Research Article

Bearing Characteristics of Moso Bamboo Micropile-Composite Soil Nailing System in Soft Soil Areas

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Based on the characteristics of moso bamboo including high short-term strength, stable performance, and ability to provide temporary support for shallow foundation pits in soft soil, the stress characteristics and supporting effects of the ecological composite supporting system have been explored through model tests and numerical calculation analysis of the moso bamboo micropile-composite soil nailing structure. The results showed that the bamboo pile can effectively control the horizontal deformation of the side wall of the foundation pit and the ground surface settlement, achieving a relatively satisfactory supporting effect. Furthermore, the bamboo pile has visibly bent in middle and lower parts, where the regional shear point is most likely to appear, the axial force of the soil nail is distributed in an oval pattern with a smaller force on both sides and a larger force in the middle part, the maximum axial strain is $447.3 \mu e$, and the axial force of the soil nails in each row follows a similar trend. The synergy of piles and soil nails can delay the formation of the slip surface, therefore enhancing the overall bearing capacity of the foundation pit. These results can shed light on the support mechanism and engineering design of bamboo piles in shallow soft soil foundation pits.

1. Introduction

At present, the main materials used in the main part of the foundation support structure in China are cement and steel, but the production of these materials will consume lots of energy and produce much pollution. The support structure is usually temporary. After the completion of the foundation, the cost of disassembling the support structure is high, and it is troublesome to transport these materials. And these processes may affect the progress of the project. But discarding these materials in the soil will leave severe construction difficulties and hidden dangers for the construction of any nearby projects to be built in the future. The pile composite soil nailing structures have been widely investigated owing to their engineering applications. Through the combination of the single soil nail wall-supporting structure and the supporting pile structure, the advantages of the two supporting structures can complement each other, thereby effectively addressing soil sliding between support piles, deformation control of the soil nail wall support, and limited supporting depth. At present, moso bamboo soil nailing wall-supporting structures have been applied in engineering and achieved excellent supporting effect, but their reinforcement mechanisms, load transfer paths, and failure modes need to be further studied [1, 2].

In recent years, scholars and engineering technicians all over the world have made more research on moso bamboo. Based on the research results of bamboo obtained in Brazilian universities and other institutes around the world, the first specification for bamboo was enacted to determine the physical and mechanical properties of bamboo. The results of the investigations have shown that bamboo can satisfactorily substitute steel. The structural elements developed and studied could be used in many building constructions [3]. In reference [4], a pilot study on two bamboo species was carried out to examine the variation of compressive strengths along the pile body. It was found that, despite large variations in external diameter, wall thickness, and dry density, representative values of mechanical properties were obtained through a systemic test. Among all the physical properties, water content was found to be the most important one in governing the mechanical properties of bamboo. Furthermore, it may be acceptable to assume that
all physical and mechanical properties are broadly constant along the pile body in Kao Jue. However, both the physical and the mechanical properties varied significantly along the pile body in Mao Jue, and thus, the nonuniformity should be incorporated when assessing their structural behavior. Liese and Schmitt [5, 6] observed the morphological changes of bamboo during the drying process and found that the bamboo responded sharply to the change of water content. The critical value of water content was 40%. Above the critical value, the bamboo will shrink in all directions as the water content decreases. Below the critical value, only radial contraction occurs. Kariuki et al. [7] studied the bending mechanical properties of laminated bamboo beams and laminated cypress beams of the same size. They found that, as a new sustainable building material, bamboo has better bearing capacity than cypress. Takagi et al. [8] used wooden piles as the pile foundation of the house and then studied and analyzed the impact and erosion effect of seawater on the pile body. They found that the wooden pile can maintain the stability of the house and have good resistance to erosion. In [9], based on the results of a static load test and numerical simulations, we used regression analysis to establish a pile bearing-capacity formula for pile top displacements that are more than 40 mm and 60 mm. Furthermore, we propose an optimization formula for pile length and its applicable conditions and provide the calculation formula for pile-length reduction coefficient. In references [10, 11], the model test and theoretical analysis were carried out for two different pile supporting types of single-row moso bamboo pipe pile and dentate bamboo pile, and the suitability of the application of moso bamboo micropiles in shallow foundation pits in soft soil was explored. The results showed that the use of bamboo micropiles in shallow foundation pit support can achieve an excellent supporting effect. Bamboo has a special structural feature, and its specific strength and specific rigidity are higher than ordinary steel. Replacing reinforced concrete row piles with bamboo pipe piles, anchor rods, and soil nails with bamboo poles can significantly reduce the construction cost of soil nail support system. The bamboo pole has nodules and stubble, and its diameter is larger than a common steel bar. Bamboo pole, driven into the sidewall of the foundation pit as soil nail, has a greater grip with the surrounding soil, which effectively increases the stability of the soil nail wall and improves the reliability of the load transfer of the support system. At the same time, the strength of the bamboo is relatively stable in the short term and gradually decreases with the decay of the bamboo fiber. The strength characteristic is just in line with the special requirements of the materials used in the temporary support structure and environmental protection.

