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Time-Varying Analysis of Retaining Structures Enhanced with Soil Nails and Prestressed Anchors

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Abstract: At present, the research results for the stress response and deformation characteristics of composite support structures are mostly based on ideal or standard working conditions. External disturbances often exist in practical engineering, which makes the monitoring data deviate from the calculation results. In order to analyze the causes of deviation and correct them in practice, it is necessary to consider the time-varying effect and study the construction mechanics behaviors of composite support structures. Based on in situ test data, the effects of soil predisturbance, excessive excavation, unloading on the surface of edges, the tensioning and lagging of the anchor, and continuous rainfall on the stress-time curves of soil nails were analyzed. On the basis of verifying the effectiveness of the model, ABAQUS finite element software (v.6.10) was used to simulate practical engineering based on ideal working conditions. Comparing the in situ test data and numerical simulation results, the development of mechanical response and deformation characteristics in the process of support structure installation and soil digging and filling were analyzed. Research shows that the time-varying effect has a significant impact on construction mechanics behaviors, especially on soil nailing combined with the use of prestressed anchors, due to layered excavation and support.

Keywords: prestress; composite soil nailing; in situ test; time-varying effect; construction mechanics

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Citation: Cheng, J.; Guo, L.; Wang, H.; Dun, Z. Time-Varying Analysis of Retaining Structures Enhanced with Soil Nails and Prestressed Anchors. *Buildings* **2022**, *12*, 458. https://doi.org/10.3390/buildings12040458

Academic Editors: Srinath Perera, Albert P. C. Chan, Dilanthi Amaratunga, Makarand Hastak, Patrizia Lombardi, Sepani Senaratne, Xiaohua Jin and Anil Sawhney

Received: 24 February 2022
Accepted: 2 April 2022
Published: 7 April 2022

1. Introduction

Soil nailing is widely used in slope support and as a bracing structure for foundation pits because of its advantages of fast construction and good economy [1–3]. For the soil-nailed slope, pullout resistance of the soil-grout interface is a critical parameter in design and analysis for geotechnical engineers. Extensive research has been conducted to investigate the pullout behavior of pressure-ground soil nails through field or laboratory tests [4–7]. In addition, numerical slope stability analyses were carried out to explore the behavior of soil nails, as reported in the literature [8–11]. However, in downtown areas where deformation of the foundation pit needs to be strictly limited [12,13], the soil-nail–prestressed-anchor-composite retaining structure is preferable as the prestressed anchors can better limit the displacement of the slope surface compared with soil nails. Specifically, results [14,15] show that the maximum displacement, bending moment, and shear force in the pit can be reduced by over 50%, 40% and 30%, respectively, by soil nailing combined with prestressed anchors compared with simple soil nailing. The differences in the two building-construction methodologies are shown in Table 1.

In such a composite retaining structure, the combined resistance of soil nail and prestressed anchor is expected to provide the required safety against rain-induced or overloaded failure [16,17]. Many experts and scholars at home and abroad have done a lot of research on reinforcement mechanisms [18], stress and deformation [19], stability analysis [20], and other factors.

Table 1. The differences in the two building-construction methodologies.

Construction Methodology	Deformation of Foundation Pit	Plastic Zone	Construction Convenience	Engineering Cost
① Simple soil nailing	larger	larger	relatively good	lower
② Soil nailing combined with prestressed anchors	smaller	smaller	relatively poor	higher

In the existing research, the interaction mechanism between soil nails and prestressed anchors is documented in the literature [21], mostly based on numerical simulations, and a number of critical issues have been fully addressed. Studies in the literature [22,23] examined the working performance and reinforcement mechanism of soil nailing based on soil stress path; Other studies [24–26], based on model tests [27] or field tests [28,29], discuss the changes in earth pressure and groundwater level caused by digging and unloading and the influence of these changes on the internal force and the deformation of the composite soil nailing structure; studies [30,31] examine the influence of design parameters on safety factors and sensitivity by establishing safety factor and sensitivity analysis models used to calculate internal stability. Studies [32–34] examine the construction mechanics behaviors of retaining structures enhanced with soil nails and prestressed anchors.

Foundation pit construction is a dynamic and asymptotic process. In the design, not only the structure itself should be considered. External disturbances, that is to say, the influences of construction steps and sequences on load conditions and mechanical responses, should also be considered. The existing research results do not consider the time-varying effect on the construction mechanics of composite support structures, which leads to a difference in the actual working conditions. In this paper, the effects of soil predisturbance, excessive excavation, unloading on the surface of edges, the tensioning and lagging of the anchor, and continuous rainfall on the stress-time history curves of soil nails under actual working conditions were analyzed. Combined with the numerical simulation results under ideal working conditions, the construction mechanics behaviors of the composite support system under prestress were analyzed. The research results provide a good theoretical and scientific basis for design and construction with the use of soil nailing combined with prestressed anchors and puts forward reasonable suggestions for the current nonstandard conditions.

2. In Situ Tests

2.1. Site Conditions

The tested foundation pit was located at the cross of Fengchan Road and Dongsan Street, Zhengzhou City. The depth was 6.53 m. A soil-nail–prestressed-anchor-composite retaining structure was used to support the north wall of the foundation pit where underground pipelines concentrate and therefore strict deformation control is required. The soil-nailed retaining structure was used to support the south wall of the foundation pit. The influence of ground water on the retaining structure could be safely ignored because of the depth between −10.9 m and −10.1 m. The layout of the foundation pit is shown in Figure 1.

There is a series of testing sites, noted as C1 through C6. C1 and C2 are soil-nail retaining structures located in the south; C3 through C6 are soil-nail–prestressed-anchor-composite retaining structure located in the north, among which there are no unbounded parts in the anchors in sites C3 and C4, whereas there are 2.5 m unbounded parts in the anchors in sites C5 and C6. In this paper, the test results of C1, C4, and C5 used for analysis.

