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Research Article

Experiment Investigation on Stress Characteristics of Grouting Microsteel Pipe Piles with Cement-Soil Wall

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Microsteel pipe piles are widely used in excavation support owing to their excellent bearing capacity, flexural rigidity, construction speed, and adaptability. In this study based on a project in soil-rock layers in Qingdao, China, a new type of support combining microsteel pipe piles mounted in cement-soil piles and anchors was adopted and studied. The inner force change laws and bearing capacity of microsteel pipe piles were discussed through in situ stress measurement and laboratory antibending tests on three microsteel pipe piles. It was found that the bending moment of the piles gradually increased with the foundation excavation and maximized at the pile head. The bending moment was larger at the upper and smaller at the lower part along the depth direction, indicating it is reasonable to design and calculate microsteel pipe piles by the pile-anchor system. The variation law of the foundation pit displacement with the excavation depth was monitored. The horizontal displacement of the foundation pit is the maximum at the base top, which is 6.5 mm. The flexural strength of the miniature steel tube pile after grouting is 40% higher than that of the miniature steel tube pile without grouting. It was indicated that the grouting microsteel pipe piles could be implanted in cement-soil piles, which improved the flexural rigidity of cement-soil piles and limited the deformation of foundation pits. This study provides reference for the design and construction of soil-rock foundation pit supporting projects. At the same time, it provides reference for the application of miniature steel pipe piles in other fields.

1. Introduction

High-rise and supertall buildings have become the mainstream of urban construction following the accelerated urbanization in China in the 21st century. Since shallow foundation was unable to meet the bearing capacity requirement of such superstructures, deep foundation was needed as the bearing stratum. Therefore, deep foundation pit projects have received growing attention in the construction of high-rise buildings.

The use of microsteel pipe piles, generally with a diameter of 70–300 mm and with relatively large slenderness ratio, is an effective support for deep foundation pits. Microsteel pipe piles are made by using geologically drilling steel pipes and then pressure grouting into piles and are especially suitable for construction in narrow areas owing to their high bearing capacity, solid pile connection, strong formation adaptability, and small construction vibration [1–4]. So far, the application of microsteel pipe piles on foundation support has been extensively studied. Doherty et al. summarised a field trial undertaken to validate the use of FBG strain sensing arrays in driven microsteel pipe pile applications [5]. Nam et al. explored the bearing mechanism of conical steel pipe piles in sand and explored the mechanical characteristics and bearing mechanism of different pile heads on microsteel pipe piles in sand [6]. In recent years, microsteel pipe piles have widely been used in slope support, and few studies have been applied to foundation pit support. Labenski and Moormann proposed a simple numerical analysis method to simulate the mechanical characteristics of the microtube piles in the process of pile jacking and proposed that the soil density around the pile has a greater influence on the lateral bearing capacity of the steel pipe piles [7]. Hazarika et al. explored the influence of different piled pile angles on the support effect of the microsteel pipe piles in the slope support and confirmed that changing the position of the pile can effectively improve the support effect. It was found that the measured internal forces of steel pipe piles and the displacement of foundation pits were more reasonable by the calculation mode in which the microsteel pipe piles were substituted into concrete piles and underground continuous wall with equal rigidity [8]. Xiang et al. studied the internal forces and deformation law of microsteel pipe piles through heaped load test and analyzed the effects of row number, row spacing, and spacing of the pile on the bearing capacity [9]. They are also often used in heat transfer systems [10–12].

The bedrock depth of urban areas in Qingdao varies greatly, and the geological conditions combining rock and soil are complex. The upper part of the strata is soil and rich in groundwater, while the lower part is rock layers. Most of the building foundations are located in the lower part of the strata. Microsteel pipe piles with unique advantages have gained growing attention in the construction in the soil-rock combined strata, but there is yet rare relevant experience. Through in situ tests and numerical simulations on the microsteel pipe piles in soil-rock combined foundation pit support, Zhao [13] and Wu and Kou [14] studied the change law of internal forces and displacements of the microsteel pipe pile supporting excavation.

At present, the design of microsteel pipe piles is generally based on engineering experiences due to the lack of relevant codes. In addition, studies on internal forces of microsteel pipe piles are rarely based on field tests. In this study, the lateral bearing capacity of the pile was studied through field load tests on microsteel pipes inside cement-mixed piles. Also the stress and deformation of steel pipe piles during the excavation were analyzed by attaching strain gauges on the steel pipes. The results will provide reference in similar foundation excavation support and underlie the design codes of microsteel pipe piles.

