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Research Article

Experimental Study on Double Row Micropiles and Anchors Composite Retaining Structure in Deep Fill Site

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In recent years, with the continuous advancement of urbanization in China and the gradual increase in the utilization scale of underground space, foundation pits may build in a narrow and compact environment. Meanwhile, miscellaneous fill layers in the city may cause construction difficulties when new foundation pits are excavated and supported. While we focus on the above problems, new retaining structure forms which are safe and economical are urgently needed. In this study, based on the excavation in a deep filling site in Jinan, the double row micropiles and anchors composite retaining structure is monitored under excavation, loading, and unloading conditions by installing sensors and testing. The stress and axial force distribution of the front and back row micropiles and anchors in the composite retaining system under different excavation depths and different loads are analyzed. The performance changes of the front and back row micropiles under different conditions and the contribution of anchors at different depths to the structure resistance during excavation and loading tests are discussed. The results show that double row steel piles and anchors composite retaining structure is feasible when excavating deep fill site in the urban area. In the composite retaining system, the stress of the front pile is greater than the back pile, the back pile has a lag when it starts working, and the axial force of the middle and upper anchor is greater than that of the bottom anchor.

1. Introduction

With the continuous progress of urbanization in China, the scale of underground excavation in urban areas is gradually increasing, and a large number of deep and complex foundation pits for new construction projects are emerging [1]. With the continuous expansion of underground space of excavation scale, the construction difficulty is increasing. The increasingly complex surrounding environment in the urban area leads to the boundary of excavation construction close to the existing buildings. Therefore, reinforced concrete vertical retaining members with larger stiffness and anchor or strut are often used as foundation pit retaining structures. But these traditional structure type in the excavation has several problems, such as high cost, low construction speed, and go against to the environmental protection of the construction industry [2]. It should also be noted that the new construction site in the city is often distributed with relatively deep under-consolidated miscellaneous fill. Due to the short backfill time and the complicated component, miscellaneous fill shows some properties of low strength and poor self-stability. These undesirable characteristics cause higher support requirements for excavations. In order to solve these adverse factors, a new retaining structure type form with good construction performances such as rapid construction, low cost, and high bearing capacity is urgently needed.

As a new kind of retaining structure used in excavation engineering in recent years, steel pipe pile has been applied in some excavation and slope engineering. This structure form has several advantages, such as good construction efficiency, high mechanical performance, low cost, and environment friendly. However, the research of theoretical calculation on steel pipe pile retaining structure form lags behind the practical application. This lead to severely restricts the promotion and application of this retaining structure in building excavation construction.

At present, plenty of research works were carried out on the retaining system of steel pipe pile and pile-anchor retaining structures in deep soil-filled excavation engineering. According to the simulation results of some model tests and finite element analysis, Wang [3] pointed out that with the increase of excavation depth, the transition point of pile positive and negative bending moment gradually moved downward, and the pile load on the top of the slope would aggravate the damage of the pile-soil system. Shi [4] found that under the same conditions, the axial force of soil nails in normal nail walls is smaller than that in steel pipe pile composite soil nailing wall, the cooperative work of steel pipe pile and soil nail limits the lateral displacement at the initial stage of excavation, soil nail material has been fully used. Wang, et al. [5] introduced a superthick backfill subgrade instance of Qianjiang-Zhangjiajie-Changde Railway in China and carried out an experimental and numerical study. Xu [6] revealed the deformation law of steel pipe micropile composite soil nailing wall and conducted a parameter sensitivity analysis on steel pipe piles. Han et al. [7] and Ding et al. [8] investigated the damage constitutive model of grouting and concrete, respectively. Sun et al. [9] introduced a new iterative process to find the bending moment and shear capacity of the micropile section, and give a new design method for micropiles for earth slope stabilization. Fu et al. [10] believed that the horizontal displacement and bending moment of cantilever double-row grouting steel pipe pile support gradually decreased with the increase of pile row spacing. However, when the row spacing is too large, pile-soil interaction will decrease. Qi et al. [11] combined with offshore engineering, tested the vertical static load test of steel pipe piles by deploying weak reflection Bragg grating sensors and achieved good results. Shao et al. [12] monitored deep and miscellaneous fill foundation pit with a pile-anchor support system and prestressed anchor cable combined with a channel steel lattice beam, and the monitoring results showed that both structures could effectively control the deformation of excavation construction. Thompson [13] studied the load transfer law of single and double steel pipe piles under lateral load by using the shear box model method. Richards and Rothbauer [14] studied the working performance of micropiles under soil lateral loading. Prat [15] presents a numerical investigation of a micropile retaining wall, and discussed the influence of overestimation soil strength and underestimation loads.

Therefore, it is generally important to obtain a proper understanding of how the micropile structure works in excavation construction. Existing research mainly adopted field tests, numerical simulations, and model tests to study single-row or double-row cantilever steel pipe piles. However, the research of double row micropiles and anchors composite retaining structure in miscellaneous fill soil is almost blank, existing results are not suitable for guiding this structure type construction. To the best of our knowledge, little work has been done on the working mode of micropile and anchor in several construction situations of excavation. In addition,

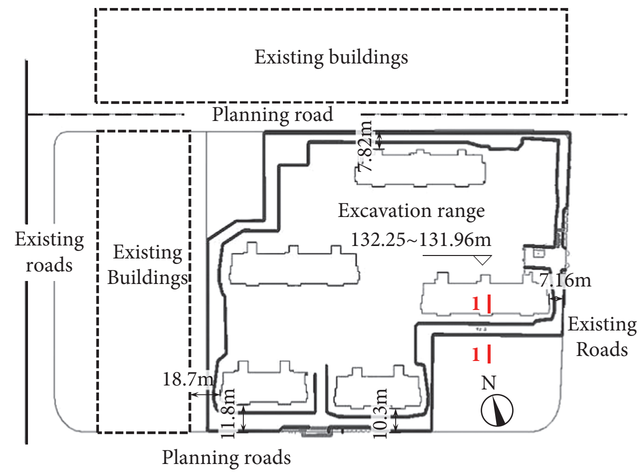


Figure 1: Surrounding environment of this excavation engineering.

vibrating wire sensors may be interfered by the field construction in the test process, and the survival ratio and data reliability will be reduced. Therefore, sensors should be properly selected and arranged during the field test.