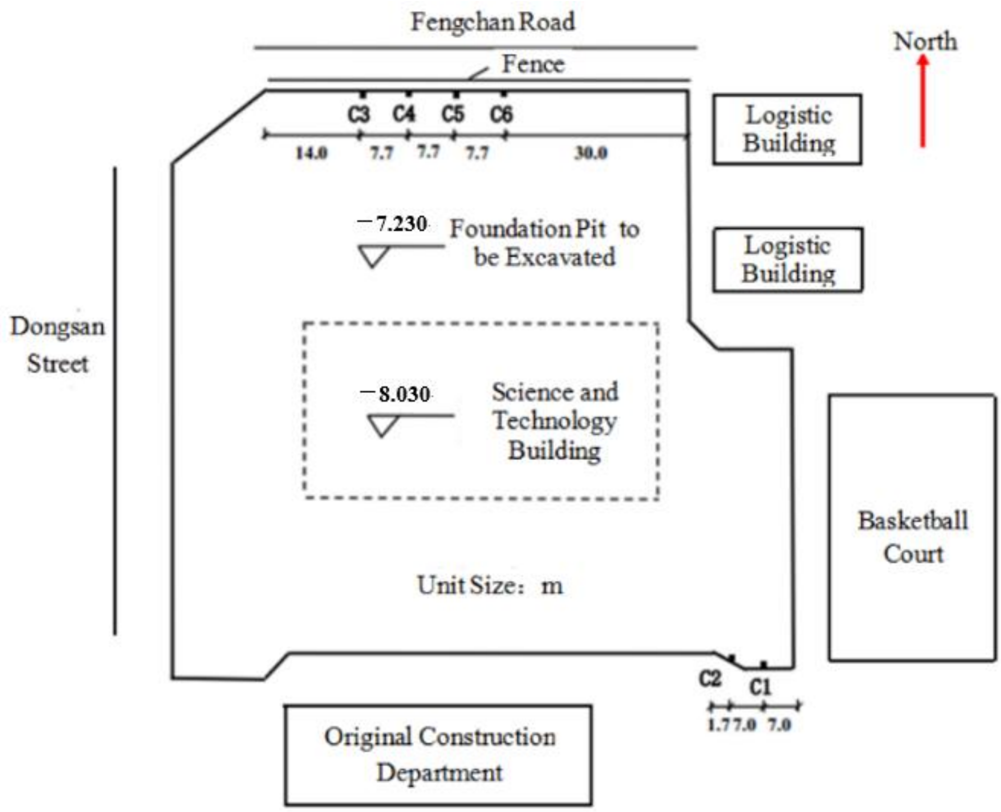


Figure 1. The plan of the foundation pit.

2.2. Soil Properties

The in situ soil layers from top to bottom were (i) silt, 2.20 m; (ii) silty clay, 2.30 m; (iii) silt, 1.10 m; and (iv) silty clay, 2.30 m, respectively. The average properties of each soil layer are listed in Table 2, in which γ is unit weight, c is cohesion, τ is the shear stress of the soil/grout interface and φ is the internal friction angle.

Table 2. The mechanical parameters of the soil.

Soil Layer	γ (kN/m^3)	c (kPa)	φ (°)	τ (kPa)
①	18.1	14.0	20.0	52.0
②	17.9	20.0	15.0	50.0
③	18.2	15.0	21.0	60.0
④	18.2	21.0	16.0	56.0

2.3. Supporting Details

Soil nails and prestressed anchors were distributed in a "square" layout with an equal vertical and horizontal spacing of 1.4 m. Boreholes with a diameter of 120 mm and an inclination of 10° were predrilled manually. After the installation of the steel reinforcement bars into the boreholes, a two-staged grouting was applied. The two-staged grouting has been used successfully in many countries and areas to reinforce cut slopes, excavations, tunnels, etc., to increase the performance of soil nails and therefore to reduce the number of required soil nails [35–37]. Each soil nail used in the experiment consisted of a ribbed steel reinforcement bar of 18/22 mm diameter, the elastic modulus of which was 200 GPa. The distribution of soil nails and anchors is shown in Figure 2.

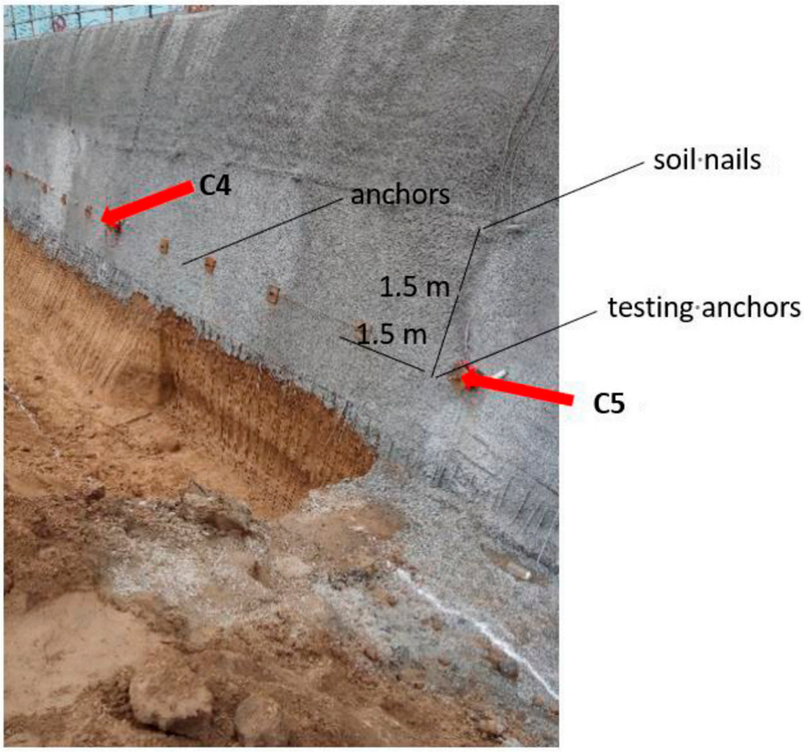


Figure 2. The distribution of soil nails and anchors.

The facing was made up of a 200 mm by 200 mm grid of thin steel mesh (6 mm in diameter). The facing was enhanced with two reinforcement bars (12 mm in diameter) in both horizontal and vertical directions. The detailed enhancement configuration of facing is shown in Figure 3.

Figure 3. The enhancement configuration of facing.

The designed value of the prestressing force of the anchor was 50 kN. The design parameters of the soil nails and prestressed anchors in different retaining structures are summarized in Tables 3 and 4.

Table 3. Design parameters of soil-nailed retaining structures.

Soil Nail	Depth (m)	Length (m)	Inclination (°)	Spacing (m)
1	1.20	9.00	10	1.50
2	2.70	9.00	10	1.50
3	4.20	9.00	10	1.50
4	5.70	7.00	10	1.50

Table 4. Design parameters of composite soil-nailed retaining structures.

Soil Nail/ Anchor	Depth (m)	Length (m)	Inclination (°)	Bonded Length (m)	Spacing (m)
1	1.20	9.00	10	-	1.50
2	2.70	12.00	10	12.0/9.5	1.50
3	4.20	9.00	10	-	1.50
4	5.70	7.00	10	-	1.50

Note: 12.0/9.5 in Table 4 indicates that there is either no unbonded part or a 2.5 m unbonded part.