2. Test Details

2.1. Engineering Situation. A key project of the comprehensive building is located in Shinan Zhangping Road and Hong Kong Road, Qingdao City, across Nanjing Road in the west and near Xiaoxun Road in the east. The project was mainly surrounded by high-rise residential buildings and used the raft slab foundation. Various underground pipelines were passing under sidewalks and greenbelts around the stadium area. There was heavy and large volume traffic. The construction site had an area of about 19300 m^2, with 27 floors above ground and 3 floors underground, and was featured by the whole frame-shear wall structure form and raft foundation form. The perimeter of the basement outer edge was about 490 m, and the excavation depth of the foundation pit was about 14.1–15.4 m.

2.2. Engineering Geological and Hydrogeological Conditions. The upper part of the strata in the project site was a rock formation and the lower part was soil layer, which were typical of soil-rock combined strata in Qingdao. The Quaternary layers in the project site were 5.7–14.5 m thick according to a site geological investigation report. The soil layers ranked from top to bottom in the order of plain fill, clay-fine sand, coarse sand, gravel sand, organic silty clay, and silty clay. The bedrocks below the Quaternary layers were granite, various dikes, and weathered granite. According to the weathering degree, the order of granite from top to bottom was strongly, medium-, and micro-weathered granite. The physical and mechanical properties of soils are shown in Table 1.

Since the field area is near sea, the rich groundwater there is mainly supplied by sea water and surface precipitation and mainly consists of Quaternary pore phreatic water and bedrock fissure water. The phreatic water mainly exists in fine sand and coarse sand layers. The bedrock fissure water mainly exists in bedrock fissures of strongly to medium-weathered granite, and the water depth is about 1.8–5.1 m. The variation range of groundwater level affected by precipitation is 1.0–2.0 m.

2.3. Foundation Pit Support Project. Since the strata in this project are soil-rock combined strata and also groundwater is considered, the structure of this foundation pit was formed by inserting the microsteel pipe pile into the cement-soil pile and setting the anchor to tensile part. The supporting structure is shown in Figure 1. As a foundation pit support structure, the impermeable cement-soil pile retained both the soil and water during the excavation of the foundation pit, which avoided the separate construction of the waterproof curtain. The cement-soil piles also played a role in retaining during the foundation pit excavation. But, the brittleness of the cement-soil pile results in good compressive resistance and low bending resistance. Soil-cement pile has less bearing capacity of soil pressure and bending moment. Implantation of a microsteel pipe pile in the cement-soil pile improved the flexural rigidity and shear strength and overcame the disadvantages of the cement-soil pile. The cement-soil pile in this project was more impermeable and had good water-proofing effect on the phreatic water in the upper layer. Meanwhile, well point dewatering was used around the foundation pit. Drilling water drainage wells to the medium-weathered granite can well control the fissured groundwater in the strongly to medium-weathered granite. In this project, the cement-soil pile was arranged in two rows, while the microsteel pipe pile was arranged similarly to the row pile. The plane layout of the piles is shown in Figure 2. The cement-soil pile, the steel pipe pile, and the seamless steel pipe with a diameter of 1200, 200, and 146 mm, respectively, were selected for the steel pipes.

The wall thickness of the steel pipes is 8 mm, and the pipe drilling a slurry hole and the slurry can be well wrapped with steel. The top of each pipe is provided with a crown beam to connect it as a whole, and the microsteel pipe pile is embedded in the medium-weathered rock layer.

3. Test Methods and Processes

3.1. Construction Process of Microsteel Pipe Piles. Microsteel pipe piles are constructed after cement-soil pile construction and cement-soil solidification. Before the

Table 1: Physical and mechanical properties of rock and soil.

Soil	Thickness (m)	Severe (kN/m^3)	Cohesion (kPa)	Internal friction angle (°)	Water content (%)	Saturation (%)
Plain fill	1.50	18.0	15	20.0	11.25	89.34
Clay-fine sand	1.80	18.7	12	18.3	23.38	91.23
Coarse sand	2.10	19.1	—	17.6	28.47	81.27
Gravel sand	2.20	19.5	—	19.1	27.32	77.49
Organic silty clay	3.60	19.6	74	13.3	19.14	88.63
Silty clay	3.70	20.1	86	14.4	18.38	92.67
Strongly weathered granite	1.60	22.4	—	45	21.56	—
Medium-weathered granite	1.80	25.3	—	55	20.39	—

c and φ were determined using the quick shear test; E_s was determined using the one-dimensional compressibility test.