In this study, we will first introduce the actual building excavation project of a deep soil-filled site in Jinan and explain the structure form of double row steel pipe piles composite supporting system. After this, introduce the plan of field tests of this foundation pit in excavation and loading conditions that were conducted. Based on the measured data of piles and anchors, the results of field tests will then be discussed. Finally, some important conclusions from this work will be presented.

2. Practical Case of Foundation Pit

2.1. Project Overview. The construction site is located in Shizhong District, Jinan, Shandong province. The miscellaneous fill of this site is mainly silty clay, construction trash, and domestic garbage. The thickness of this soil layer filled is 1.10~18.40 m, and the average value is 9.44 m. Investigation of the hydrogeological environment showed that there is no underground water trace in the depth range of the proposed site. The investigation of the engineering environment showed that the silty clay layer is under the miscellaneous fill layer of this site. The foundation type of the proposed main structure is the pile-raft composite foundation. The retaining structure of this excavation project adopts the double row micropiles and anchors composite retaining structure. The construction unit adopts a vertical excavation plan, and the excavation depth is 5.70~7.14 m. There are existing roads to the east and west of the construction boundary, planning roads will be built close to the north and south boundary, and existing residential building areas were located to the west and north boundary. The specific distribution of the construction area and surrounding environment is shown in Figure 1.

2.2. Design of Composite Retaining Structure. The safety level of the excavation project retaining structure of this

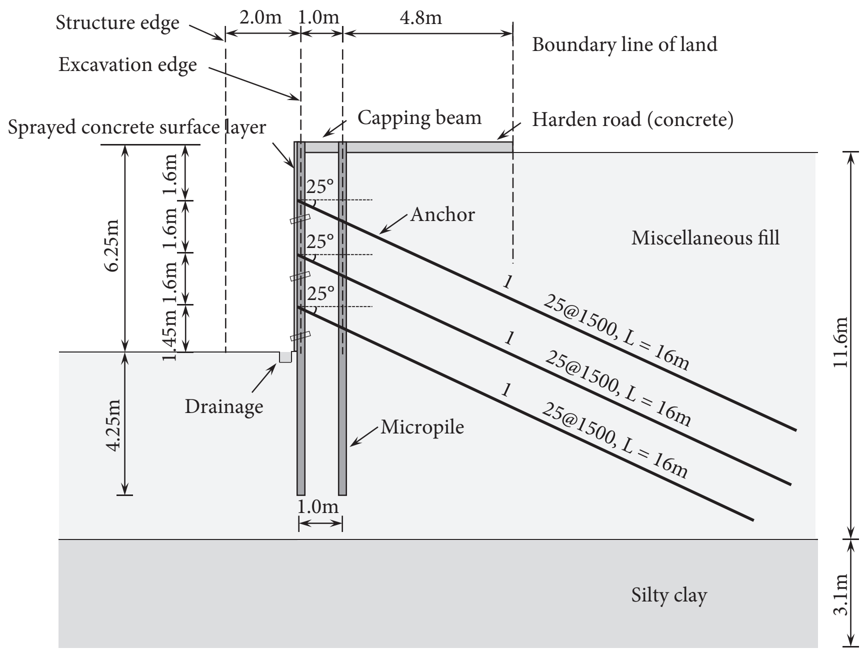


Figure 2: Typical section of double row steel pipe micropile composite retaining structure.

construction project is level 2, and its design work life is 18 months. The distance between the foundation line of the external wall and the bottom line of the vertical slope is 2.0 m. The schematic diagram of typical section 1-1 (shown in Figure 1) of the composite retaining structure system of double row steel pipe micropiles is shown in Figure 2. The outer diameter of the steel pipe which the micropile used is 159 mm, and the pipe thickness is 8 mm. Steel pipes should be placed in the pre-bored hole, then start cement grout pouring. Reinforced concrete cast-in-place capping beam that geometry is 1300×300 mm is set on the double row micropile top, and the beam is integrated with the surrounding hardened road by the cast-in-place concrete process. This excavation section is designed with three prestressed steel bar anchors, all of them have a dip Angle of 25° and a locking value of 50 kN. The horizontal spacing of each anchor is 1.5 m and the vertical spacing is 1.6 m. One steel bar (type is HRB400, diameter = 25 mm) is adopted for the anchor body, and a transverse channel steel waist beam is arranged at the anchor head. The excavation was divided into three stages. After the completion of each layer of excavation, anchors and 80 mm steel mesh hanging shotcrete surface layer belonging to this layer are constructed.

