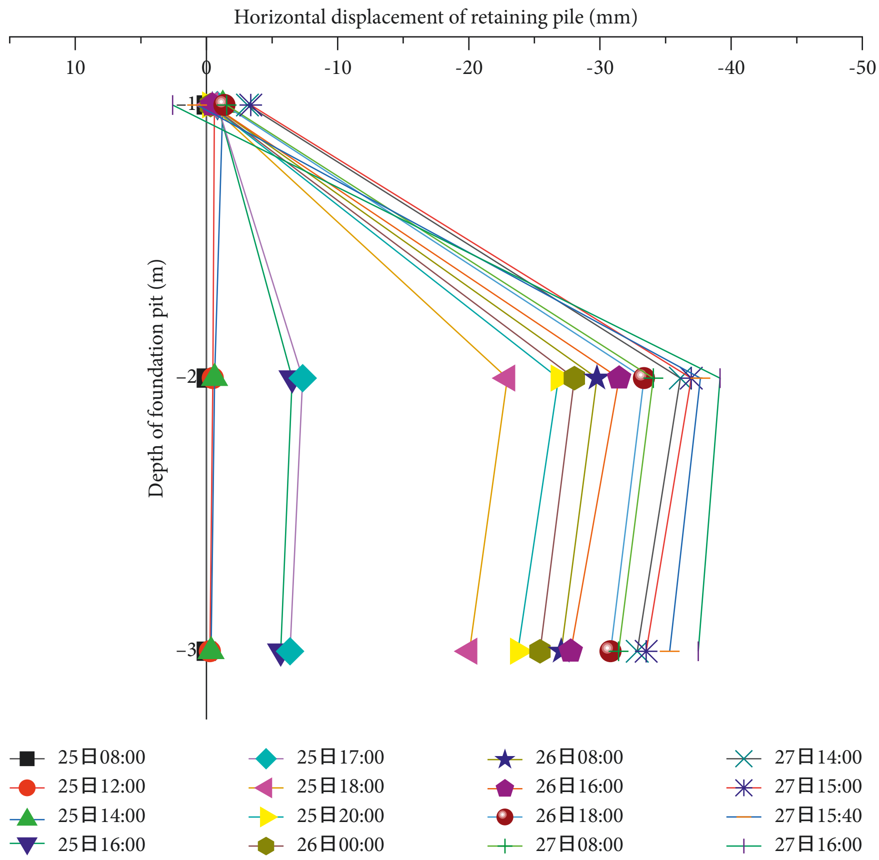


FIGURE 9: Lateral displacement of steel pipe pile with rigid joint.

−36.84 mm. The lateral displacement of rigid joint retaining pile is −39.15 mm and −37.49 mm. It shows that the frame support structure can reduce the overall lateral displacement of the foundation pit and is more conducive to maintaining the stability of the foundation pit.

In Table 2, from the beginning of loading to the end of leakage of underground water pipe, the horizontal displacement increment of lap joint connection retaining pile at −1 m depth is 10.95 mm, and the horizontal displacement increment of rigid joint retaining pile is 3.07 mm, which is reduced by 71.96%. The horizontal displacement increment of the retaining pile with lap joint at −2 m depth is 9.42 mm, and the horizontal displacement increment of the retaining pile with rigid joint is 7.61 mm, which is reduced by 19.21%. The horizontal displacement increment of the retaining pile with lap joint at −3 m depth is 8.88 mm, and the horizontal displacement increment of the retaining pile with rigid joint is 7.71 mm, which is reduced by 13.18%.

The above data analysis can prove that the frame support structure composed of rigid joint between steel strut and retaining structure is more favorable to control the deformation of foundation pit and maintain the stability of foundation pit.

3.2. Strain Analysis of Steel Strut. The steel plate gauge measures the surface strain of the steel strut and is arranged on the first and second layers of steel strut. There are 8 measuring points in total. The measuring points of the two layers of steel plates are in the same position. Taking the first layer as an example, the number of measuring points is shown in Figure 12.

When analyzing the strain gauge data, focus on the stress and deformation law of the support under the influence of working conditions. Take the data after 18:14 pm on December 26 and draw the monitoring data of steel strut strain of each layer in Figure 13.