Most of the research on moso bamboo focused on the test of small-sized bamboo pieces. Although there are many studies on the pile-soil nail wall composite support system, the use of moso bamboo in the support system is little. At present, there is no standard for testing the physical and mechanical properties of the whole round bamboo poles in China. Therefore, the use of reasonable support forms and environmentally friendly and energy-saving building materials is an urgent task to solve the current shallow foundation pit support project, and it is also a requirement for sustainable development construction. In this study, the model tests and numerical calculations of the moso bamboo micropile-composite soil nailing structure for wall support have been conducted. The bearing characteristics and supporting effect of the moso bamboo micropile-composite soil nailing system have been discussed in detail from the aspects of surface settlement, internal force and deformation of pile, pressure of the soil around pile, and the soil nail axial force of the supporting structure, to provide a reliable theoretical basis and analysis method for the application of moso bamboo composite-based supporting systems in soft soil shallow foundation pits.

2. Anti-Overturning Calculation

According to the demands of Technical Specification for Retaining and Protecting of Building Foundation Excavation (JG 120-2012), the embedded depth of the supporting pile should be no less than 0.4 times the excavation depth of the foundation pit. It is assumed that the embedded depth Ie of the bamboo pile is 2 m, the excavation depth is 4 m, and the ground additional loading q is 20 kPa. As shown in Figure 1, the anti-overturning calculation was carried out without considering the influence of the groundwater level by considering only the effect of single soil Pile top displacement and settlement quality [11].

Active Earth pressure intensity:

\[
\sigma_a = (\gamma z + q)K_a - 2C\sqrt{K_a},
\]

\[
K_a = \tan^2\left(45^\circ - \frac{q}{2}\right).
\]

Passive Earth pressure intensity:

\[
\sigma_p = \gamma zK_p + 2C\sqrt{K_p},
\]

\[
K_p = \tan^2\left(45^\circ + \frac{q}{2}\right).
\]

Stability coefficient:

\[
K_q = \frac{M_p}{M_a} = \frac{E_p h_p}{E_a h_a} = \frac{181.10 \times 0.85}{77.06 \times 1.48} = 1.35 \geq K_e.
\]

When the safety level is first class, Kq should not be smaller than 1.25. Therefore, the embedded depth of the micropile meets the stability requirements, and the embedded depth of can be selected as 2 m.

3. Overview of the Foundation Pit Model Test

3.1. Test Schematic Design. In this test, a steel model box with dimensions 5 m x 2 m x 2 m was used with a plastic film covering the inside to reduce the boundary effect and ensure the integrity of the artificially tamped foundation soil. The original excavation stratum was simulated by layering and tamping the silty clay, and tamping tests were conducted to make sure the number of tamping required has been
reached. During the filling process, on-site sampling was conducted to test the volumetric weight and water content. After tamping, the volumetric weight of actual soil was 18.4 kN/m³, and the water content was 14.35%. The physical and mechanical properties of the soil sample are shown in Table 1.

The piles used in the model were bamboo piles with an outer diameter of 16 mm and an inner diameter of 12 mm. Strain gauges were attached to the opposite sides of each bamboo pile. The length of the pile was 600 mm, and its Young modulus was 15 GPa. The bamboo piles were numbered from 1 to 14, as shown in Figure 2. The soil nails were bamboo nails with an outer diameter of 14 mm, an inner diameter of 10 mm, and a length of 400 mm. The same method for attaching strain gauges was applied to the soil nails. When filling the soil, the piles were pre-buried in the soil. The angle between the soil nail and the horizontal plane was 10°. The size of the foundation pit was 1.2 m × 1.1 m × 0.4 m, the distance between piles on the short side was 150 mm, and the distance between piles on the long side was 200 mm. The material parameters of bamboo piles and soil nails are shown in Table 2.

3.2. Similarity Ratio Design of the Model Test. The basic similarity ratio of the model test takes the geometric length similarity ratio and the elastic modulus similarity ratio as \(C_l = 10\), \(C_E = 1\), respectively. According to the principle of the similarity theory, \(\pi\) formula and similarity criterion equation are listed to calculate the similarity ratio of other relevant physical quantities, as shown in Table 3. The volumetric weight of the model pile is 10 times that of the prototype, which is difficult to satisfy in the test. Because the single row of bamboo tube micropiles in the foundation pit mainly bears the horizontal earth pressure and the volumetric weight of the pile has little influence on the test results, the requirements of this similarity ratio can be appropriately relaxed [12–14].

3.3. Measurement System

3.3.1. Deformation Measurement. Resistance strain gauges were used to measure the deformation of the pile body. The dimensions of the strain gauge base were 7.3 mm × 4.1 mm, and the dimensions of the wire grid were 3.0 mm × 3.1 mm. The strain gauges were arranged on the opposite sides of the pile body every 0.1 m along the length of the pile. The strain gauges on the soil nail were arranged on the opposite sides of the soil nail along the lengths of 0.05, 0.2, and 0.35 m. After the strain gauge attachment was completed, epoxy resin was applied to prevent moisture. Consequently, the bamboo piles and soil nails were calibrated by preapplying an external force on the top and recording the strain value during the loading process with strain gauges.