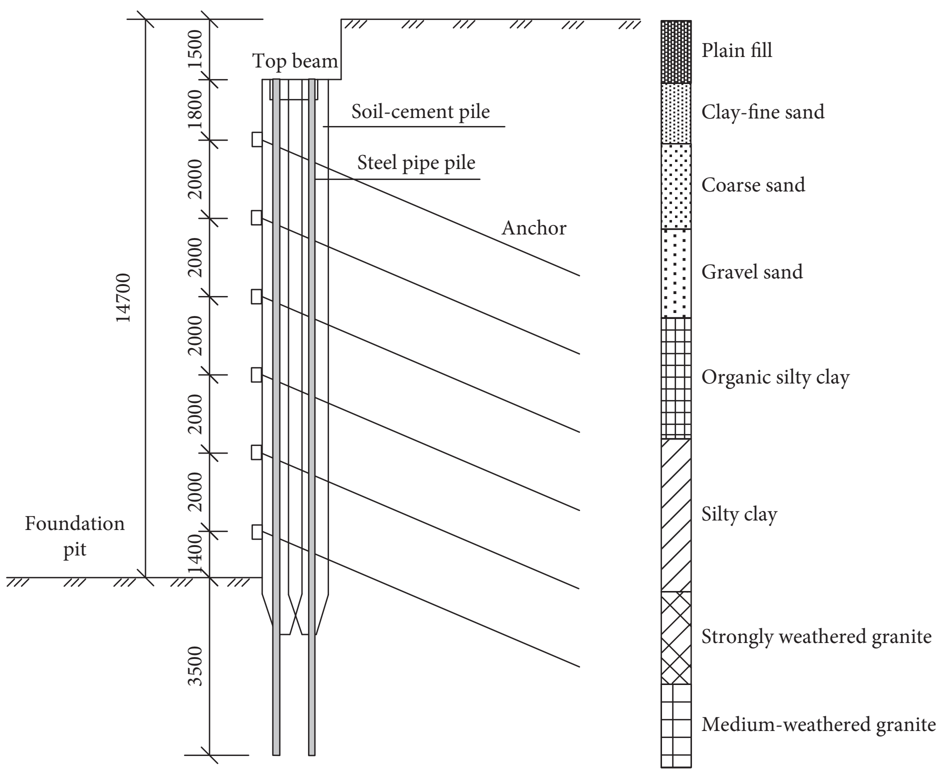

Figure 1: Cross section of the supporting structure (unit: mm).

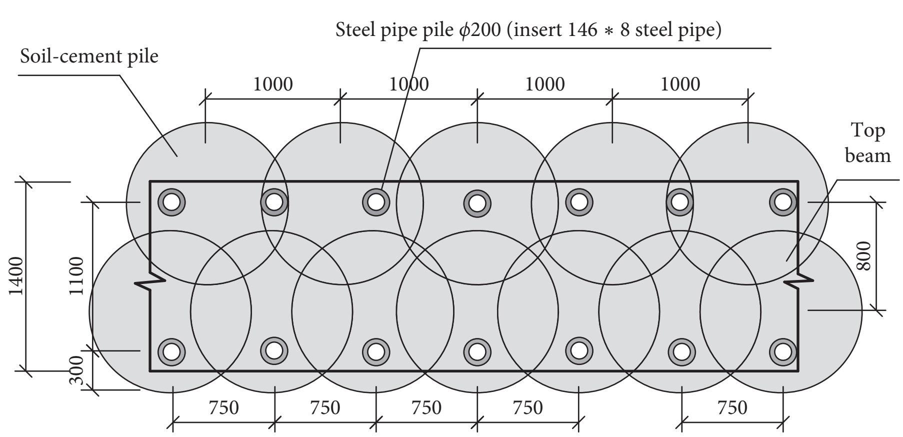

Figure 2: Brief diagram of the pile layout (unit: mm).

foundation pit excavation, the microsteel pipe pile as an advance support was set in the cement-soil pile. Along the foundation pit, the cement-soil pile was constructed firstly and solidified. Then a microsteel pipe was inserted into the cement-soil pile with a drilling rig, forming a microsteel pipe pile after the high-pressure grouting to further limit the soil deformation during the excavation. The construction of each microsteel pipe pile in a cement-soil pile was performed as follows: ground leveling ⟶ pile position calibration ⟶hole drilling ⟶ hole cleaning ⟶ decentralized steel pipe ⟶ grouting into pile ⟶ set the top crown beam.