As can be seen from Figures 13(a) and 13(b), in the excavation and loading stage, the surface strain of the strut in the middle of the foundation pit is significantly greater than that on both sides of the foundation pit; that is, the axial force of the support is greater. This is because the spatial effect of the foundation pit inhibits the development of earth pressure and displacement in the adjacent area of the pit angle so that the earth pressure and displacement in the center of the pit wall are greater than those in a certain range of the pit angle.

In Figure 13(a), in the process of underground water pipe leakage, the surface strain of the first layer of steel strut decreases rapidly, and the surface strain of the overlapped steel strut (L_1 and L_2) decreases to about 0 and tends to be stable, but the surface compressive strain of the rigidly connected steel strut (R_1 and R_2) decreases rapidly and changes to a larger tensile strain, which is consistent with the lateral displacement law of the retaining pile in Figure 12.

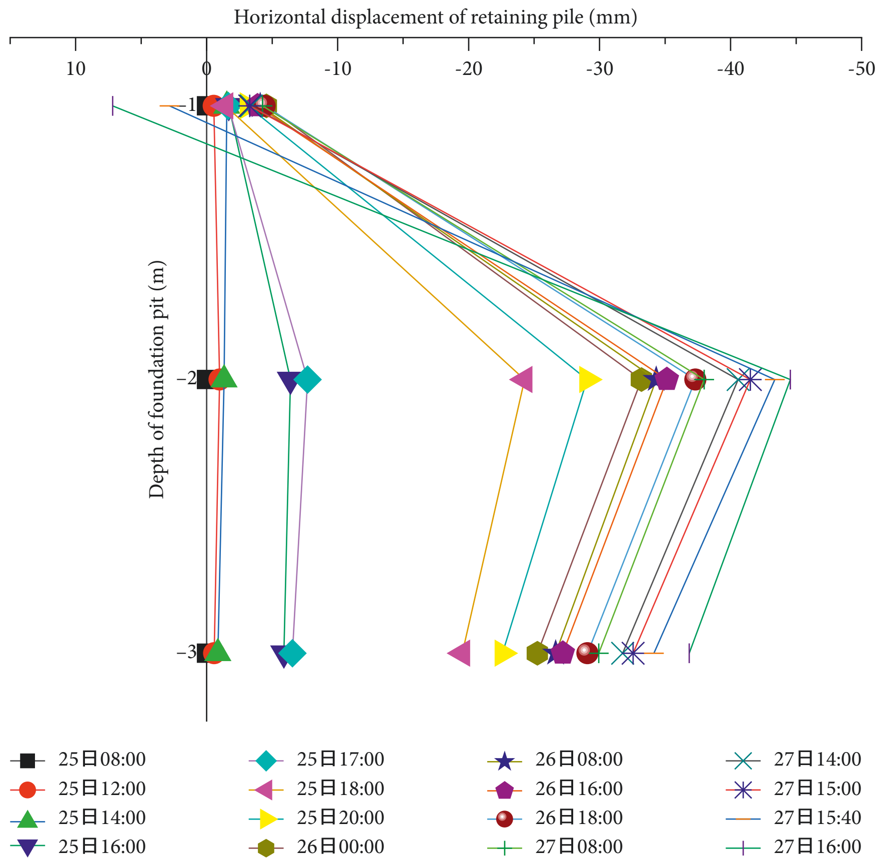


Figure 10: Lateral displacement of steel pipe pile with lap joint connection.