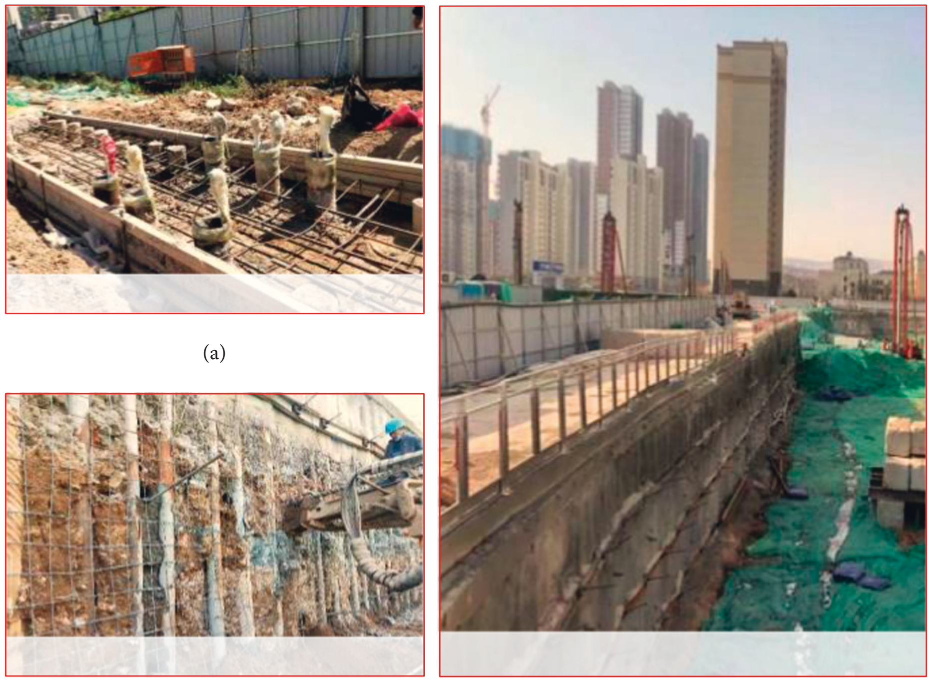
2.3. Construction Process. In the field construction of double row steel pipe micropile composite retaining structure, the hole sinking and grouting of steel pipe pile are first carried out. After the construction of steel pipe piles is completed, the reinforced anchor and shotcrete surface layer are applied along with the layered excavation of soil until the excavation reaches the basement. Figure 3 shows the key construction process of the double row steel pipe micropile composite retaining structure.

3. Field Test of Foundation Pit Excavation and Loading Condition

3.1. Field Test Scheme. The typical double-row steel pipe micropile composite retaining structure position of 1-1 section which was located on the south side of the excavation area was selected as the test area. The supporting structure layout of the test area is shown in Figure 4. In this field test, different sensors were installed to double-row steel pipe piles and steel anchor rods. Continuous monitoring was carried out for the double row steel pipe pile composite retaining structure in the excavation process and the loading-unloading process at the slope top of the foundation pit. Based on the monitoring data obtained, the working situation and retaining mechanism of the double row steel pipe micropile and steel bar anchor in deep miscellaneous fill excavation are analyzed. To ensure the accuracy of the test results, sensors were arranged for three groups of adjacent double-row steel pipe piles (i.e., every single pile from 1# to 6# in Figure 4) and one group of anchors.

Specifically, the steel pipe pile surface along the length of a certain distance arranged on the surface of the pile, to sense the deformation and internal force changes of the steel pipe pile under different working conditions, the sensor type selected ZX-FBG-S02D steel structure strain sensor with a range of $\pm 1500\mu\varepsilon$, accuracy 0.5% F.S. The data acquisition device is TV-200 portable fiber grating demodulation instrument. By getting the central wavelength drift caused by deformation and temperature of the grating from this device, the relationship between wavelength drift and strain or temperature is established according to the following formula:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - P_e\right)\varepsilon + (\alpha + \xi)\Delta T, \tag{1}$$



(a) (b) (c)

Figure 3: Double row steel pipe pile composite support construction process. (a) Micropiles and capping beam. (b) Anchor construction. (c) Excavation completed.

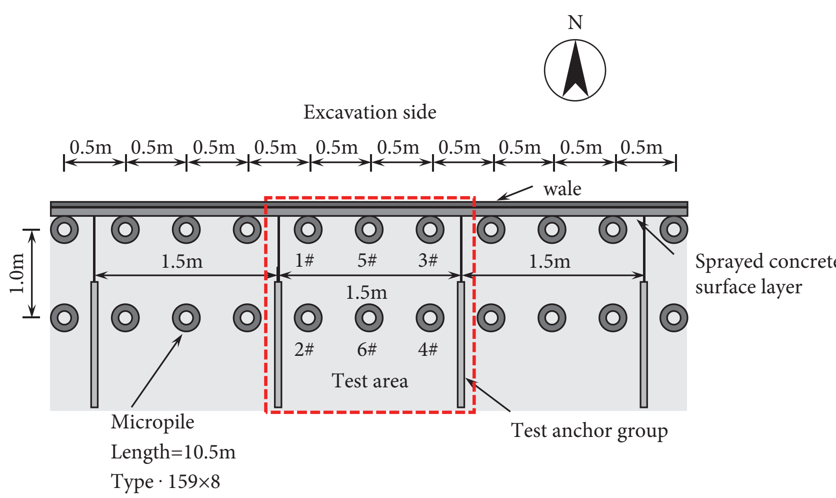
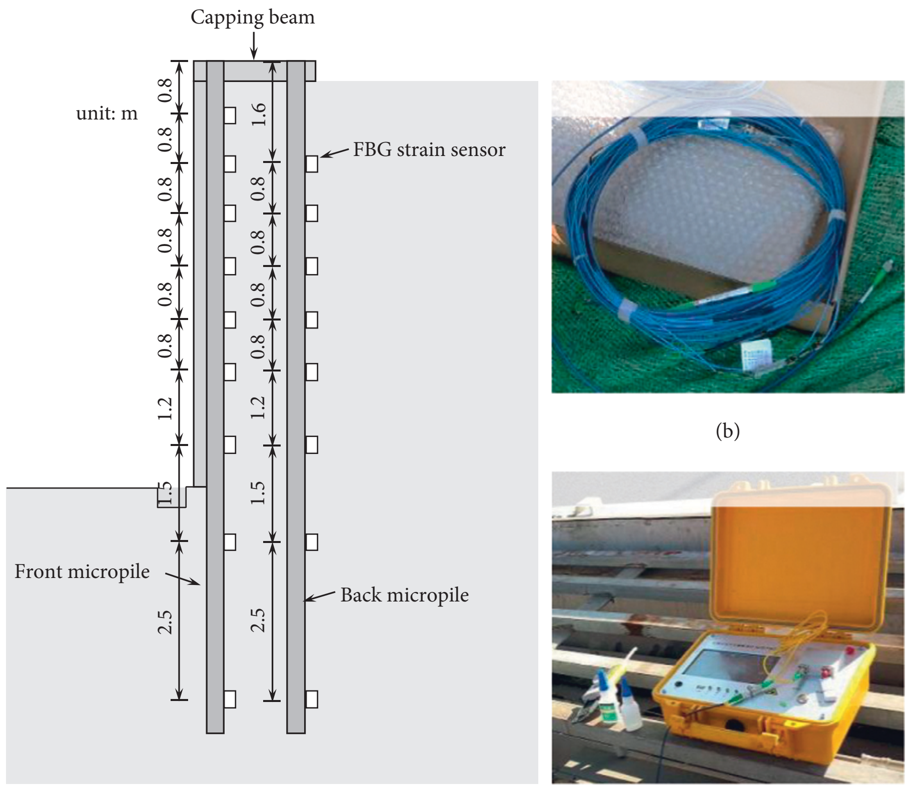