3.2. Production of Microsteel Pipe Piles. The variation laws of the internal force of the microsteel pipe pile during the foundation pit excavation were studied through stress test analysis involving the 3 microsteel pipe piles. Before the construction of microsteel pipe piles, a strain gauge is pasted at the outer wall of the pile. The way of attaching and sealing the strain gauge is shown in Figures 3 and 4. The strain gauges were arranged symmetrically every 1.5 m along the depth direction on the excavation face and the soil surface of the foundation pit (Figure 5), and a hole with a diameter of 50 mm was formed where each strain gauge is attached [15]. The shield line was connected with the strain gauge pierced through the round hole from the top of the pipe. After the strain gauge was pasted, its survival rate was checked using an ohmmeter, and an epoxy resin mixed curing agent was used to package when the requirements are met. After the curing agent was cured, the strain gauge and the lead wire were protected by the thin iron sheet through a dual role. In order to eliminate the influence of temperature on the test results, a temperature compensation piece was set at the two ends and the middle of the microsteel pipe pile. The specific installation of strain gauges was performed as follows: positioning of measuring points ⟶ opening ⟶ threading ⟶ buffing to where the strain gauge is affixed ⟶ pasting the strain gauge- ⟶ welding lead wire ⟶ testing the survival rate of strain gauge ⟶ epoxying package after welding thin iron for double protection. When the steel pipe was hoisted, it should control two strain gauge wires at the same cross section vertical to the excavation line, which ensures the precision of the stress test. In this test, the data acquisition system is Donghua strain tester DH3816N, and the uncertainty of the system is $\leq 0.5\% \pm 3\,\mu\varepsilon$.

The test process is shown in Figure 6.

The grouting holes were hit on the steel pipe wall and in the space of 0.5 m, which ensured that the slurry could spread to the surrounding soil. The grouting pressure from high-pressure grouting was controlled at 2-3 MPa, and 32.5R ordinary Portland cement is used. The grouting amount less than 1 L/min and regulated for 3 minutes could stop grouting normally. The grouting pipe was inserted into the bottom of the steel pipe to start grouting. When the slurry passes through its mouth, the grouting pipe should be slowly drawn out and its mouth was always kept in the slurry. When pit excavation was stratified, the depth was 2.3 m in the first excavation and then was 2.0 m. After the excavation of each layer, the prestressed anchor should be constructed.

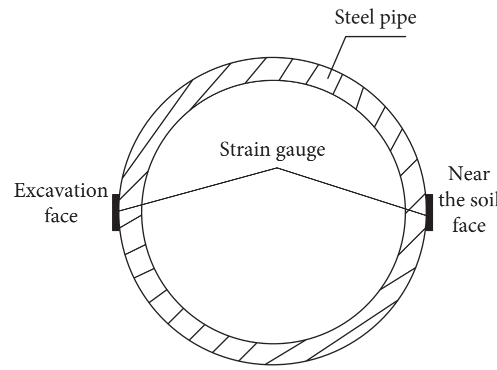

Figure 3: Schematic diagram of outside wall installation.

When the anchor grouting body reaches 75% of the design strength, the next excavation can be carried out. Anchor prestress and the anchor force of excavation are shown in Table 2. The axial tension of the anchor in the new type of support structure is small, and the anchor deformation is not large.

4. Stress Characteristics of Microsteel Pipe Pile in Cement-Soil Pile

During the excavation of the foundation pit, the fender piles mainly receive horizontal load, including earth pressure (which is dominant), water pressure, construction machinery load, and material heaped load. The cement-soil pile within the microsteel pipe pile is the main force-bearing structure in the excavation process. The load is jointly undertaken by the cement-soil pile, the microsteel pipe pile, the prestressed anchor, and soil. However, because of its poor flexural and shear behaviors, the built-in microsteel pipe pile as an important force component may share larger loads due to its higher flexural rigidity. The foundation pit excavation is a soil unloading process in the foundation pit [16]. As the advanced support in the entire support system, the microsteel pipe pile can effectively restrain the surrounding soil deformation and bear the earth pressure in the excavation, which plays a critical role in the foundation pit support. When the microsteel pipe pile is subjected to pressure grouting, the grout or concrete is forcibly poured into the foundation cracks and the cement-soil pile, which subject the pile to larger side friction around so as to obtain the pressure resistance and antitensile strength required by the bearing capacity [17]. Meanwhile, the bearing capacity of micropiles can be significantly increased by changing the spacing and arrangement of micropiles. The damage is the destruction of pile-soil composites [18, 19].

5. Test Results and Analysis

5.1. Pile Internal Force Analysis. During the excavation of foundation pit, the microsteel pipe pile in the cement-soil pile is bent and deformed when subjected to water-soil pressure and the pile body produces moment. If the bending deformation of the pile body overwhelms the bending

(a) (b) (c)

Figure 4: Diagram of installation of the strain gauge. (a) Pasting the strain gauge. (b) Epoxy protection. (c) Iron welding protection.