2.4. Fabrication of Testing Components

In the in situ tests, the soil nails were equipped with vibrating wire strain gauges (labelled JMZX-416A), which were attached to the steel tendon of each soil nail. JMZX-416A was applied to measure the stress of stressed reinforcement in reinforced concrete structures, the measuring range and sensitivity of which are 200 MPa and 0.1 MPa, respectively. The instruments were supplied by Shandong lidaxin Instrument Equipment Co., Ltd. (Qingdao, China). Readings were obtained and stored in a data logger labelled JMZX-3001. JMZX-3001 was supplied by Beijing Heng Company Limited Company of Science and Technology (Beijing, China). Different from soil nails, each anchor (25 mm ribbed, high-yield steel bar) was equipped with a vibrating wire load cell, labelled MJ-101, at the head to monitor the anchor force, with the exception of strain gauges. MJ-101 was manufactured by Shandong Shengxin Mining Equipment Co., Ltd. (Liaocheng, China). The designation of all gauges was authorized. Figure 4 shows details of the equipped soil nails for tests. Figure 5 presents the manufactured testing anchors.

2.5. Instrumentation

As mentioned above, to investigate the mechanics behavior of composite soil nailing, a series of in situ tests was carried out under different retaining conditions. The measuring results from the testing profiles of 1, 4, and 5 were analyzed and compared such that the effects of two important characteristics, comprised of prestressing force and unbonded length, on the nail forces could be studied. Special note: the testing profiles of 1, 4, and 5 were simplified with the labels No. 1, No. 4, and No. 5 in the following analyses. For the first parameter, the influence on the deformation of the pit wall and the internal force of surrounding soil nails were examined in this paper. In particular, the construction sequence of prestressing is a research focus. For the second parameter, it can be expressed in terms of the length ratio L_u/L, where L_u = the length of the unbonded part and L = entire length of the anchor. As shown in Table 4, two different unbonded lengths for the anchors were given. No. 1 represented a simple soil-nailed retaining structure; No. 4 represented a composite soil-nailed retaining structure enhanced with a prestressed anchor without an unbonded part; and No. 5 represented a composite retaining structure with a 2.5 m unbonded length. The layout of instruments is shown in Figures 6–8.

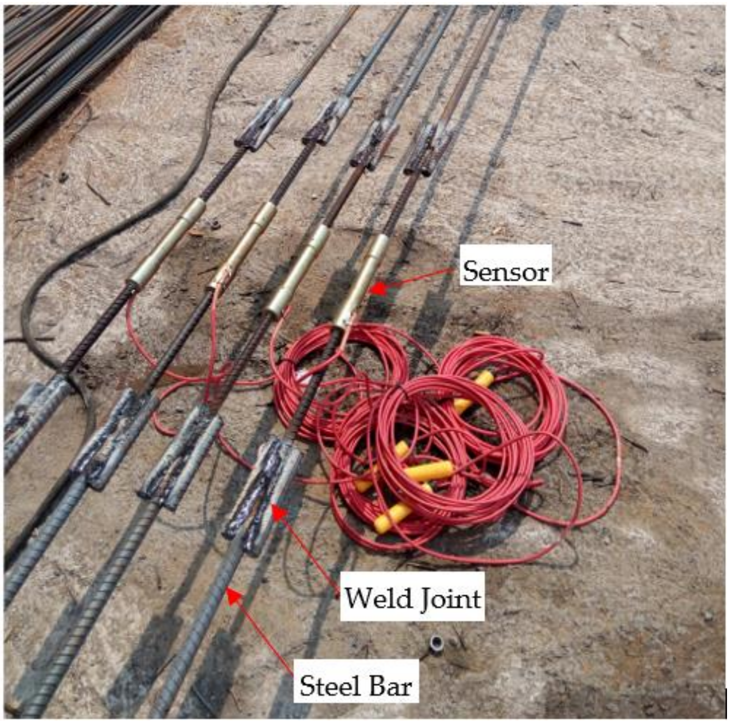


Figure 4. The manufactured testing soil nails.

Figure 5. The manufactured testing anchors.

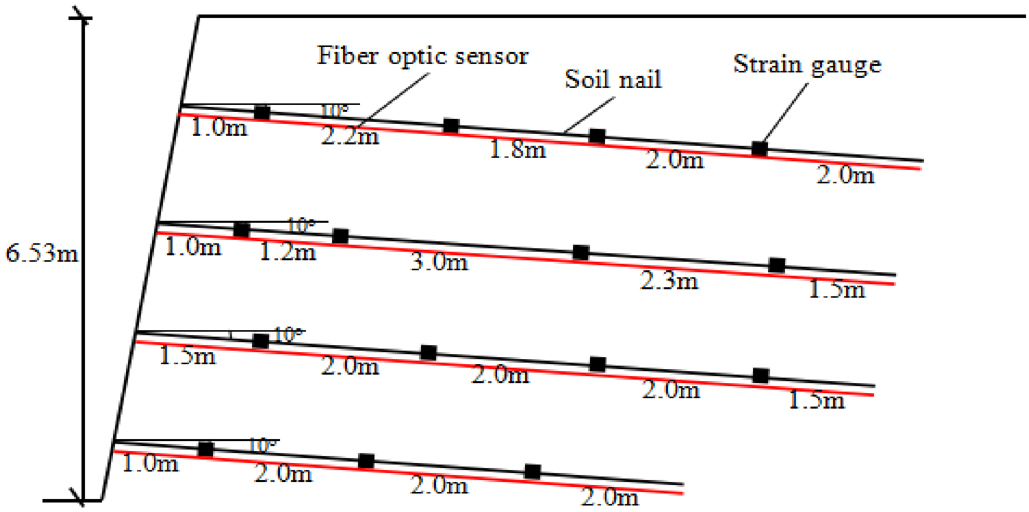


Figure 6. Location of instruments for No. 1.

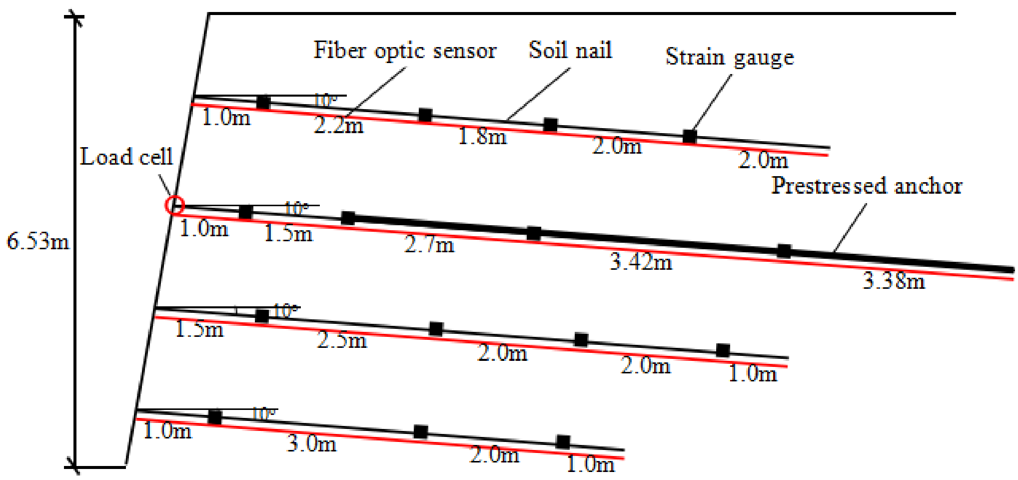


Figure 7. Location of instruments for No. 4.