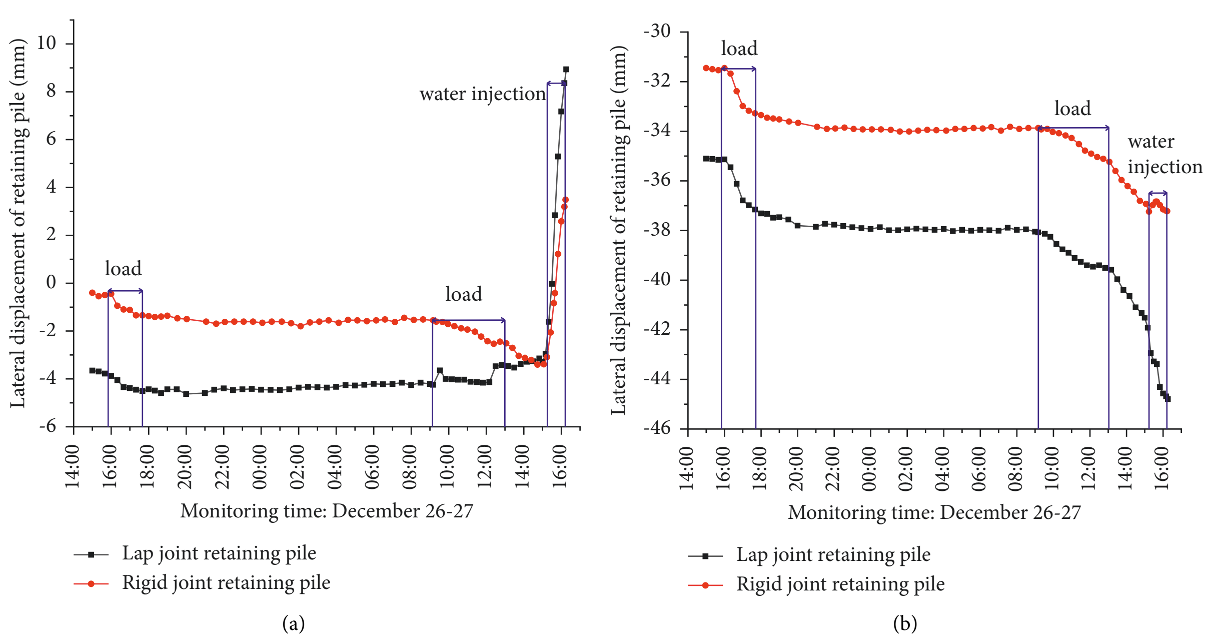
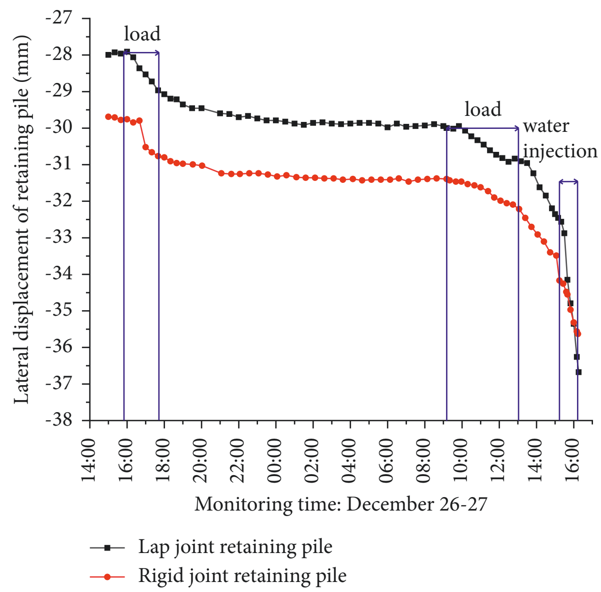


Figure 11: Continued.



(c)

Figure 11: Comparison diagram of horizontal displacement of retaining pile at each measuring point. (a) Measuring point at −1 m depth, (b) measuring point at −2 m depth, and (c) measuring point at −3 m depth. (Note: the value "−" in the figure indicates the horizontal displacement of the retaining pile to the foundation pit; "+" indicates the horizontal displacement of the retaining pile towards the soil layer outside the foundation pit).

In Figure 13(b), the surface compressive strain of the steel strut with rigid joint is less than that of the steel strut with lap joint ($R_1 < L_1$ and $R_2 < L_2$). This is because the steel strut with rigid joint on the first floor bears the tensile stress and shares part of the surrounding rock pressure, which shows that the frame support structure can not only bear the tensile stress caused by the displacement of the retaining pile to the outside of the foundation pit, but also distribute the support axial force more evenly and reduce the occurrence of stress concentration.

3.3. Analysis of Foundation Pit Collapse Process. Remove the two layers of steel struts in the middle of the foundation pit in turn, a total of four, and observe the failure process of the foundation pit. The duration of the foundation pit collapse process is short, a total of 3 minutes, which cannot be accurately described by the monitoring data. Therefore, the damage process is recorded and analyzed by high-definition camera, as shown in Figure 14.

After the removal of the four steel struts in the middle of the foundation pit, the side wall of the foundation pit began to peel off local small pieces of soil blocks, gradually developed into large-area soil blocks and peeled off at the same time, and the foundation pit began to collapse, as shown in Figures 14(a) and 14(b).

In the process of collapse, the lateral displacement in the middle of the foundation pit develops fastest, and the retaining pile in the middle breaks first and dumps into the foundation pit, as shown in Figure 14(c). At the same time, the ground settlement near the foundation pit develops rapidly. The closer to the middle of the foundation pit, the greater the settlement, as shown in Figure 14(d).