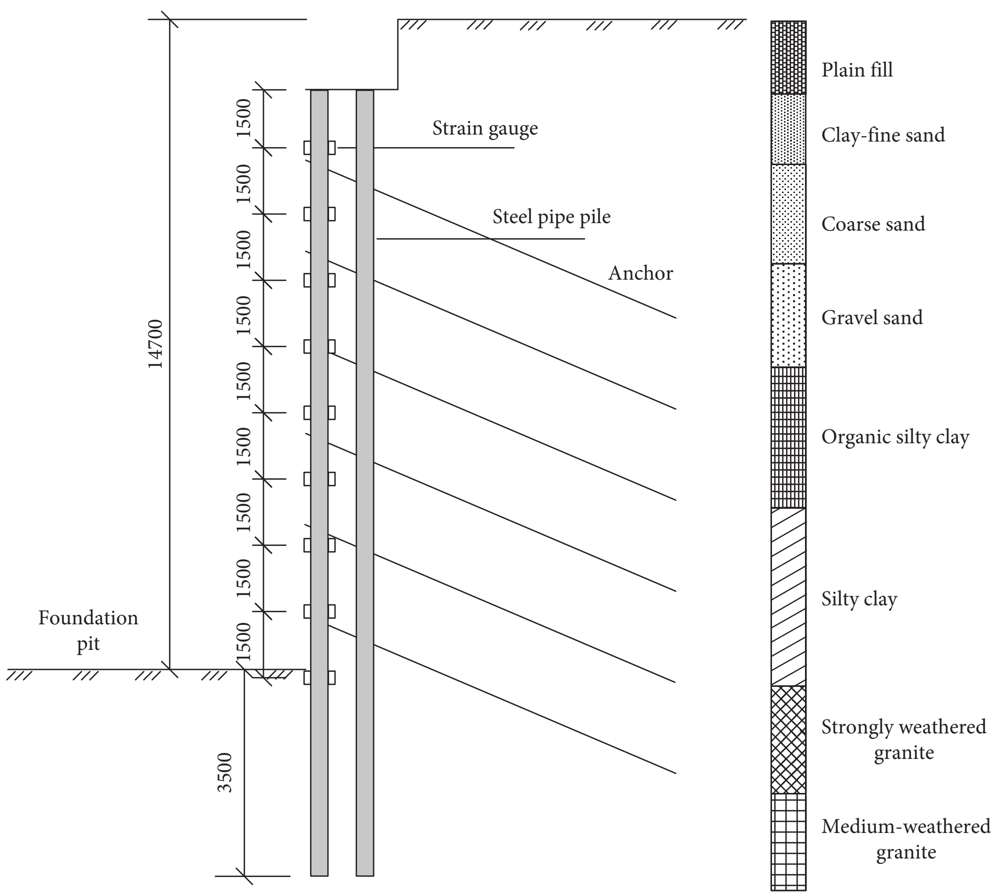

Figure 5: Diagram of arrangement of the strain gauge (unit: mm).

resistance of the microsteel pipe pile, the structure will be destroyed. Therefore, the internal force changes of the micropile during the excavation should be monitored in real time. The pile moment distribution obtained by monitoring the stress of three microsteel pipe piles arranged in the retaining wall near the excavation face is shown in Figure 7, and data were acquired after the pit excavation was completed.

In order to obtain the bending moment according to the strain, it is first calculated that the pile's W was 305530 mm^3. Then, according to the following formula, the bending moment of the pile body can be obtained:

$$\varepsilon = \frac{\varepsilon_{i1} - \varepsilon_{i2}}{2}, \tag{1}$$

where ε_{i1} is the strain of soil approaching surface of the steel pipe pile and ε_{i2} is the strain of the steel pipe pile on back soil surface.

$$\sigma = \frac{\sigma_{i1} - \sigma_{i2}}{2}, \tag{2}$$

where σ_{i1} is the stress of the steel pipe pile on soil approaching surface and σ_{i1} is the stress of the steel pipe pile on back soil surface.

(a) (b)

Figure 6: Test process. (a) Grouting. (b) Testing.

When $\varepsilon < f_y/E_s$,

$$\sigma_i = E_s \cdot \varepsilon. \quad (3)$$

When $\varepsilon > f_y/E_s$,

$$\sigma_i = \left[E_t \times \left(\varepsilon - \frac{f_y}{E_s}\right) \times 10^{-6}\right] + 235, \quad E_t = 0.03E_s, \quad (4)$$

where E is the elastic modulus of steel, F is the yield strength of steel, and E is the strain.