3.3.2. Displacement Measurement. Because the pile bodies were symmetrically arranged and loaded in the direction of the short side, the dial gauges needed to be arranged only on the top of piles #2, #4, and #7 to collect the displacement of the pile top. Displacement gauges were arranged on the short side of the foundation pit to monitor the foundation pit settlement changes in real time.

3.3.3. Earth Pressure Measurement. The earth pressure on the sides of the pile was measured using TXR-2030 strain-type miniature earth pressure gauge. When the soil was layered and filled, the pressure gauge was preburied in the vicinity of piles #2, #4, and #7 according to the excavation depth of the foundation pit and position of the bamboo pile. An earth pressure measurement point was arranged every 0.1 m along the length of the bamboo pile, as shown in Figure 3.

3.4. Excavation and Foundation Pit Loading

3.4.1. Excavation of the Foundation Pit. This step was divided into three levels: the first level excavation was 0.15 m, then, the first row of soil nails was driven; the second level excavation was 0.15 m, and the second row of soil nails was driven; the third level excavation was 0.1 m, and the total depth of excavation was 0.4 m. Meanwhile, real-time data measurement was performed for each excavation level, and the data values were obtained after stabilized before proceeding to the next level of excavation, as shown in Figure 4(a).

3.4.2. Loading. The loading around the foundation pit was realized by stacking standard mass blocks (the dimensions of each mass block were 0.6 m × 0.2 m × 0.2 m, and the mass was 36 kg), and each level of loading was 3 kPa. Real-time data measurement was performed for each loading, and stabilized values were taken before proceeding to the next level of excavation, as shown in Figure 4(b).

4. Results and Discussion

4.1. Earth Pressure Analysis. Considering that the influence of the boundary on the middle piles was small [15–17], the
stress and deformation of pile #4 were analyzed. The change distribution of the earth pressure and bending moment of the pile during the excavation and loading process were investigated.

4.1.1. Analysis of Earth Pressure Change on the Back of the Pile during Excavation. As shown in Figure 5(a), above the excavation surface of the foundation pit, the stress in the soil is released, and the earth pressure gradually transits from the static earth pressure state to the active earth pressure state. With the increase in the excavation depth, the earth pressure on the side of the pile decreases gradually. For some measurement points, due to the partial pile-soil separation, the earth pressure was zero [18–21]. Under the excavation surface of the foundation pit, the overall variation range of the earth pressure was small from the start to the end of the excavation, and the fluctuation range of the earth pressure data was small. According to the above analysis, the excavation process changes the distribution of earth pressure on the back of the pile, and the stress state of the soil body is adjusted and changes with the increase in excavation depth; the earth pressure above the excavation surface gradually decreases with a relatively large variation range, and the variation range of the earth pressure below the excavation surface is small, suggesting that the damage of the soil mainly occurs above the excavation surface and will extend beneath the excavation surface, then gradually developing toward deep damage.

4.1.2. Analysis of Earth Pressure Change on the Back of the Pile during Loading. As shown in Figure 5(b), the earth pressure gradually increases with loading. The growth rate was fast in the early stage, slowed down in the later stage, and finally stabilized. During this process, the change and increase rate of the earth pressure above the excavation surface below the excavation surface is small, suggesting that the damage of the soil mainly occurs above the excavation surface and will extend beneath the excavation surface, then gradually developing toward deep damage.
continuously weakened in the transmission process, and pores between the soil particles are further squeezed, infinitely approaching high density that leads to the rapid change in the earth pressure above the foundation pit bottom. However, the change below the excavation surface is small: rapid increase occurs in the initial stage, followed by a stable increase in the later stage.

4.2. Stress Characteristics of the Pile Body. According to the deformation rules of the pile and the monitoring data, the strain values of piles #2, #4, #5, #6, and #7 were selected for analysis to reduce the influence of the boundary effect. The change in the pile bending moment at each stage of excavation and deformation rules of the pile body in the step loading stage were studied.

4.2.1. Analysis of Pile Bending Moment during Excavation. The bending moment of each point of the micropile can be obtained by attaching strain gauges to both sides of the pile and using the bending theory calculation in material mechanics. The calculation formula is as follows:

\[ M = \frac{EI(\varepsilon_- + \varepsilon_+)}{h}, \]  

where \( M \) is the bending moment of the pile, \( EI \) is the bending stiffness of the micropile, and \( \varepsilon_- \) and \( \varepsilon_+ \) are the tensile and compressive strains of each measurement point; \( h \) is the distance between the measuring points of the tensile and compressive strains at the same cross section, taken as 0.022 m.