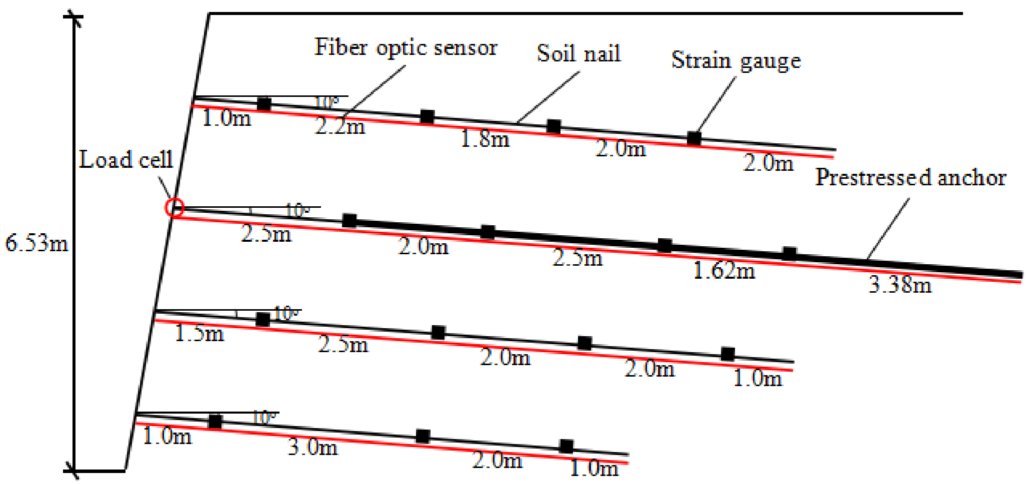


Figure 8. Location of instruments for No. 5.

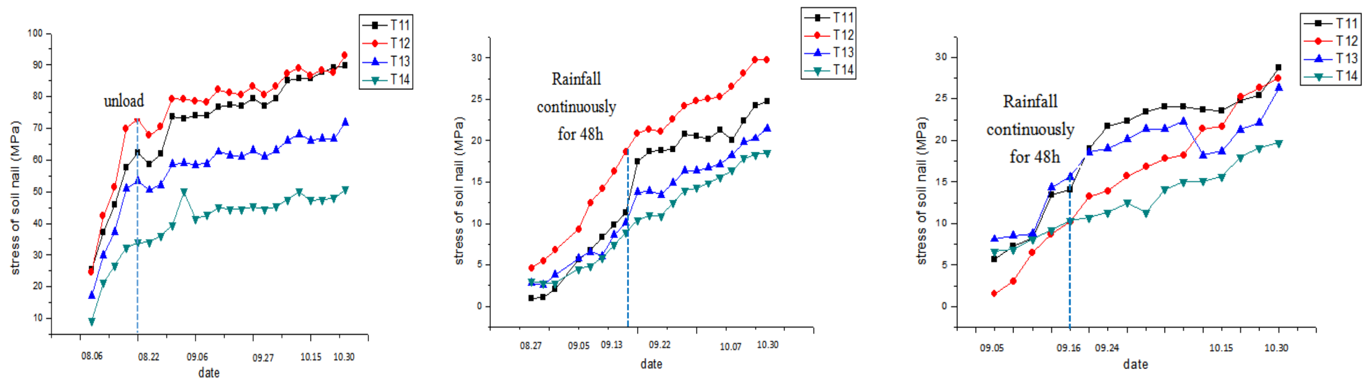
In Figures 6–8, the black lines indicate soil nails or prestressed anchors, the black squares indicate strain gauges, and the red lines indicate fiber-optic sensors arranged on soil nails or prestressed anchors.

2.6. Test Results

2.6.1. Stresses of Soil Nails

After excavation and installation of the soil nails and prestressed anchors, the data acquisition system was established, and the mechanics behavior of the soil-nail–prestressed-anchor retaining slope was monitored for about three months. Figure 9 plots the curves of stress–date relationship obtained from the in situ tests during the period of three months, in which T_{ij} presents the stress value of the j strain gauge calculated from the nail head in the i row of soil nail.

(i) As shown in Figure 9, particularly a1, b1, c1 and d1 for the No. 1 section, it is evident that there was a sudden increment in the nail force with each excavation and it gradually tended towards stability when the excavation was completed, which shows that there are effects of time and effects of excavation on the internal force of the soil nail. This is consistent with the results achieved in the literature, as reported by [28]. Compared with the No. 1 section, the effect of the excavation of the No. 4 and No. 5 sections is not so obvious; moreover, the overall stress level was relatively small, on the whole. According to stress mechanism, increments in earth pressure due to unloading are transferred to soil nails through shear stress of soil-grout interface, which drives the nail force. For this project, the foundation pit was adjacent to Fengchan Road in the north, under which a gas pipeline is buried parallel to the enclosing wall. The pipeline is 86.0 m in length and 1.0 m in depth, which was about 1.5 m away from the side of the foundation pit. Consequently, the soil at the upper part of the foundation pit for No. 4 and No. 5 sections had been disturbed before and was more loose compared to the undisturbed soil in the No. 1 section. Therefore, the friction resistance of soil/grout interface for No. 4 and No. 5 sections decreased, accordingly, and the earth pressure increment transferred to the soil nails was less. According to the above analysis, the conclusion can be drawn that the stress distribution was affected by the density of the soil, that is, it was concentrated and larger when the soil was dense, and it was uniform and smaller when the soil was loose. The obtained results are consistent with the literature, as investigated in the work of Barley [33,34];