Pay attention to the damage of the struts. With the dumping of the side wall of the foundation pit, the second layer of steel strut is damaged first. The steel strut that can only bear pressure on the south side falls off from the waist beam and loses the support function, as shown in Figure 14(f), while the rigid connected steel strut on the north side is damaged and dropped together with the waist beam, as shown in Figure 14(e). Then, the first layer of steel strut was damaged, the south steel strut fell, and the north steel strut tilted. Finally, the side wall of the foundation pit is completely dumped, and all retaining piles are broken from the middle.

The lap connected steel strut that can only bear pressure directly falls off from the waist beam when it is damaged, which is completely invalid, while the rigid connected steel strut and the waist beam fail and fall together. Therefore, when the foundation pit is damaged, the safety of the frame support structure is higher, which can retain part of the support capacity, prolong the collapse time of the retaining pile, and reduce the project loss.

Table 2: Horizontal displacement values of each measuring point.

Condition		Horizontal displacement value of retaining pile (mm)					
		−1 m deep measuring point		−2 m deep measuring point		−3 m deep measuring point	
		Lap joint retaining pile	Rigid joint retaining pile	Lap joint retaining pile	Rigid joint retaining pile	Lap joint retaining pile	Rigid joint retaining pile
First load	Before loading	−3.77	−0.49	−35.15	−31.54	−27.96	−29.78
	After loading	−4.43	−1.38	−37.31	−33.35	−29.07	−30.80
Second load	Before loading	−4.16	−1.52	−37.96	−33.87	−29.94	−31.38
	After loading	−3.46	−2.51	−39.96	−35.60	−31.24	−32.70
Underground water pipe leakage	Before water injection	−3.28	−3.38	−41.52	−36.96	−32.56	−34.20
	After water injection	+7.18	+2.58	−44.57	−39.15	−36.84	−37.49
Total displacement increment		10.95	3.07	9.42	7.61	8.88	7.71

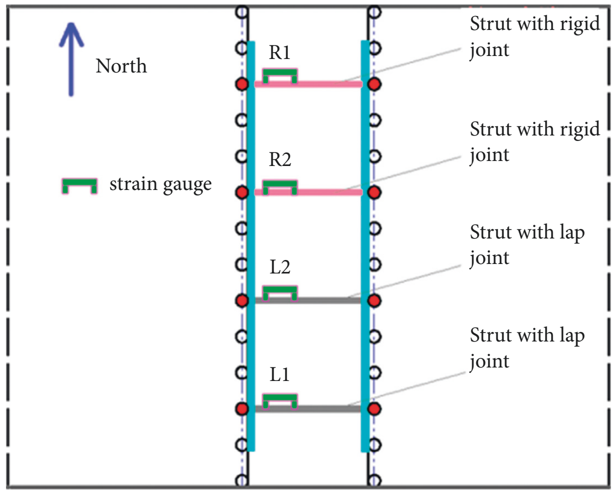


Figure 12: Strain gauge measuring point number of the first layer of steel strut.