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Figure 3: Layout of measurement points. (a) Schematic diagram of monitoring system. (b) Schematic diagram of on-site monitoring.

Figure 4: (a) Excavation and (b) loading of foundation pit.
As shown in Figure 6, the variation in the bending moment of the pile body above the excavation surface was relatively large, while the variation in the bending moment below the excavation surface was relatively small. The maximum increase reached 199.06 N·m, the maximum positive bending moment of the pile body was 556.16 N·m, and the maximum negative bending moment was −436.73 N·m. The bending of the pile body was similar to that of a cantilever beam under loading; the transition point of the bending moment that the pile body borne during excavation was on or close to the excavation surface, after which the bending moment gradually decreased with the increase in excavation depth; the middle and lower parts of bamboo piles were visibly bent, and the local shear action points appeared in these parts. Through subsequent comparison of the bending moments between the piles, it is found that the pile body in the middle area of the bamboo pile is deformed by a large force, and the bending is obvious. The pile body adjacent to the long side of the foundation pit has a small force deformation and a small bending moment. The growth rate is less than the middle area. After the soil nails are placed, the bending deformation of the pile body is reduced, and the growth rate and amplitude significantly slowed down, indicating that the soil nails can effectively improve the distribution of the stress field behind the pile. Thus, during the excavation process, the magnitude and point of action of the pile body both change as the excavation depth increases, and the local shear effect of the pile body is significant.

4.2.2. Analysis of Pile Body Deformation during Loading. To reveal the deformation of the bamboo pile in the loading process, with the symmetry of the supporting structure and loading taken into account, the strain data of supporting piles #2, #4, #5, and #7 were selected for analysis, and the curves of change in pile strain with burial depth were plotted.
The spacing of each layer of soil nail were 15 cm with an inclination angle of 10°.

The construction environment in the excavation stage is complex, and the collected data greatly fluctuates; thus, it is impossible to analyze the stress of the soil nail. Therefore, only the stress of the soil nail in the loading stage was analyzed in this section. Under the external loading, the soil nail is in a combined deformation state of bending and axial tension. In this study, the stacking method was used for loading, and the load value used was relatively small. The soil nail strain was measured by attaching strain gauges on both sides of the soil nail. The collected data is regarded as soil nail deformation caused by axial tension, and the bending strain of the soil nail was not considered. The upper and lower surface strains of the soil nail were $\varepsilon_1 = \varepsilon_p + \varepsilon_m$ and $\varepsilon_2 = \varepsilon_p - \varepsilon_m$, respectively; thus, the axial strain of the soil nail can be obtained as $\varepsilon_p = (\varepsilon_1 + \varepsilon_2)/2$. Combined with $\sigma = F/A$ and $\varepsilon_p = \sigma/E$, it can be obtained that $F = EA\varepsilon_p$. As long as the strain value of a certain point on the soil nail is obtained in the test, the tensile force at that point can be calculated.

4.3.1. Change in Axial Force of Soil Nail during Loading.

As shown in Figure 8, the axial strain of the soil nail was distributed in a pattern such that the strain was small on both sides and large in the middle part. The maximum axial strain value appeared in the middle position of the soil nail with a value of 447.3 $\mu$ε, which is equivalent to 1.87 kN when converted to axial force. The ultimate tension measured by the steel bar puller was 25.68 kN. The maximum axial force of the soil nail in this loading stage was significantly smaller than the ultimate tension, which meets support requirements.

As the loading level increased, the axial strain of each layer of soil nails showed an increasing trend. The axial
strain increase rate of the soil nail near the surface layer was higher than that from the surface layer, and the axial strain of the soil nail on the upper layer was generally greater than the axial strain of the soil nail at the bottom of the foundation pit, indicating that the soil body on the upper part of the foundation pit was relatively more deformed under upper loading. Therefore, as the load increases, the axial force of the soil nail gradually increases. Among all parts of the soil nail, the middle part is obviously stretched. It shows that the soil nails can redistribute the stress of the soil, restrict and strengthen the surrounding soil, limit the deformation of the foundation pit, increase the strength of the foundation pit, and maintain the stability of the foundation pit.

4.4. Analysis of Pile Top Displacement and Settlement. In the test, the displacement variation data of support piles #2, #4, and #5 in each loading stage were collected, and the pile top displacement curves are plotted in Figure 9(a). During the loading process, the displacement of the pile top of the support pile continuously increased, and the maximum horizontal displacement occurred in pile #4 with a maximum value of 2.06 mm; the pile top displacement in the edge area was relatively small. After continuous loading for a period of time, the pile top displacement suddenly increased by a large margin, and small soil blocks start to fall off from the front edge of the bamboo pile top; the side wall of the foundation pit is observed to be slightly raised because sliding occurs inside the slope body with a tendency to slide into the foundation pit. After continuous loading, the growth rate of the pile top displacement slowed down, indicating that the damage gradually developed from the shallow layer to the deep layer. When the slope body’s antisliding force was exceeded, the soil body sheared and slipped, and the slope body slipped. As shown in Figure 9(b),
The surface settlement of the foundation pit is relatively small with no large fluctuation during the excavation process. With the increase in stacking loading, the settlement gradually increases. When the loading reached 9 kPa, the settlement value was 0.63 mm, which is within a reasonable settlement range. After continuous loading, the settlement first increases and then stabilizes because the loading exceeds the maximum bearing limit of the foundation pit, after which the slip surface occurs, damage sliding takes place inside the slope body, and the damage of the foundation pit is formed.