(a1) **(a2)** **(a3)**

Figure 9. *Cont.*

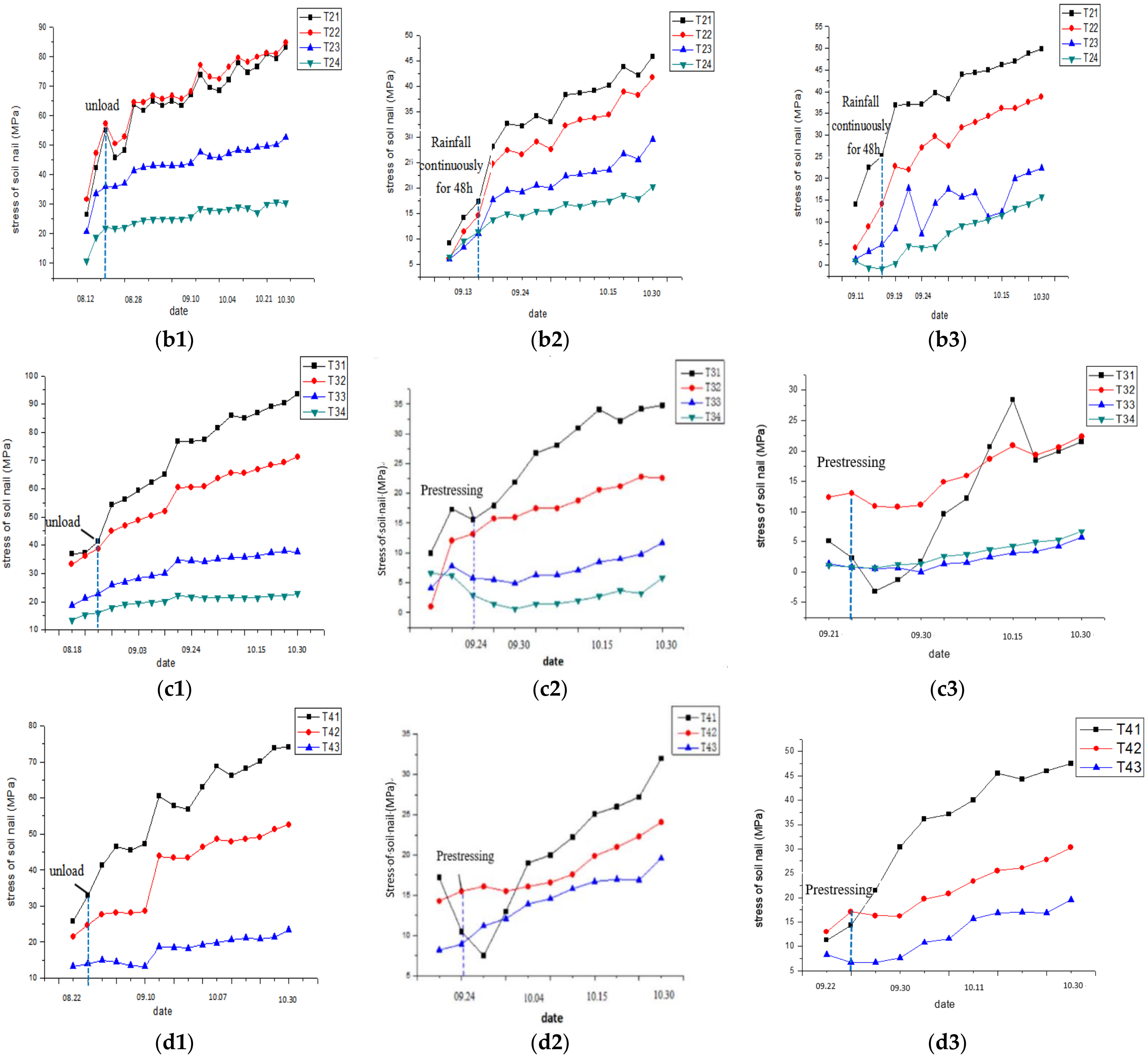


Figure 9. (**a1**) stress of 1st row of soil nail for No. 1, (**a2**) stress of 1st row of soil nail for No. 4, (**a3**) stress of 1st row of soil nail for No. 5. (**b1**) stress of 2nd row of soil nail for No. 1, (**b2**) stress of 2nd row of soil nail for No. 4, (**b3**) stress of 2nd row of soil nail for No. 5. (**c1**) stress of 3rd row of soil nail for No. 1, (**c2**) stress of 3rd row of soil nail for No. 4, (**c3**) stress of 3rd row of soil nail for No. 5. (**d1**) stress of 4th row of soil nail for No. 1 (**d2**) stress of 4th row of soil nail for No. 4, (**d3**) stress of 4th row of soil nail for No. 5. The stress-date relationship curves: (**a1**–**d1**) = No. 1 Section; (**a2**–**d2**) = No. 4 Section; (**a3**–**d3**) = No. 5 Section.

(ii) As can be seen from a1–a2, the stresses on soil nails decreased due to unloading, which was only manifested in that the first and second rows of soil nails close to the ground surface were affected a lot; however, the third and fourth rows were less influenced;

(iii) As can be seen from stress-history curves for No. 1 and No. 5 sections, the stresses were less affected by continuous rainfall for 48 h. This is because the infiltration rates of rain into the clay or silty clay are extremely slow, and accordingly, the depth of infiltration was relatively shallow. Furthermore, the actual locations of the first row of soil nails were moved down to keep them off the gas pipeline, and the exact location for the two test profiles was −2.0 m and −2.2 m, separately;

(iv) The stresses on the soil nails in the upper two rows were less affected when prestressed; in contrast, the stresses of the lower two rows decreased a lot. Based on the technical specifications, the bonded tendons can be tensioned when the strength reaches at least 15 MPa. However, in fact, the next layer was removed and followed by the second excavation as a result of arranged rapid construction, and after that, tensioning was performed. Consequently, the soil mass influenced by prestressing was the lower not upper part of the foundation pit. The conclusion can be drawn that the magnitude and distribution of the stresses on the soil nails were nearly affected by different prestressing periods: the upper rows were influenced a lot during timely tensioning; the lower rows changed greatly during lagging tensioning;

(v) The influence of prestress on the stresses of the third and fourth rows of soil nails was only manifested as a part of the nail forces changed, which was close to the slope surface. Comparatively, another part, which was away from the slope surface along the longitudinal axis of the nail, was almost not affected, which shows that the range of influence of prestress is very limited;

(vi) When comparing the measured results from the No. 4 and No. 5 profiles, the influence of unbonded length on nail forces can be investigated. As can be seen from Figure 9, the main difference lies in the distribution of nail forces on the first row. For No. 4 section, without an unbonded part, the distribution of nail forces was consistent with the documented results, which presents an inverted saddle shape, that is "small in the end and big in the middle". However, for the No. 5 test profile, with a 2.5 m unbonded length, the distribution was manifested as "double peaks", which shows there may be more than one potential slip surface in the loose fill materials. For the No. 4 section, due to grouting conducted in the overall length, there was deformation of the steel reinforcement bar when transferring the load from the anchor head to the slope, and accordingly, the anchorage effect could not function adequately. In other words, it amounted to a longer prestressed soil nail. For the other three rows of soil nails, the difference between the two sections is not so obvious. The effect of unbonded length, which is considered to be the main reason for slope stability in dense materials, is negligible in loose fill materials.