During the excavation of the foundation pit, the microsteel pipe pile as the main force component of the supporting structure is subjected to a large load (Figure 7). When the foundation pit is excavated to the basement, the maximum moment occurring on the top of steel pipe piles is about 3.83, 3.61, and 3.28 kN·m, respectively. The moment of microsteel pipe piles is large in the upper part and small in the lower part and maximizes to about 5.15, 4.42, and 4.31 kN·m, respectively, at the top of the steel pipe piles. When the pit is excavated, the upper section of the steel pipe pile bears a larger load. In this case, the deep pile embedded deeper in the rock can be regarded as a fixed end, which has not yet taken effect and undertakes a small load. With the increase of the excavation depth, the steel pipe pile in the lower section gradually works, and its internal force extends downward along the pile body. The internal force of the pile body increases accordingly, and that of steel pipe piles maximizes when it is excavated to the basement.

From the stress of the whole pile-anchor retaining structure, the prestressed anchor largely prevents the steel pipe pile from further deformation, and the moment of steel pipe piles obviously decreases at the location of the anchor, especially the upper two bolts. With the increase of the excavation depth, the influence range of the joint support between the microsteel pipe pile and the anchor continuously extends to the bottom of the foundation pit, and the moment near the pit excavation face varies greatly. The test results from the excavation of the whole foundation pit are slightly discrete. The moments of the pile body in the clay-bearing fine sand layer and the organic silty clay layer are relatively large during the excavation, which may be because their relatively poor properties largely influence the internal force of steel pipe piles. Through the moment analysis of the microsteel pipe pile, comparison of force characteristics suggests that the pile-anchor calculation model is more reasonable for designing and calculation of the microsteel pipe pile.

5.2. Microsteel Pile Section Strength Verification. To further ensure that the steel pipe pile is not damaged by the excessive stress during excavation, it is still necessary to verify whether the moment of the steel pipe pile exceeds its maximum limit. To verify whether the test value is qualified, the maximum moment of the steel pipe pile can be calculated from the strength according to the flexural rigidity formula in *Code for Design of Steel Structures* (GB 50017–2014) [20]:

$$\frac{M_x}{\gamma_x W_{nx}} + \frac{M_y}{\gamma_y W_{ny}} \le f_s, \quad (5)$$

where M_x and M_y are the x-axis and y-axis bending moments at the same calculated section, respectively; γ_x and γ_y are the x-axis and y-axis plastic deformation coefficients of the section, respectively (here γ_x and $\gamma_y = 1.15$); W_{nx} and W_{ny} are the x-axis and y-axis cross-sectional moments of resistance, respectively; and f_s is the designed tensile strength of steel (here $f_s = 215$ MPa).

The above formula ignores the effect of grouting material body on the stiffness of steel pipe piles. In this case, the calculated maximum moment of steel pipe piles is 23.42 kN·m. An alarm occurs when the tested moment exceeds 70% of the maximum value and the maximum tested moment does not exceed 25% of the alarm value, suggesting the supporting structure is safe during excavation of the whole foundation pit.

5.3. Foundation Pit Horizontal Displacement Analysis. During excavation of the foundation pit, the side wall of the pit, which losses the restraint effect of the soil in the pit, will undergo horizontal displacement under the water-earth pressure. Meanwhile, to further confirm the influence of the microsteel pipe pile on the pit stability during excavation,