We deduce that the displacement of pile top and surface settlement are relatively small in the excavation process, unaffected by the step excavation but becomes larger in the loading process. With increased loading, the displacement continuously increases. At a certain stage, the displacement goes through a sudden increase and then gradually stabilizes. The reason lies in the internal damage of the foundation pit, which gradually develops from the shallow layer to the deep layer.

5. Numerical Calculation and Analysis

5.1. Selection of Model Sizes and Calculation Parameters. Figure 10 shows the FLAC3D-based numerical calculation model diagram. The origin of the model is located at the geometric center of the supporting structure of the foundation pit. The soil body is simulated with solid elements: the beam element is used to simulate the moso bamboo micropile, and the cable element is used to simulate the soil.
nail. The overall model size of the foundation pit is 15 m × 10 m × 4 m, the soil layer is pure silty clay, the constitutive relationship of the soil body adopts Mohr-Coulomb elastoplastic model, the outer diameter of the bamboo pile is 150 mm, the wall thickness is 12 mm, the pile length is 6 m, the embedded solid depth of the pit is 2 m, and the horizontal spacing between piles is 1500 mm. The soil nail has a diameter of 80 mm and length of 4 m, and the angle with the horizontal line is 10°. The surface layer is concrete, the parameter selection and settings of which are detailed in Table 4. The foundation pit is shallow, and the flow of groundwater is blocked in the scope defined by the depth of excavation and the bottom of the foundation pit to eliminate the impact of groundwater on the supporting structure. A total of 79,654 elements and 92,548 nodes were established in the model. The four sides of the model limit horizontal displacement, and the bottom limits both horizontal and vertical displacements.

5.2. Calculation Process

(1) Generate the initial mesh for foundation pit excavation, and establish the initial calculation model. Apply the displacement constraint boundary condition at the boundaries. Perform iterative calculation under the initial stress and pore water pressure conditions to reach initial stress balance.

(2) Construct the supporting structure.

(3) Excavate the first layer of soil, and construct the first row of soil nails.

(4) Excavate the second layer of soil, and construct the second row of soil nails.

(5) Excavate the third layer of soil until the bottom of the foundation pit is reached.

5.3. Result Analysis

5.3.1. Analysis of Foundation Pit Displacement Field. The analysis of the foundation pit displacement field mainly involves settlement analysis (vertical displacement), the horizontal displacement of slope top, and displacement of the side wall layer of the foundation pit in the excavation and step loading stages to summarize the activity pattern of the soil body in the foundation pit.

(1) Foundation Pit Settlement. According to the foundation pit settlement data of seven points near each pile collected after each excavation and step loading balancing, the settlement curves in Figure 11 were obtained. The overall ground settlement of the foundation pit is small in the excavation stage. With the increase in excavation depth, the settlement value slowly increases. The settlement value of each monitoring point is close to one another, and the relationship between the settlement value and excavation depth is not obvious. The maximum settlement was 0.25 cm. In the loading stage, with increased loading, the settlement remarkably increased, while the vertical displacement gradually increased as well. However, the increase in the settlement slowed down after subsequent loading, indicating that the slope body of the foundation pit has a downward sliding trend due to the probable shear damage in the soil. When the continuous load reached 40 kPa, the maximum settlement occurred near pile #3 (2.68 cm). The ground settlement value of the foundation pit was relatively large; thus, reinforcement is required to ensure the safety of the foundation pit.

(2) Displacement of Foundation Pit Wall Surface Layer. According to the FLAC3D postprocessing, the surface displacement data of the foundation pit wall outside of pile...
was extracted, and the displacement curves of the surface layer along the depth direction were plotted in Figure 12. At the beginning of the excavation, the amount of displacement was relatively small. With the increase in excavation depth, the displacement at all levels gradually increased, but the increase rate of displacement in the later period notably slowed down, indicating that the supporting piles started to provide effective support. Meanwhile, the horizontal displacement of the surface layer had both positive and negative values within the 2 m range from the bottom of the foundation pit. The displacement values are positive around 0–2 m and negative around 2–4 m. A positive value indicates that the surface layer is inclined to the inside of the pit, and a negative value indicates that the surface layer is concave and inclined to the outside of the pit. This phenomenon is related to the stress deformation of the supporting piles. The middle

Table 4: Material parameters.