Figure 4: Layout plan of double row micropiles and anchors composite retaining structure test area.

where λ_B and $\Delta\lambda_B$ are the central wavelength and its variation value of FBG respectively, P_e is the effective elastic-optical coefficient, ε is the strain variable perceived by the fiber sensor, and α and ζ are the thermal expansion coefficient and thermal-optical coefficient of the fiber sensor respectively.

Through the above formula, the change of the perceived physical quantity can be obtained according to the change of the central wavelength of the fiber Bragg grating. The fiber grating strain sensor layout scheme and testing equipment are shown in Figure 5.

The fiber Bragg grating (FBG) steel bar axial force sensors are arranged on the free part and the anchor part to obtain the axial force variation of the anchor body under different working conditions. ZX-FBG-F100 steel bar axial force sensors are selected for the anchor monitoring, with the range of 0~400 MPa and the accuracy of 0.5% F·S. Axial force sensors are installed by welding, and its basic principle is the same as that of the fiber Bragg grating strain gauge. The difference is that the axial force sensors indirectly calculate the steel bar stress and axial force through the strain perceived by the grating. In this study, TV-200 portable fiber Bragg grating demodulation instrument is used for data collection for both two different sensor types. The layout scheme and testing equipment of the FBG reinforcement



(a) (b) (c)

Figure 5: Micropile sensors layout plan and testing equipment. (a) Experimental setup of micropile. (b) FBG strain sensor. (c) FBG signal demodulator.

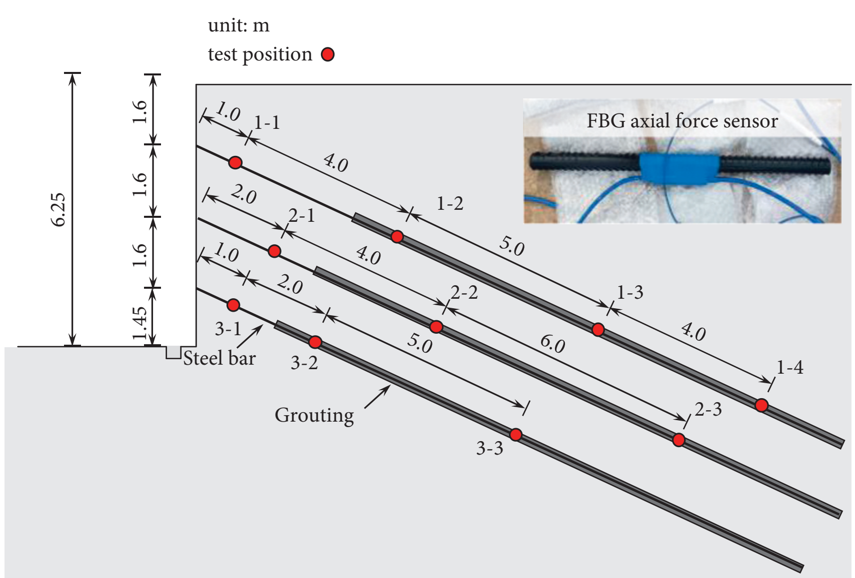


Figure 6: Anchor sensor layout.

dynamometer for reinforcement anchors are shown in Figure 6.

3.2. Sensor Installation. Because the using environment of geotechnical sensors is generally bad, it is vulnerable to failure and disturbance. In order to ensure the safety of the test sensors during the installation and use phase, it is necessary to protect and encapsulate them. To reduce the effect on the performance of the sensor installation and protection measures, patch type grating strain sensor using bonding agent paste in polishing surface of the steel pipe

(a)

(b)

Figure 7: Steel pipe pile and anchor sensor installation. (a) Installation of FBG strain sensor. (b) Installation of FBG axial force sensor.