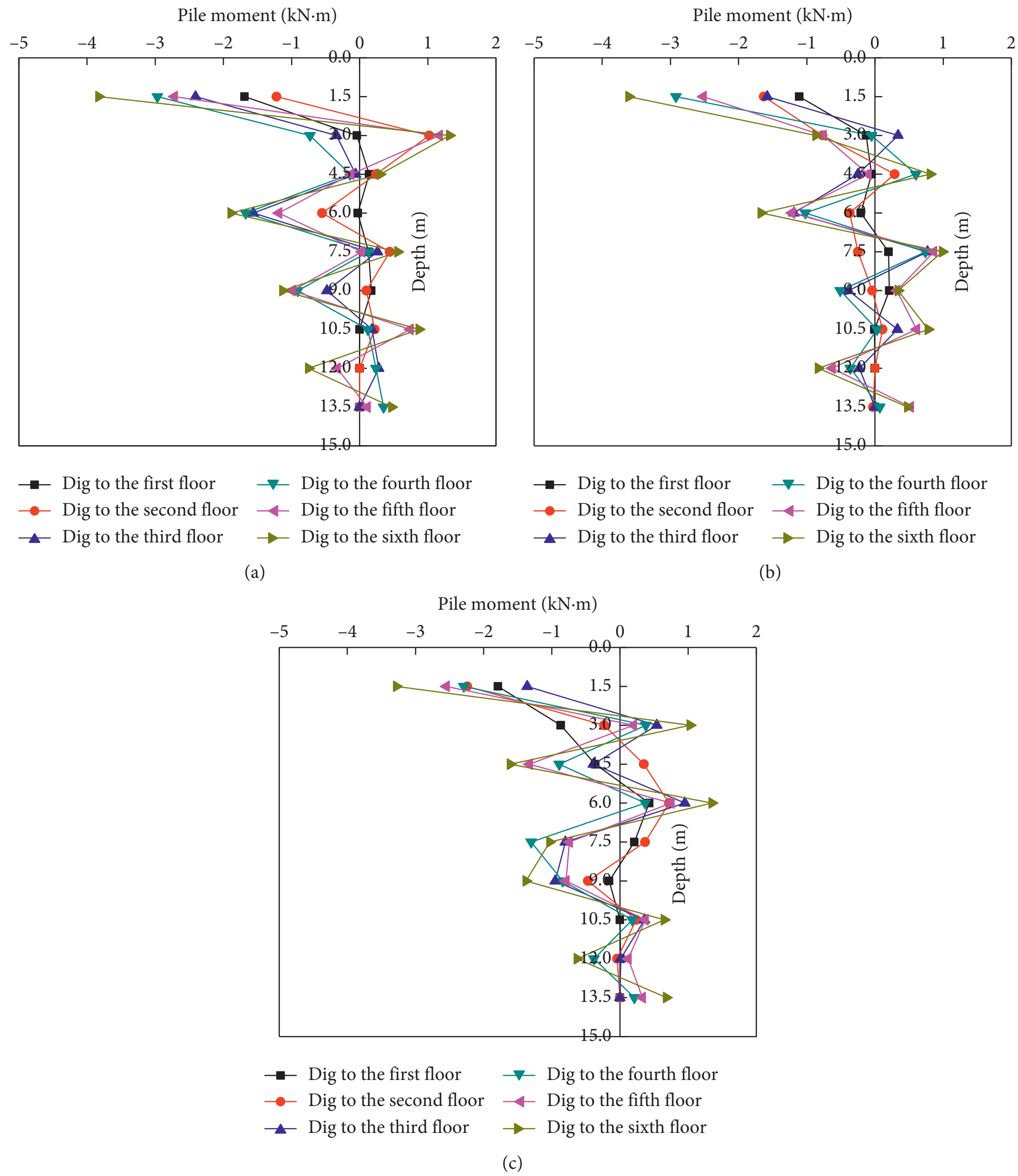

Figure 7: The moment distribution diagram of the pile body. (a) MSP1. (b) MSP2. (c) MSP3.

Table 2: The prestress and internal force value of anchor.

Anchor	First layer	Second layer	Third layer	Fourth layer	Fifth layer	Sixth layer
Prestress (kN)	150	100	100	50	100	50
Internal force of anchor (kN)	195.38	128.36	158.91	56.90	114.72	72.29

the horizontal displacement of the pit should be monitored and analyzed. In the experiment, the horizontal displacement obtained by embedding the measuring pipe near the microsteel pipe pile is close to the horizontal displacement of the microsteel pipe pile, which can be approximated as the horizontal displacement of the foundation pit. The variation curve of horizontal displacement versus depth during the excavation is obtained (Figure 8).

The horizontal displacement of the foundation pit increases with the raising excavation depth and maximizes when the pit is excavated to the basement (Figure 8). Under the same excavation depth, the horizontal displacement

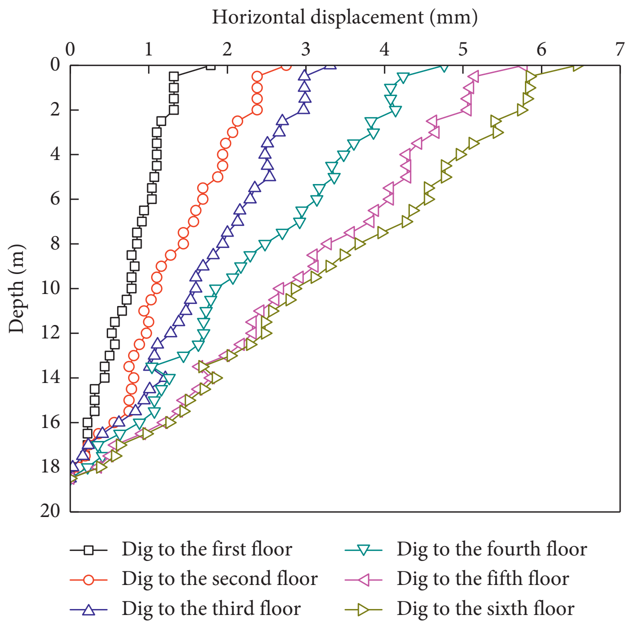

Figure 8: The variation curve of horizontal displacement of foundation pit with depth.

decreases with depth and maximizes at the pit top. The maximum displacement during excavation is about 6.5 mm, and the deformation of the foundation pit is small, indicating the support of the microsteel pipe pile is better, which meets the requirements of pit stability. At the same time, it can be seen that at the bolt position, the deformation is relatively smaller than other parts, which indicates the use of the anchor further limits the pit deformation, and the pile-anchor combined support well controls the pit displacement.