2.6.2. Foundation Pit Deformation

As can be seen from the monitoring results, two months after the excavation was finished, the lateral displacement of deep soil for all testing sets basically tended to be stable, and the distribution of lateral displacement along the excavation depth of the foundation pit is shown in Figure 10.

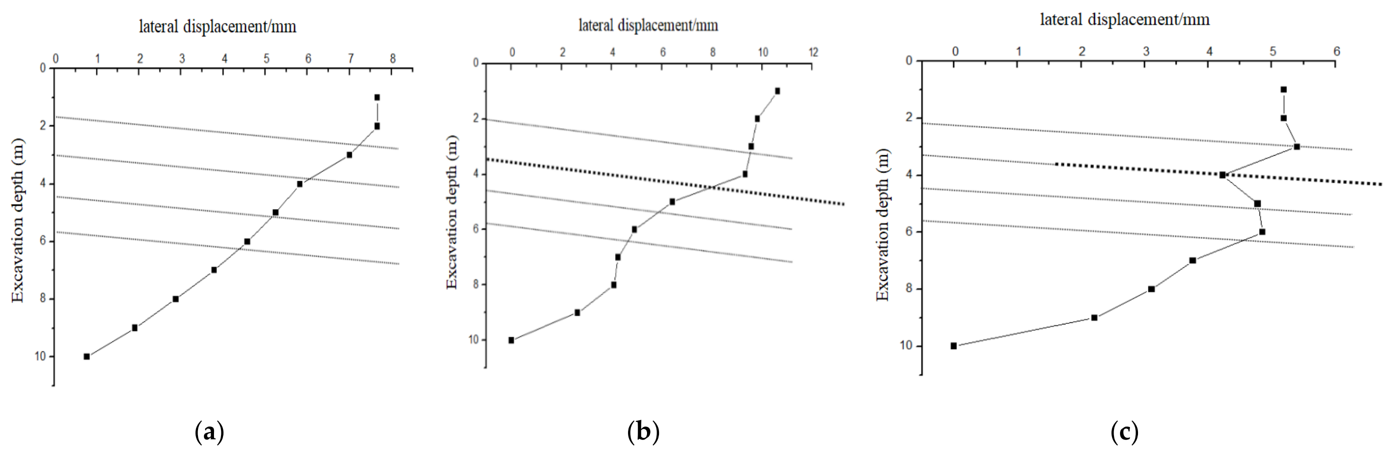


Figure 10. Distribution of lateral displacement along excavation depth. (**a**) Testing set No. 1 (**b**) Testing set No. 4 (**c**) Testing set No. 5.

According to the analysis of the lateral displacements in Figure 10, No. 5 is the smallest, No. 1 is placed in the middle, and No. 4 is the largest. Although both No. 4 and No. 5 were supported by prestressed-anchor-composite soil nailing, No. 4 represents a prestressed anchor without an unbonded part, and the transmission of prestress in loose materials was limited, which cannot limit the slope deformation well; No. 5 was provided with a free part, the length of which was 2.5 m, and the load applied to the anchor head could be better transmitted and distributed to the bonded part through the elastic deformation of the reinforcement.

The lateral displacement of the pit wall was limited by stress diffusion, and the surface displacement was reduced by about 32%. If the soil of No. 5 was the same as that of No. 1, which was relatively dense, the prestress would play better. The distribution of lateral displacement along the depth of No. 1 showed a regular "wedge", while the deformation curves of No. 4 and No. 5 were no longer smooth due to the reverse constraint from prestress, and there were sharp concave "inflection points" at the action positions of anchors, as shown in Figure 10b,c.

3. Numerical Simulation

The in situ test was performed under external disturbances, including soil predisturbance, excessive excavation, unloading on the surface of edges, tensioning and lagging of the anchor, and continuous rainfall. In order to analyze the influence of construction conditions on the stress-time history curve of the soil nails, numerical simulation was carried out based on standard conditions. ABAQUS 6.10 ® was used to conduct three-dimensional simulation of the three kinds of supporting structures with the testing sets for No. 1, No. 4, and No. 5. The numerical model is shown in Figure 11.

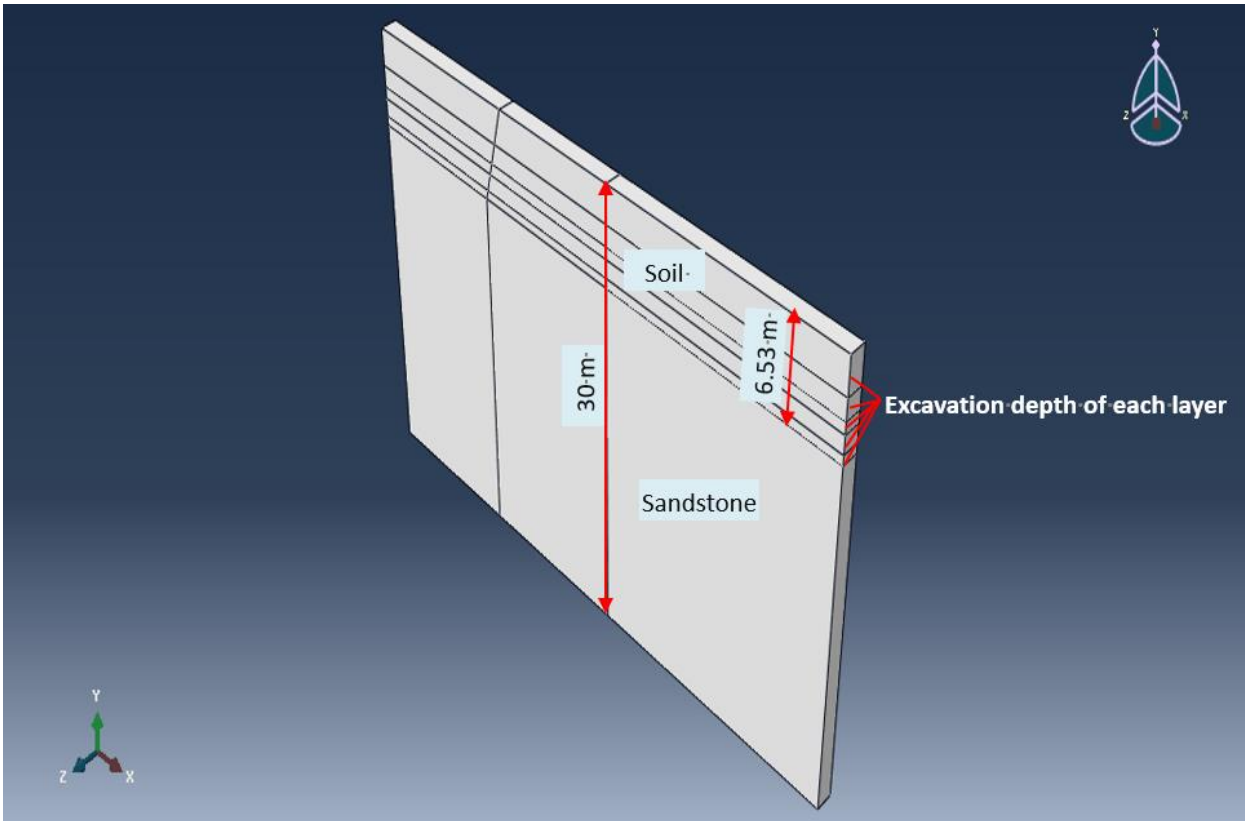


Figure 11. Numerical model.