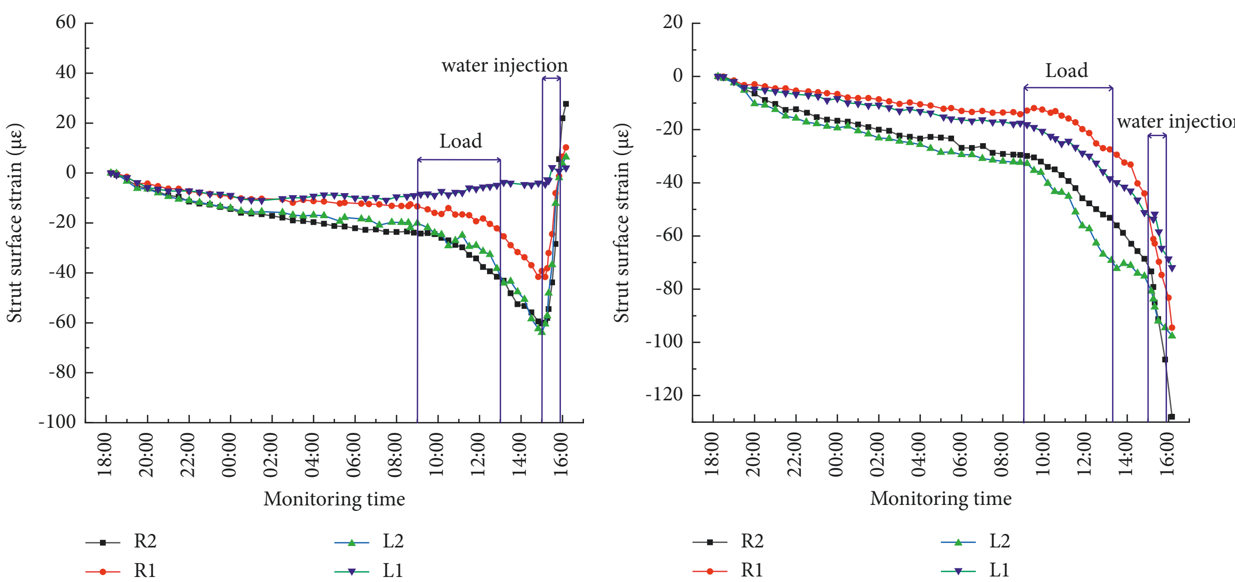


Figure 13: Strain curve of steel strut with time. (a) Surface strain of first layer strut. (b) Surface strain of second layer strut.

(a) (b) (c)

Figure 14: Continued.

(d) (e) (f)

Figure 14: The collapse process of the foundation pit. (a) Small soil blocks on the side wall fall. (b) Many soil blocks on the side wall fell. (c) The middle of the foundation pit begins to topple (north view). (d) The middle of the foundation pit begins to topple (south view). (e) The waist beam on the second floor on the north side fell. (f) Falling failure of second floor strut.

4. Conclusion

In view of the defect that the lap joint used in the traditional strut can only resist pressure, this paper discusses the support performance of the frame support structure with the rigid joint of steel pipe strut and retaining pile, designs the outdoor foundation pit failure test, and compares the foundation pit stability under the two support types by simulating various working conditions. The main conclusions are as follows:

(1) In the process of working condition simulation, the displacement of foundation pit presents a typical "belly-shaped" deformation law. In the three working conditions of soft soil replacement, pit side loading, and groundwater pipe leakage, groundwater has the greatest impact on the deformation of the foundation pit, resulting in the horizontal displacement of the retaining pile outside the foundation pit.

(2) Compared with the strut of lap joint, the frame support structure with rigid connection between strut and retaining pile not only has tensile capacity to limit the displacement of the top of retaining pile to the outside of the foundation pit, but also can significantly reduce the overall lateral displacement and improve the stability of the foundation pit. In this test, from the beginning of loading to the end of underground water pipe leakage, the lateral displacement of the retaining pile under the frame support structure is smaller than that of the retaining pile with lap joint, and the horizontal displacement increment at −1 m, −2 m, and −3 m is reduced by 71.96%, 19.21%, and 13.18%, respectively.

(3) In the process of foundation pit failure, the steel strut that can only bear compressive stress falls off directly from the waist beam and fails completely, while the steel strut with rigid connection always fails with the falling or dumping of the waist beam. When the foundation pit collapses, the frame support structure can retain part of the support capacity and prolong the collapse time of the retaining pile so as to reduce the project loss.

This paper proves the superiority of the foundation pit frame support structure from the mechanism. The focus of the follow-up research is the realization of the rigid connection between the steel strut and the retaining structure, including the rigid connection between the flexible end and the fixed end and the steel purlin, and the rigid connection between the steel purlin and the retaining pile. The development or improvement of the connection joint with convenient disassembly and assembly is conducive to the promotion and application of the fabricated support of the foundation pit.

Data Availability

The data used to support the findings of this study are included within the article. Some or all data, models, or codes generated or used during the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Authors' Contributions

H.M. and Z.Z. conceptualized the study; C.B. curated the data; H.M. carried out funding acquisition; Z.Z. investigated the study; Z.Z. helped with software; H.M. supervised the study; W.H. validated the study; Z.Z. wrote the original draft; Z.Z. wrote, reviewed, and edited the study.

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References

[1] L. Shi, W. Yu, and L. Fu, "Deformation analysis of deep foundation pit in soft soil area considering space–time effect," *Journal of Engineering*, vol. 2019, pp. 8274–8281, 2019.

[2] T. Bhatkar, D. Barman, A. Mandal, and A. Usmani, "Prediction of behaviour of a deep excavation in soft soil: a case study," *International Journal of Geotechnical Engineering*, vol. 11, no. 1, pp. 10–19, 2017.