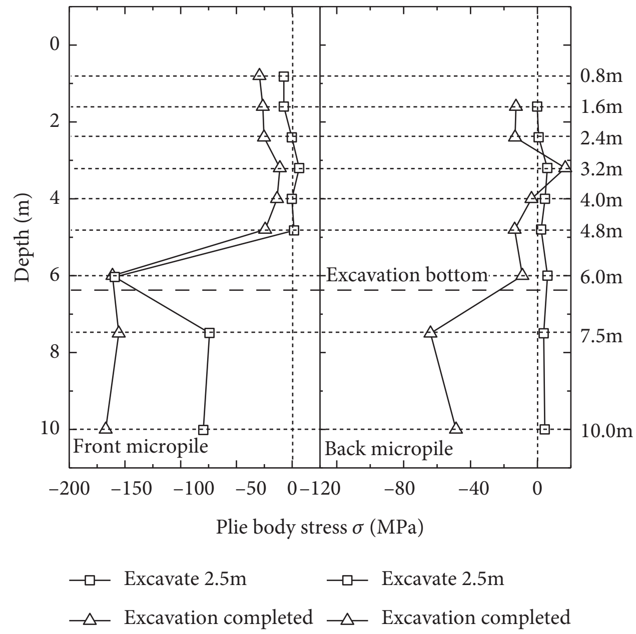


Figure 8: Stress distribution of pile at different excavation depths.

pile, using anhydrous alcohol clean the paste surface before paste. After being pasted firmly, put all the single fiber Bragg grating strain sensors in series, and grating position coating glue to seal sensors. The transmission fiber was fixed by adhesive tape and protected by structural adhesive coating along the length of the fiber. The fiber end was left on the top of the slope for data collection.

When fiber Bragg grating reinforcement was arranged on the anchor body. The anchor body for this test was cut off at the predetermined measuring point of the test scheme, and then the anchor was welded with the sensor connector. Finally, a layer of structural adhesive was coated on the surface of the anchor for protection. Sensors installation of pile body and anchor is shown in Figure 7.

3.3. Field Test of Supporting Internal Force under Excavation Condition

3.3.1. Stress Variation of Steel Pipe Micropile under Excavation Condition. After all kinds of sensors were set up, the initial strain value of all sensors was measured as the starting value before the excavation work started, and the body edge of the front and back pile strain was monitored during the excavation. Due to the interference of the construction process, the data of some measuring points could not be obtained or the distortion was serious. Therefore, a group of double-row steel pipe micropiles (1# and 2# piles) with relatively complete data collection were selected for analysis.

Figure 8 shows the stress distribution of the front and back steel pipe micropiles when the soil is excavated to 2.5 m and the bottom of the foundation pit (at this time, the excavation depth is 6.25 m and the embedded depth of steel pipe micropiles is 4.25 m). The stress value is converted by the strain value, to get strain data, the strains were measured by the fiber Bragg grating strain gauge and obtained by conversion according to (2) according to the elastic theory. The E_s is the elastic modulus of steel, value is 2.06×10^5 MPa.

$$\sigma_s = \frac{\Delta\lambda_B}{(1 - P_e)\lambda_B} \cdot E_s. \tag{2}$$

With the construction of the layered excavation of excavation project, the stress distribution of the cross-section of the double row steel pipe micropiles changed significantly, and the internal force distribution situation of the front and back micropile was very different. When the soil was excavated to 2.5 m, the front pile stress in the depth range of 0~4.8 m did not change significantly, but there was a mutation point of pile stress at the 6.0 m measuring point, which was 161.1 MPa.

According to the data of each measuring point below the mutation point, the pile body stress gradually decreases with the increase of depth. When excavated to the bottom of the excavation, the stress distribution in the steel pipe micropile was similar to that in the 2.5 m excavation, and the micropile stress increased further. The stress in the upper part of the micropile increased by about 20 MPa in the range of 0~4.8 m, while the stress increment measured below the depth of 6.0 m is about 81.4~87.5 MPa, the increment range is 90%.

In addition, the stress variation of the back steel pipe micropile is significantly different from that of the front steel pipe micropile under the same working conditions. When the soil was excavated to 2.5 m, the stress of the back pile body changed slightly and was evenly distributed along the pile length, and the maximum stress of the pile body is only 6.1 MPa, which reveals that the back steel pipe micropile has not fully entered the working state at this time, and the front steel pipe pile bears most of the soil load. When excavated to the bottom of the pit, the back row micropile gradually works and its stress distribution changes. At this time, part of the stress of the steel pipe micropile increased in the depth of 0~6.0 m, and tensile stress occur on the soil side of the steel pipe micropile at the measuring point 3.2 m below the excavation slope top. Different from the steel pipe micropile in the front row, the stress value does not abruptly change at the bottom of the excavation pit, and the position of the abrupt change moves down to about 1.5 m from the bottom of the pit. Below the abrupt change point, the pile stress gradually decreases with the increase of the depth. By comparing the same excavation condition front and back row pile body stress distribution, in the mass, the change of stress value of the front steel pipe micropile is greater than the back steel pipe micropile. It is shown that the front steel pipe micropile plays a more important role in bearing soil pressure, and because the front micropile limits the displacement of soil behind the slope surface, and back row micropile bearing capacity is limited. When the excavation continues, because the soil displacement increases further, the back row steel pipe micropile begins to work and contribute to its capacity, so there is an obvious lag in the work situation of the back row steel pipe micropile.

Therefore, some emphasis should be placed on points of the design composite double row steel pipe micropiles retaining structure. Considering the large force of the front row steel pipe micropiles, the section parameters of the front row steel pipe micropiles may be appropriately increased, and the section parameters of the back steel pipe micropiles may be reduced as appropriate, by this way to improve the mechanical performance and economy of this kind of composite support structure. In addition, it can be seen from the deformation and stress distribution of the back row piles that the micropile body stress above the embedded section changes little, while the stress value of the micropile below the foundation pit bottom is large.