| Name                        | Volumetric weight $\gamma$ (kN/m$^3$) | Cohesive force $c$ (kPa) | Internal friction angle $\varphi$ (°) | Poisson’s ratio $\mu$ | Elastic modulus $E$ (MPa) | Element type | Constitutive model |
|-----------------------------|--------------------------------------|--------------------------|--------------------------------------|-----------------------|--------------------------|--------------|-------------------|
| Silty clay                  | 17.9                                 | 13.14                    | 22.3                                 | 0.35                  | 6.8                      | Solid        | Mohr-Coulomb      |
| Moso bamboo pipe pile       | 20                                   | —                        | —                                    | 0.22                  | 1.5 × 104                | Beam         | Elastic           |
| Moso bamboo soil nail       | 8                                    | —                        | —                                    | 0.22                  | 1.5 × 104                | Cable        | Elastic           |
| Connecting beam (C30)       | 25                                   | —                        | —                                    | 0.22                  | 1.5 × 104                | Beam         | Elastic           |

Figure 10: Foundation pit model.

Figure 11: Distribution curves of foundation pit ground settlement. (a) Excavation stage. (b) Loading stage.
part of the bamboo pile is greatly deformed, and the reverse bending point appears in the middle and lower parts of the bamboo pile. Therefore, the surface displacement of the side wall of the foundation pit is affected by the reverse bending point of the supporting pile, exhibiting both positive and negative values. After the soil nails were driven one after another, the horizontal movement of the soil body was significantly restricted. Meanwhile, the maximum horizontal displacement of the side wall of the foundation pit was 0.57 cm, and the maximum lateral displacement occurred at the point of the surface layer, where $h = 0$, that is, the pile top position. This amount of displacement lies within the allowable value of the lateral displacement of the surface layer and will not cause any impact on the safety of the foundation pit.

According to the horizontal displacement nephogram of the side wall of the foundation pit at each loading stage in Figure 13, with the increase in loading, the horizontal displacement gradually increases, and the maximum horizontal displacement is 1.48 cm. The study found that the horizontal displacement of each point of the surface layer is basically the same, and there is no obvious large deformation phenomenon. The growth rate of surface displacement is faster in the early stage and slower in the later stage, which is related to the compaction of the soil and the strengthening of the support system. The horizontal displacement value of the upper region in the surface layer is a little larger than that of the lower region. The analysis shows that the upper area of the supporting structure is deformed by large forces and bears more loading, which results in a relatively large horizontal displacement of the middle surface layer. However, the displacement values are within a reasonable and controllable interval. The central area of the foundation pit and the supporting pile bear a relatively large force, proving that the central part of the pile body shears and the pile body deforms in the indoor model test stage.

5.3.2. Internal Force Analysis of Supporting Structure

(1) Deformation Analysis of Bamboo Pile. Pile #4 with a loading of 40 kPa was selected for analysis. A monitoring point was set every 0.5 m along the length of the pile, combined with the horizontal displacement nephogram of the pile body. We found that the maximum horizontal displacement of the bamboo pipe pile appeared at the top of the pile, and the maximum horizontal displacement was 1.68 cm, which is consistent with the results of the indoor test.

Figure 14 shows that the loading was symmetrically applied on both sides of the model. Under the same conditions, piles #1, #3, #4, and #6 were selected for the analysis and comparison of pile deformation. When the initial stress field was loaded, with the increase of calculation and analysis steps, the vertical deformation of bamboo pile was small with insignificant differences in the early stage. The top and middle areas of the bamboo pile were under pressure, and the end area was under tension, suggesting that, under this condition, the reverse bending point of the pile body is located in the middle and lower areas of the pile body, the strain of the pile body at different measuring points reaches the maximum value in this area, and there is only one zero point. With increased loading, the vertical strain of the pile body gradually increases, while the strain increase rate decreases in the later stage as the growth range decreases. The reason may be that the gap between the soil particles is
Figure 13: Horizontal displacement nephogram of the side wall of the foundation pit at each loading stage. (a) 10 kPa, (b) 20 kPa, (c) 30 kPa, and (d) 40 kPa.

Figure 14: Continued.
continuously reduced, the soil becomes increasingly dense, and the loading is further weakened in the downward transmission process, resulting in a small pile deformation. The distribution rule of vertical strain is that the strain value in the middle of the pile is the largest, followed by that in the top of the pile, and the strain value at the end of the pile. The maximum strain of the pile body appears in pile #4 with a value of 464.87 με. The deformation of bamboo pile is relatively large, the increase rate is high, and the stress deformation is obvious, altogether suggesting that this supporting area is a shear-weak area, which is prone to causing instability of the foundation pit. Therefore, in actual engineering projects, it is necessary to strengthen the deformation control and dynamic monitoring of the middle and lower areas of the pile body and take relevant reinforcement measures to improve the shear resistance of the pile body.

(2) Analysis of Soil Nail Axial Force. The soil nail generates frictional force with the surrounding soil body along its length so that a passive tension is exerted on the soil nail inside the soil body. In the simulation, a monitoring point is set every 0.5 m along its full length, and the strain changes of the soil nail in each loading stage are collected via sampling, and the axial force distribution rules of the soil nail are obtained through calculation. Since there is no uniform consensus in the industry on the bending and shearing forces exerted on the soil nail inside the soil, we considered only tension on the soil nail.