3.1. Soil Constitutive Model

At present, in the finite element analysis of soil nailing, the soil constitutive models mainly include the Mohr–Coulomb elastic–plastic model [38], the modified Cambridge model [39], the extended D–P model [40], and others. Because the parameters required by the M-C elastic–plastic model can be accurately determined by laboratory tests, the change in yield surface, hardening or softening, can be considered by controlling the cohesion. A large number of experiments and engineering practices have confirmed that M-C strength theory can better describe the strength of geotechnical materials. Therefore, it has been widely used in the field of geotechnical engineering. In this paper, an elastic perfectly plastic model with the Mohr–Coulomb strength rule for the soil, characterized by the calculation parameters listed in Table 5, was adopted. The bonded parameters of soil nails and surface are as shown in Table 6. Gravity was not considered for the above materials.

Table 5. The calculation parameters of the soil.

Soil Layer	Thickness (m)	ρ (g/cm^3)	E (MPa)	c (kPa)	φ (°)	ν
①	2.8	1.81	27.3	14.0	20	0.25
②	1.9	1.79	11.7	20.0	15	0.30
③	2.42	1.82	30.6	15.0	21	0.25
④	22.88	1.89	90.0	3.0	27	0.23

Table 6. The bonded parameters of soil nails and surface.

Bonded Body	Diameter (mm)	ρ (g/cm^3)	E (GPa)	ν
soil nail 1	18	2.60	29.43	0.20
soil nail 2	22	2.50	31.37	0.20
surface	-	2.50	25.50	0.20

3.2. Model Parameter Selection

(i) The depth of the foundation pit was 6.53 m, and the slope of the foundation pit wall was 1:0.3; the width of the upper opening was 15 m, the width of the lower opening was 13 m, the finite element calculation area was within 35 m outward from the foundation pit wall and 23.47 m downward from the final excavation surface, and the model thickness was 1.5 m;

(ii) The origin of the coordinate system is located at the lower left corner of the model, with the *x*-axis facing right, the *y*-axis facing inward, and the *z*-axis facing up. The boundary conditions of the model were: the top was free and unconstrained; symmetrical constraints were imposed on the front and back sides, U2 = UR1 = UR3 = 0; sliding bearings were used on the left and right sides to restrict the degrees of freedom in the horizontal direction, U1 = 0; fixed hinged supports were used at the bottom to restrict the degrees of freedom in three directions, U1 = U2 = U3 = 0;

(iii) The first row, the third row and the fourth row of the retaining structure were soil nails, and the lengths of soil nails from the rows, top to bottom, was 9 m, 9 m, and 7 m, respectively. For the second row, testing sets 1, 4, and 5 corresponded to soil nails (L = 9 m), full-length bonded anchors (L = 12 m), and anchors with an unbonded section of 2.5 m (L = 12 m). Each row of soil nails and anchors was distributed in a rectangle, with horizontal spacing of 1.5 m and an inclination angle of 10°;

(iv) Combined with the actual construction conditions on site, the excavation was carried out in five steps, with excavation depths of 2.5 m, 1.4 m, 0.8 m, 1.2 m, and 0.63 m from top to bottom, respectively.

3.3. Analysis of Calculation Results

3.3.1. Comparison of the Horizontal Displacement of Soil

The simulation results of horizontal displacement of soil were compared with the monitoring data of soil nailing and soil nailing combined with prestressed anchors. The comparison results are shown in Figure 12.

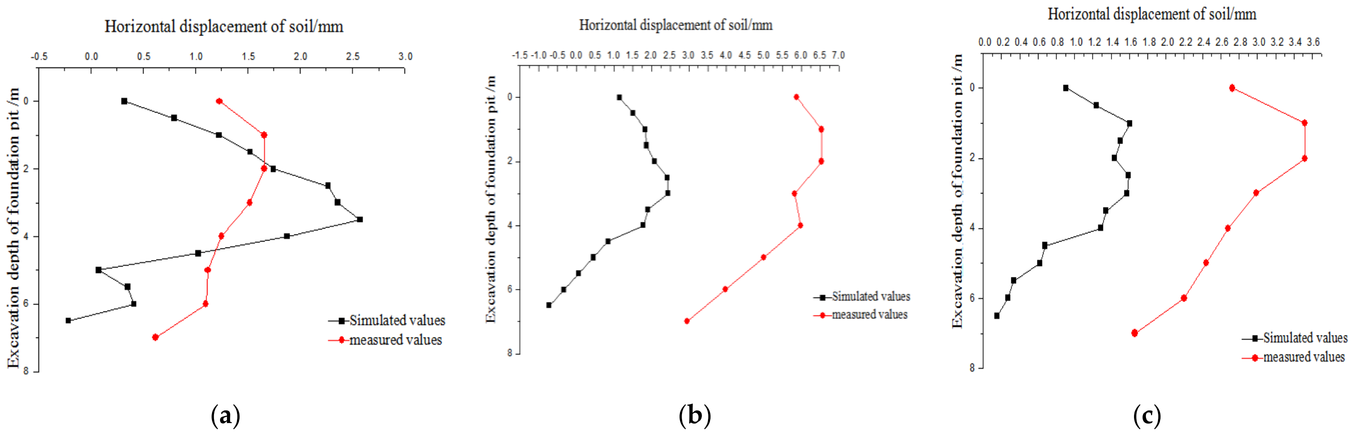


Figure 12. Comparison between simulated and measured values of horizontal displacement of soil. (**a**) Testing set No. 1: soil nailing. (**b**) Testing set No. 4: composite soil nailing. (**c**) Testing set No. 5: composite soil nailing.