3.3.2. Stress Variation of Anchor under Excavation Condition. Figure 9 shows the axial force test results of the group of three test anchors from top to bottom. Among them, the data of measuring points 1-4 of the top anchor and measuring points 2-3 of the anchor in the second row are partially missing. According to the test results, when the construction of the upper anchor was completed, the axial force of the anchor is small and evenly distributed due to the shallow excavation depth. With the gradual excavation of the soil, the axial force of the anchor increases by 45%~60%, and the axial force of the anchor along its length is still evenly distributed.

During the middle anchor was prestressed to excavation finished, the axial force of the middle anchor is larger than other anchors in different layers, and its axial peak value is about 135 kN, The axial force increases evenly and gradually with the excavation process.

Axial force values of the bottom anchor at each measuring point are small under different working conditions, indicating that the double row steel pipe micropiles and the upper anchor can effectively suppress the deformation of the supporting soil. In addition, the axial force of the bottom anchor body attenuated significantly when it was transferred

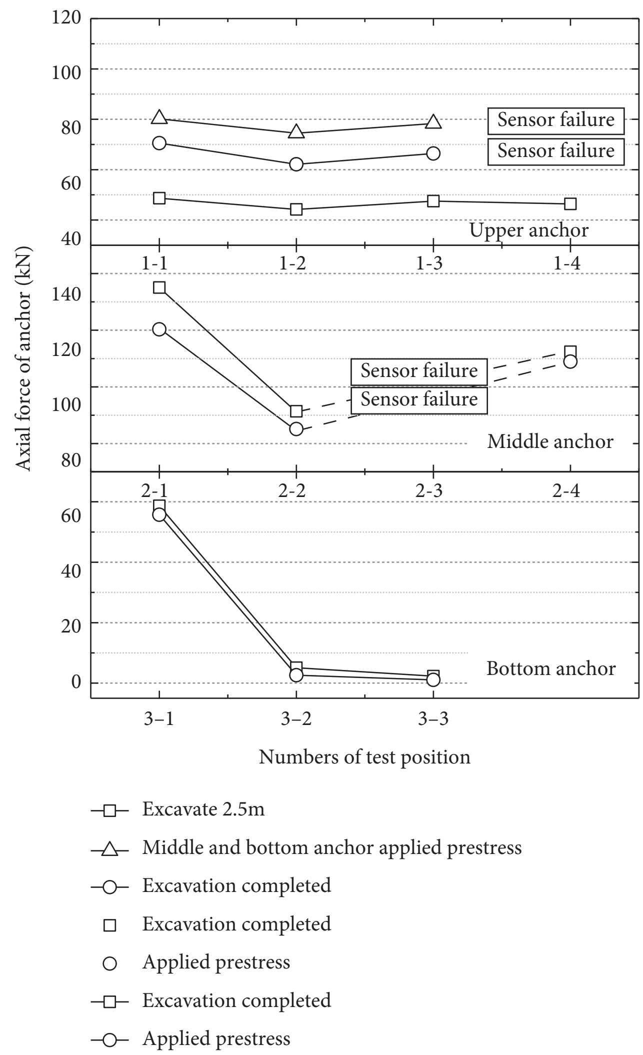


Figure 9: Axial force distribution of each row of anchors under different working conditions.

from the free part to the anchor part, while the axial force tended to be stable within the measuring point 3-2~3-3 in the anchor part, and the axial force of the anchor part was small, only about 5 kN.

3.4. Experimental Study on Slope Top Loading and Unloading Test. After the foundation pit was excavated to the design bottom, in-situ pile foundation testing equipment and counterweight were used to carry out loading and unloading tests on the top of the foundation pit slope, and the variation tendency of pile stress and axial force of anchor in double row steel pipe micropile composite retaining system with or without load is analyzed.

In this section, the distance between the load position of counterweight blocks and the edge line of the foundation pit top was 2.0 m, and the load action was divided into two times with each stage load 25 kPa (i.e., apply design load and 2 times design load). Value changes in micropile stress and anchor axial force were recorded after each load stabilization and unloading. The layout of the test site is shown in Figure 10.

Figure 10: Arrangement of loading and unloading test.

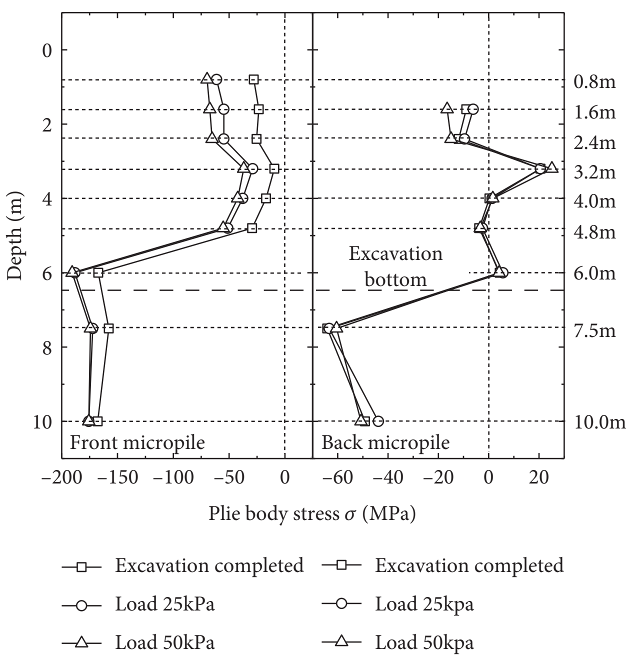


Figure 11: Stress distribution of steel pipe pile before and after loading.