In the excavation stage, the soil nail in the middle of each row was selected as the research object, and the axial force distribution curves of the moso bamboo soil nail along its full length in different excavation stages were plotted, as shown in Figure 15. We found that the axial force of the soil nail is unevenly distributed along the nail body, the axial force at both ends of the soil nail is small, and the axial force is large in the middle and frontal area, because the middle front area (top to middle) of the soil nail is subject to frictional resistance from soil tending to prevent the extraction of the soil nail, thereby resulting in the oval distribution of soil nail axial force. Combined with the data rule of the indoor model test, the numerical simulation result is consistent with the test result. After calculating and comparing the axial force of each row of soil nails, we found that the overall axial force of each row of soil nails increases with excavation depth, and each row of soil nails obtains the maximum axial force in the middle area. The maximum values are 88.5, 105.2, and 127.7 kN from the top to the bottom, and the integrity of the foundation pit is relatively good with no instability.

According to the nephogram of the axial force change of each row of soil nails in the loading stage, the deformation of the middle area of each layer of soil nails is obvious, and the deformation of the soil nails near the long side of the foundation pit is small and the soil nails in the long side direction are less affected by the loading, and the axial force changes are not obvious. As the loading increases, the axial force of each layer of soil nails continues to increase. The increase in magnitude and value of the axial force of the second layer of soil nails is greater than that of the first layer of soil nails. Similarly, the axial force of the third layer of soil nails is greater than that of the second layer soil nails; when loaded to 40 kPa, the maximum axial force is 62 kN. The numerical simulation results are opposite to the laboratory test results. The study shows that the foundation pit model in the model test is small, and the size effect is not obvious. Secondly, the upper loading is small, the sliding zone is formed late, or no sliding zone appears, so the upper region soil nailing is the first. When the force is contacted, the growth is faster, and the simulation is restored to the actual working conditions. As the loading increases, the sliding
surface is gradually formed, and the axial force of the soil nail gradually increased. Therefore, it is necessary to strengthen the design and reinforcement of soil nails in the middle area in actual engineering projects. According to the stress and deformation pattern of the soil nails, the influence of different lengths, materials, incident angles, and sizes on soil reinforcement can be taken into account to realize the reinforcement of the foundation pit by divisions and blocks.

6. Conclusions

In this study, bamboo pipe is used as the main material of the supporting system. To study the working mechanism, stress state and deformation characteristics of the bamboo pile-anchor system in the foundation pit supporting project, indoor model tests, and corresponding numerical simulations were carried out. The main conclusions as follows:

1. Earth pressure around the pile. During the excavation stage, the earth pressure behind the pile above the bottom of the foundation pit gradually decreases with the increase of the excavation depth and then stabilizes; below the bottom surface of the foundation pit, from the excavation to the end, the fluctuation of the earth pressure behind the pile is small. In the loading stage, the earth pressure is proportional to the loading. When the loading reaches a certain level, the earth pressure increases suddenly above the bottom of the foundation pit, and the pile-soil system is completely destroyed.

2. Pile bending moment. The bending deformation of the pile body is similar to the cantilever beam. Above the excavation surface, the pile bending moment gradually increases with the increase in excavation depth, and the variation range is relatively large;
during the loading process, the pile bending moment near the bottom of the foundation pit varies greatly, and the pile bending deformation is significant. The middle and lower parts of the bamboo pile are obviously bent; the bending moment transition point is on or near the excavation surface and gradually decreases with the increase in excavation depth.

(3) Soil nail axial force. In the early stage of excavation and support, the axial force of soil nail shows great randomness, which rises in the middle stage and fluctuates steadily in the later stage, reflecting the lack of order of foundation pit excavation. During the loading process, the axial strain of soil nail displays an oval rule with a smaller strain on both sides and a larger force in the middle, and the axial force distribution of each soil nail is proportional to the loading. The increase rate of the axial force in the middle area of the same row of soil nails is higher than that of the soil nails adjacent to the long side of the foundation pit, and the change value of the axial force of the upper layer is higher than that of the lower layer.

(4) Pile top displacement and settlement. In the excavation process, the variation in the surface settlement is not large; when the side of the foundation pit is loaded, the settlement and displacement of the pile top slowly increase with loading. When the loading reaches a certain level, the settlement is accelerated, and the local horizontal displacement of the side wall of the foundation pit is significant.

(5) According to the FLAC3D simulation analysis results, the moso bamboo pile composite supporting system improves the bearing capacity of the supporting structure and has good restraining capacity to control foundation pit settlement, pile top displacement, and horizontal movement of the surface layer. The numerical calculation results and related rules are consistent with the results of the indoor model test, further demonstrating the feasibility and suitability of the novel supporting system as soft soil foundation pits.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] Z. H. Dai, W. D. Guo, G. X. Zheng, Y. Ou, and Y. J. Chen, “Moso bamboo soil-nailed wall and its 3D nonlinear numerical analysis,” *International Journal of Geomechanics*, vol. 16, no. 5, Article ID 04016012, 2016.