6. Analysis of Grouting Effect on Flexural Stiffness of Steel Pipe Piles

In the experiment, the design calculation of the microsteel pipe pile is carried out by the hollow steel pipe. Ignoring the grouting effect on the flexural rigidity of the steel pipe pile is obviously unreasonable. Therefore, the effects of the grouting material on the flexural rigidity of microsteel piles were analyzed by the simply supported bending tests of hollow or grouted microsteel piles carried out on a universal testing machine (Figure 9) [21].

The universal testing machine contains a set of tensile, bending, compression, shear, ring stiffness, and other functions in one of the material testing machine, mainly used for metal, nonmetallic material mechanical properties test, and the universal testing machine used in this experiment is the oil pendulum. The test speed can reach 1 mm/min~100 mm/min, and it can add the load of 20 t.

The steel pipes used in the laboratory test are the same size (length = 1.2 m) and type as in the field test (taken from the grouted microsteel pipe pile in the field), and the bending stiffness under different loads is calculated through the test (Figure 10). The average bending stiffness of grouted and hollow steel pipes are 2226.7 kN·m^2 and 1540.6 kN·m^2,

Figure 9: The simply supported bending test.

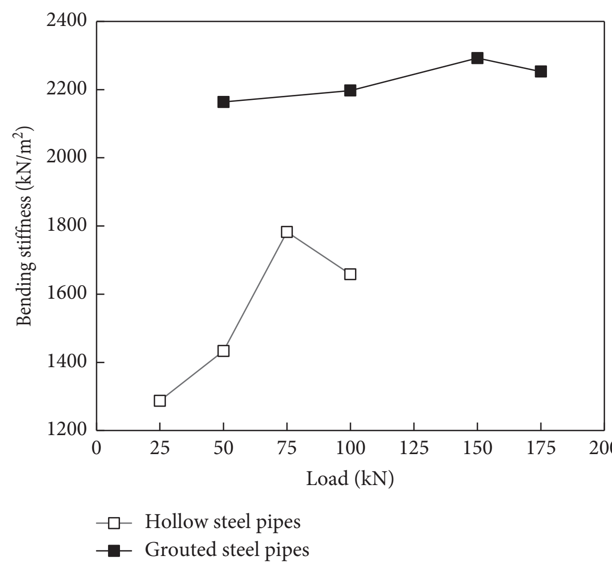

Figure 10: The variation curve of bending stiffness between grouted and hollow steel pipes with load.

respectively. Clearly, the bending stiffness of the grouted microsteel pipe pile is about 1.4 times that of the hollow steel pipe pile. The bending stiffness of microsteel pipe piles is increased more obviously by grouting, and the design calculations do not consider the effect of grouting increase is too conservative. Moreover, due to the existence of grouting, the deformation of grouted microsteel pipe piles under the same load is smaller, which better limits the deformation of the foundation pit.

7. Conclusions

This paper has given a study of the inner force change laws and bearing capacity of microsteel pipe piles. From the results of this study, the following conclusions are briefly drawn based on the given output:

(1) Aiming at the characteristics of the soil-rock combined strata in Qingdao, the use of cement-soil pile implanted with microsteel pipe piles and combined

with prestressed anchor support provides good support. The large bending stiffness of microsteel pipe piles well compensates the poor bending performance of cement-soil piles. Steel pipe piles are the main flexural strength parts in foundation pit support, bear great water and soil pressure, and play a very good supporting role during the foundation pit excavation.

(2) The moment of the microsteel pipe pile increases with the pit excavation, while the moment of the pile body is large in the upper part and small in the lower part and maximizes at the top of microsteel pipe pile. As for the entire support system, the moment distribution conforms to the conventional pile-anchor model, indicating the pile-anchor supporting model is reasonable for the design calculation of the microsteel pipe pile.

(3) The displacement of the foundation pit increases with the rising excavation depth, maximizes at the top, and gradually decreases along the depth direction. The maximum tested displacement is about 6.5 mm, and the displacement of the foundation pit is small, indicating the microsteel pipe pile can well limit the deformation of the foundation pit and thus offer better support.

(4) The grouting body can remarkably improve the flexural rigidity of the microsteel pipe pile, which is 40% higher than that of the ungrouted microsteel pipe pile, suggesting the accretion effect of grouting on the flexural rigidity of microsteel pipe piles should be considered in the design and calculation.

Data Availability

The experimental data used to support the findings of this study will be made available upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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