3.4.1. Stress Variation of Steel Pipe Micropile under Loading and Unloading Conditions.

The change of pile body stress of front and back steel pipe piles during slope top loading are shown in Figure 11. The pile body stress of the front row micropile increases significantly after the initial loading, and the pile body stress above the excavation bottom increases about 115.7%~205.3%. Loading causes a severe impact on the working state of front row piles. Therefore, if the bending stiffness of front row piles is low, the micropile composite structure may lead to excessive deformation, buckling, or even damage during service. These phenomena will cause slope collapse and damage to the foundation pit. The pile body stress of the front row micropiles under the bottom also increases, but the relative increment is smaller than the part above the bottom.

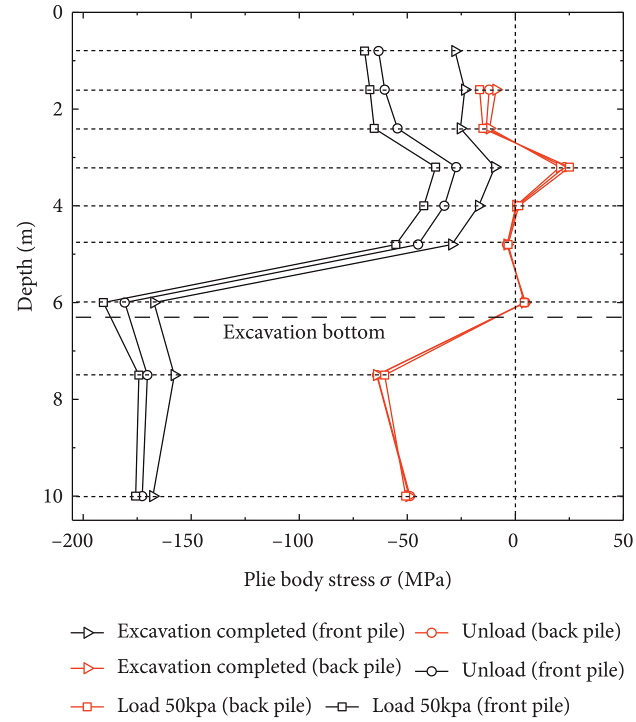


Figure 12: Comparison of stress distribution of pile in excavation completed, loading, and unloading condition.

The stress distribution of the pile body has not changed significantly under the two loading conditions of the back pile compared with the unloading condition, and the loading has little influence on the working state of the back pile, which can be almost ignored. This phenomenon reveals that the material of this micropile is partially damaged due to loading and cannot be completely recovered after unloading [8].

Figure 12 shows the comparison of stress distribution of the front and back steel pipe micropiles before loading (i.e., excavation completed), loading stage finished (i.e. apply 50 kPa pressure), and unloading on the foundation slope. After unloading, the pile body stress of the front steel pipe pile has not fully recovered to the state before loading, under the double design load, the unrecoverable plastic deformation occurs in the miscellaneous fill soil, and the pile body stress of the back steel pipe micropile has slightly changed in the whole process. The reason for this phenomenon may be explained that the under-consolidated miscellaneous fill soil behind the excavation surface being deformed due to the loading. The recoverable deformation of the soil after unloading is small. After unloading, the front row steel pipe piles are constrained by the soil and cannot return to the initial state before deformation. The back row steel pipe micropiles are less affected by this factor due to their small stress and deformation. There is no significant change in the stress of the back row micropile before and after unloading.

3.4.2. Variation of Axial Force of Anchor Rod under Loading and Unloading Conditions.

In the process of unloading, the distribution of axial force along the anchor body of three test anchors in the group was tested. The axial force test results of

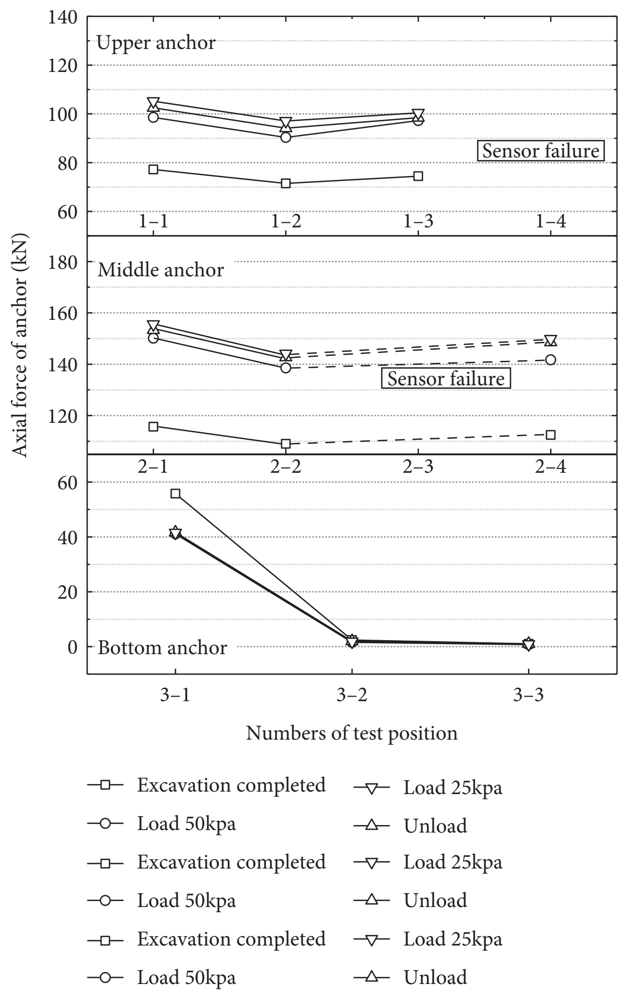


Figure 13: Axial force distribution of each row of anchor rod body before and after loading.

the anchor body in each layer are shown in Figure 13. The axial force of the first row of anchor increased significantly after the first loading of 25 kPa. After the loading increased to 50 kPa and the unloaded phase, the axial force of the tested anchor did not increase or decrease significantly. Similar to the upper anchor, the axial force of the middle anchor also increased significantly during the first loading phase, and the overall stress distribution and values of the anchor changed little during the subsequent loading and unloading process. After the first loading phase, the axial force of the free part of the bottom anchor was decreasing, and the axial force of the anchor part is similar to that before loading, but there is no significant floatation in the axial force of the bottom anchor in the subsequent loading and unloading process.