[2] Z. H. Dai, Y. J. Chen, G. X. Zheng et al., “Numerical analysis on mechanism of bamboo soil nails and bamboo piles in rows for retaining deep foundation pit,” in *Proceedings of the Tunneling and Underground Construction*, vol. 242, no. 2, pp. 720–730, Shanghai, China, May 2014.

[3] K. Ghavami, “Bamboo as reinforcement in structural concrete elements,” *Cement and Concrete Composites*, vol. 27, no. 6, pp. 637–649, 2005.

[4] K. F. Chung and W. K. Yu, “Mechanical properties of structural bamboo for bamboo scaffolding,” *Engineering Structures*, vol. 24, no. 4, pp. 429–442, 2002.

[5] W. Liese, “International workshop on bamboo industrial utilization,” *Journal of Bamboo and Rattan*, vol. 4, no. 2, pp. 203–206, 2005.

[6] W. Liese and U. Schmitt, “Development and structure of the terminal layer in bamboo culms,” *Wood Science and Technology*, vol. 40, no. 1, pp. 4–15, 2006.

[7] J. Kariuki, R. A. Shuaibu, T. Nyombo et al., “Flexural strength of laminated bamboo beams,” *International Journal of Advances in Engineering & Technology*, vol. 7, no. 5, 2014.

[8] H. Takagi, S. Sekiguchi, N. Danh Thao et al., “Do wooden pile breakwaters work for community-based coastal protection?”, *Journal of Coastal Conservation: Planning and Management*, vol. 24, no. 9, pp. 256–265, 2020.

[9] Z. J. Feng, Y. X. Dong, J. Q. Wen et al., “Method for calculating bearing capacity of bridge pile foundation in Ningbo soil with deep soft base,” *Journal of Tianjin University (Science and Technology)*, vol. 52, no. S1, pp. 16–22, 2019.

[10] Y. S. Deng, H. Wang, M. Yang et al., “Model tests on shallow excavation support through bamboo micro-piles,” *Rock and Soil Mechanics*, vol. 37, no. 2, pp. 294–300, 2016.

[11] Y. S. Deng, Z. H. Cheng, M. Z. Cai et al., “An experimental study on the ecological support model of dentate row piles,” *Advances in Materials Science and Engineering*, vol. 2020, Article ID 6428032, 12 pages, 2020.

[12] J. K. Yan, Y. P. Yin, Y. M. Men et al., “Model test study on the ecological support model of dentate row piles,” *Advances in Materials Science and Engineering*, vol. 2020, Article ID 6428032, 12 pages, 2020.

[13] J. K. Yan, Y. P. Yin, Y. M. Men et al., “Model test study on landslide reinforcement with micropile groups,” *China Civil Engineering Journal*, vol. 44, no. 4, pp. 120–128, 2010.

[14] H. D. Gu and M. Yang, “Experimental study on reinforcement effect of soil-nailed wall in pit excavation supported with scattered row piles,” *China Civil Engineering Journal*, vol. 48, no. 1, pp. 129–148, 2015.

[15] J. X. Sha and F. C. Chang, “Mechanical mechanism analysis of tension type anchor based on shear displacement method,” *Journal of Central South University of Technology*, vol. 15, no. 1, pp. 106–111, 2008.

[16] Q. J. Zhou, X. Q. Chen, and G. G. Xu, “Centrifugal model test and numerical simulation of soft foundation pit,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 11, pp. 2342–2348, 2013.

[17] J. Q. Jia, J. C. Gao, B. X. Tu et al., “Centrifugal model test of flexible retaining structures with pressured prestressed anchor in deep excavation,” *Rock and Soil Mechanics*, vol. 38, no. S2, pp. 304–310, 2017.
[18] J. Q. Wang, L. L. Zhang, Y. Lai et al., "Large-scale model tests on static and dynamic mechanical characteristics of reinforced earth retaining wall," *Rock and Soil Mechanics*, vol. 40, no. 2, pp. 497–505, 2019.

[19] X. Xu and H.-l. Chen, "Adaptive computational chemotaxis based on field in bacterial foraging optimization," *Soft Computing*, vol. 18, no. 4, pp. 797–807, 2014.

[20] X. Zhao, D. Li, B. Yang, C. Ma, Y. Zhu, and H. Chen, "Feature selection based on improved ant colony optimization for online detection of foreign fiber in cotton," *Applied Soft Computing*, vol. 24, pp. 585–596, 2014.

[21] M. J. Wang, H. L. Chen, B. Yang et al., "Toward an optimal kernel extreme learning machine using a chaotic moth-flame optimization strategy with applications in medical diagnoses," *Neurocomputing*, vol. 267, pp. 69–84, 2017.