[3] P.-G. Hsieh and C.-Y. Ou, "Simplified approach to estimate the maximum wall deflection for deep excavations with cross walls in clay under the undrained condition," *ActaGeotechnica*, vol. 11, no. 1, pp. 177–189, 2016.

[4] F. Liu and M. Guo, "Study on deep foundation pit support scheme of subway station with connecting line under complex environment in soft soil area," *Tunnel construction*, vol. 41, no. S2, pp. 421–428, 2021.

[5] S. Song, "Design optimization and construction of deep foundation pit support structure of Beijing Metro," *Tunnel construction*, vol. 37, no. S1, pp. 91–98, 2017.

[6] Z. Zhu, W. Zhao, S. Li, X. Ji, and Z. Tang, "Study on calculation method of subway deep foundation pit support structure," *Journal of underground space and engineering*, vol. 9, no. 05, pp. 1109–1114, 2013.

[7] S. Zhang, *Deformation Monitoring and Numerical Simulation Analysis of Subway Foundation Pit in Soft Soil Area of Suzhou*, Wuhan University of Technology, Wuchang, 2018.

[8] S. Zhang, C. Kang, and Y. Hao, "Analysis of vertical displacement and deformation characteristics of the wall top of metro foundation pit in soft soil area of Suzhou," *Journal of China & Foreign Highway*, vol. 38, no. 06, pp. 1–6, 2018.

[9] X. Shi, C. Rong, H. Cheng, L. Cui, B. Wang, and S. Sun, "Analysis on deformation and stress characteristics of a multibraced pit-in-pit excavation in a subway transfer station," *Advances in Civil Engineering*, vol. 2020, p. 1, Article ID 8844461, 2020.

[10] B. Xu, *Analysis of Deformation Effect Caused by Excavation of Deep Foundation Pit of Metro Station in Hangzhou Soft Soil Area"*, Zhejiang University of Technology, Hangzhou, 2016.

[11] Y. Tan, Z. Kang, W. Bin, and G. Deng, "Case study on deep foundation pit of a subway air shaft in soft soil area of Shanghai," *Journal of Zhejiang University*, vol. 50, no. 06, pp. 1048–1055+1072, 2016.

[12] S. He, "Stress analysis and risk control application of the first reinforced concrete support in deep foundation pit," *Railway Investigation and Surveying*, vol. 43, no. 06, pp. 53–56+60, 2017.

[13] B. C. B. Hsiung, "Observations of the ground and structural behaviours induced by a deep excavation in loose sands," *ActaGeotechnica*, vol. 15, no. 6, pp. 1577–1593, 2020.

[14] K. Zhang and J. Li, "Analysis of "08.11.15" foundation pit collapse accident in Xianghu station of Hangzhou Metro," *Journal of geotechnical engineering*, vol. 32, no. S1, pp. 338–342, 2010.

[15] Z. Zhou, Q. Li, X. Deng, and Y. Cai, "Analysis of subway collapse based on accident mechanism and management factors," *China Safety Science Journal*, vol. 19, no. 09, pp. 139–145+181, 2009.

[16] X. Liu, Y. Zhang, M. Gu, and H. Zhuang, "Analysis of the influence of the replacement rate of pit bottom reinforcement on the safety of deep foundation pit of Xianghu station of Hangzhou Metro," *Chinese Journal of Geotechnical Engineering*, vol. 3 8, no. S2, pp. 136–142, 2016.

[17] Li Yuan, W. Liu, B. Wang, and S. Yang, "Research on Application of fabricated concrete filled steel tubular support," *National Defense Transportation Engineering and technology*, vol. 17, no. 02, pp. 69–71, 2019.

[18] Y. Jin, Y. Zhang, J. Yan et al., "Application of new steel support axial force servo system in deep foundation pit adjacent to subway," *Building and Construction*, vol. 43, no. 10, pp. 2040–2042, 2021.

[19] J. Chen, H. di, S. Zhou, L. Xu, H. Guo, and W. Lu, "Axial force compensation and excavation deformation control effect of servo steel support in foundation pit of urban rail transit station," *Urban rail transit research*, vol. 23, no. 10, pp. 13–16, 2020.

[20] J. Sun and T. Bai, "Research on setting mode of axial force servo system for steel support of subway foundation pit," *Journal of underground space and engineering*, vol. 15, no. S1, pp. 195–204, 2019.