4. Discussion

4.1. Test Result Analysis. During the whole process of excavation, the absolute value of stress of the front pile is larger than that of the back pile, and the maximum value of the front pile is about 2.16~2.42 times that of the back pile. With the excavation of the foundation pit to the bottom, the axial force of upper anchors presents a sharp change, the increment percent is about 45~60%. However, the anchor axial force of other layers did not change a lot. This means during the foundation pit excavation, the proportion of earth pressure that is resistant by upper anchors is gradually increased. Thus, attention should be paid to the upper anchor in the design work.

In the Experimental study on slope top loading and unloading test, With the increase of the slope top load, the absolute value of the front pile stress increases obviously, and the absolute value of pile stress increases with the increase of depth. The back pile stress increases not obviously. Under the condition of slope top load, the absolute value of the front pile is larger than that of the back pile. When slope top load = 25 kPa, the maximum stress of the front pile is about 2.45 times that of the back pile. When slope top load = 50 kPa, the maximum stress of the front pile is about 2.9 times of that of the back pile. It shows the importance of the front pile in this composite retaining structure. The performance of these test anchors in the loading and unloading test reveals that during the first loading process, the miscellaneous filling soil behind the excavation is consolidated, resulting in the redistribution of the stress field so that the axial force of anchors does not change significantly in the second loading and unloading process. At the same time, the displacement of miscellaneous fill behind the excavation caused by the loading on the top of the slope is constrained by double-row steel pipe micropiles and upper anchor anchors. The influence range of loading on the support system is limited to the middle and upper layers of the excavation slope, so the axial force of the bottom anchor body is effectively reduced.

4.2. Suitability of Double Row Steel Piles Composite Structure in Deep Fill Site. Due to the low strength and complex composition of deep fill soil, the retaining structure form of the foundation pit excavation is limited. Step-slope excavation and soil nailing wall may cause large deformation when use in deep foundation pit with poor soil strength. Due to the large boulder and construction waste in the deep filling soil, it is difficult to carry out cement soil mixing reinforcement and high-pressure rotary jet grouting reinforcement. The reinforced concrete pile or wall retaining structure may lead to high cost, long construction period, and large consumption of cement materials, using these structure forms is not helpful for environmental protection.

As a new composite retaining structure, double row steel piles and anchors composite retaining structure has several advantages, such as short construction period, low cement consumption, and better retaining performance (compared to soil nail and soil reinforcement method). But it needs to be pointed out that the bending stiffness of this composite structure is weaker than the large reinforced pile or wall retaining structure. Therefore, with the increase of foundation pit design depth, its economy gradually decreases, and its optimal application depth is 6~10 m.

4.3. Other Possible Applications in Civil Engineering. The application instance of double row steel piles and anchors composite retaining structure in a deep fill site showed that this retaining structure form is suitable for supporting weak soil layers. Meanwhile, its good economic property makes it easier to promote applications. Besides the foundation pit excavation engineering, this retaining structure form also has the suitability for slope sliding resistance structure or reinforced measures, or other engineering projects.

5. Conclusions

In this study, field tests for the double row steel piles and anchors composite retaining structure in a deep fill site with excavation and loading conditions were carried out. Based on these test results, the distribution of double row micropile stress and anchor axial force of piles is revealed. Some main conclusions can be drawn:

(1) It is feasible to apply the double row steel pipe micropile composite retaining system to the excavation in the deep miscellaneous fill area. In addition, material strength advantages of steel pipe pile and steel bar anchor can be brought into full play.

(2) During the excavation, the absolute value of stress of the front pile is larger than that of the back pile, and the maximum value of the front pile is about 2.16~2.42 times that of the back pile. The stress of the back pile in the double row steel piles and anchors composite retaining structure system is less than the front one, the soil load is preferentially borne by the front pile. There is a lag before the back pile starts working. In loading and unloading tests, the loading on the top of the slope has a severe impact on the working state of the front row piles and the influence on the back pile is relatively small. After unloading, the stress of the pile body of the front pile does not completely recover to the initial state, while the stress of the back pile body has slightly changed. Based on the above experimental results, the engineering economy may be improved by reducing the bending stiffness of the back pile or enhancing the bending stiffness of the front pile. Meanwhile, it is important to control the stacking on the top of the slope.

(3) The field test shows that the axial force of the middle and upper anchor is greater than the bottom anchor of the foundation pit. With the excavation of the foundation pit, the axial force of upper anchors presents a sharp change, the increment percent is about 45~60%. While the axial force value of the bottom anchor is small under different working conditions. Resistance redundancy of structure components like middle and upper anchors should be increased in the design phase of the excavation project.

(4) Optimal application depth in deep fill foundation pit of the double row steel piles and anchors composite retaining structure is 6~10 m. Based on the performance and the good economy of this composite structure, besides the foundation pit excavation engineering, this composite structure form may have the suitability for slope sliding resistance structure or reinforced measures, or other engineering projects.

Data Availability

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

There is no conflicts of interest regarding the publication of this paper.

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