As can be seen from Figure 12, for testing set No. 1 for soil nailing, since the soil was never disturbed and was relatively dense, the simulated value of horizontal displacement of soil was therefore in good agreement with the measured value; For testing sets No. 4 and No. 5 for composite soil nailing, due to the early distribution, the soil was disturbed and relatively loose, resulting in poor consistency between the simulated value and the measured value. It can be seen from Figure 12b,c, the development trend of two curves is consistent, although the measured results are larger than the simulated values. It proves that the proposed idea is reasonable, namely, slope deformation is mainly controlled by the filling properties because of the greater looseness and compressibility compared with other media.

3.3.2. Comparison of Soil Nail Stress

Taking testing set No. 5 as an example, after the foundation pit excavation was completed, the comparison results between the simulated value and the measured value of the stress for each row of soil nails are shown in Figure 13.

As can be seen from Figure 13, for the first row of soil nails in the upper part, the field measured values are basically consistent with the numerical simulation values, but the simulation curve is relatively smooth, with a "single peak" around 1.23 m at the end of the nail; however, the measured curve has a sharp "double peak". This is consistent with the previous analysis results, indicating that there may be 2 or more potential slip surfaces in the loose materials. For the third and fourth rows of soil nails in the lower part, the field measured value decreased greatly compared with the numerical simulation value. This is because the first row of soil nails was moved down for bypassing the previously buried natural gas pipeline (about 1.0 m deep), which brought about a small relative distance between the third and fourth rows of soil nails at the lower part. In addition, "layered excavation and layered support" were not strictly observed during construction. Instead, the third and fourth layers of soil were excavated together. In addition, during the construction of prestressed anchors, according to the specifications, the anchor was tensioned before the lower soil excavation and after the grouting materials of the anchor reached a certain strength. However, during the actual construction, due to the tight construction time period, the lower soil was excavated, then prestress was applied to the second row of anchors. Moreover, the prestress loss was large, and the design requirements could be met only after secondary supplementary tensioning. This shows that the stress of soil nails is greatly affected by the construction process, and the application of prestress has a "sequence effect": when it is delayed, the stress reduction of soil nails in the lower part is large, and the impact on soil nails in the upper part is relatively small.

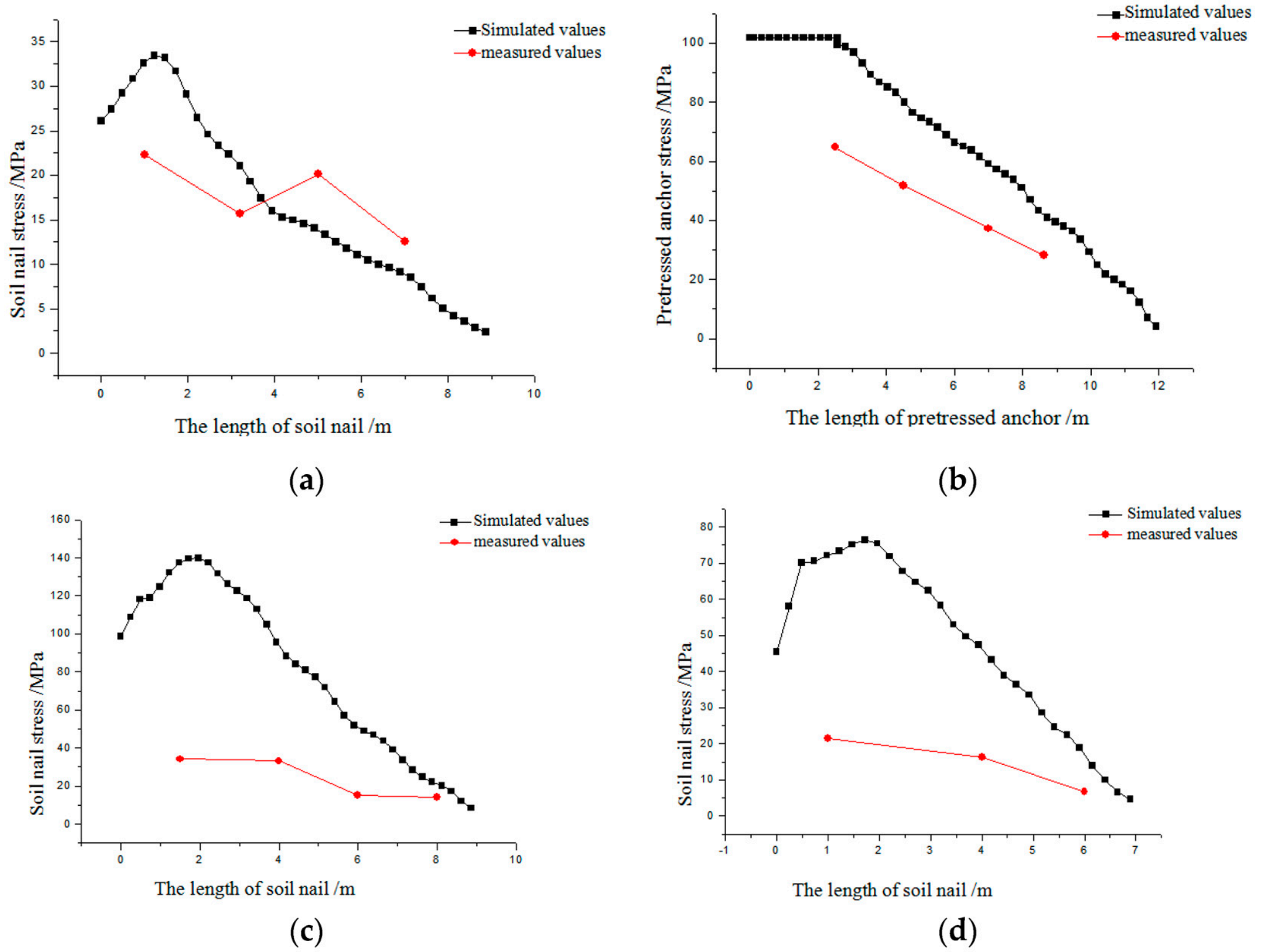


Figure 13. Comparison between simulated and measured values of soil nail stress. (**a**) Stress of the first row of soil nails, (**b**) stress of the second row of soil nails, (**c**) stress of the third row of soil nails and (**d**) stress of the fourth row of soil nails.

4. Time-Varying Analysis

According to the working mechanism of passive support structures, the stress of soil nails depends on soil deformation, and the "excavation effect" shows that the deformation of foundation pits is the most severe in the excavation period, and the stress of soil nails increases fastest; after the excavation, the bottom row of soil nails was installed. At this time, the deformation of the foundation pit tended to be stable, and the stress growth of soil nails should have been relatively slow. Time history curves for the deformation of soil for testing sets No. 1, No. 4, and No. 5 are shown in Figure 14. It can be seen that the deformation of the foundation pit increased steadily during the 3-month monitoring period. These phenomena show that the time effect of soil rheology is obvious on soil nailing and prestressed-anchor-composite soil nailing.

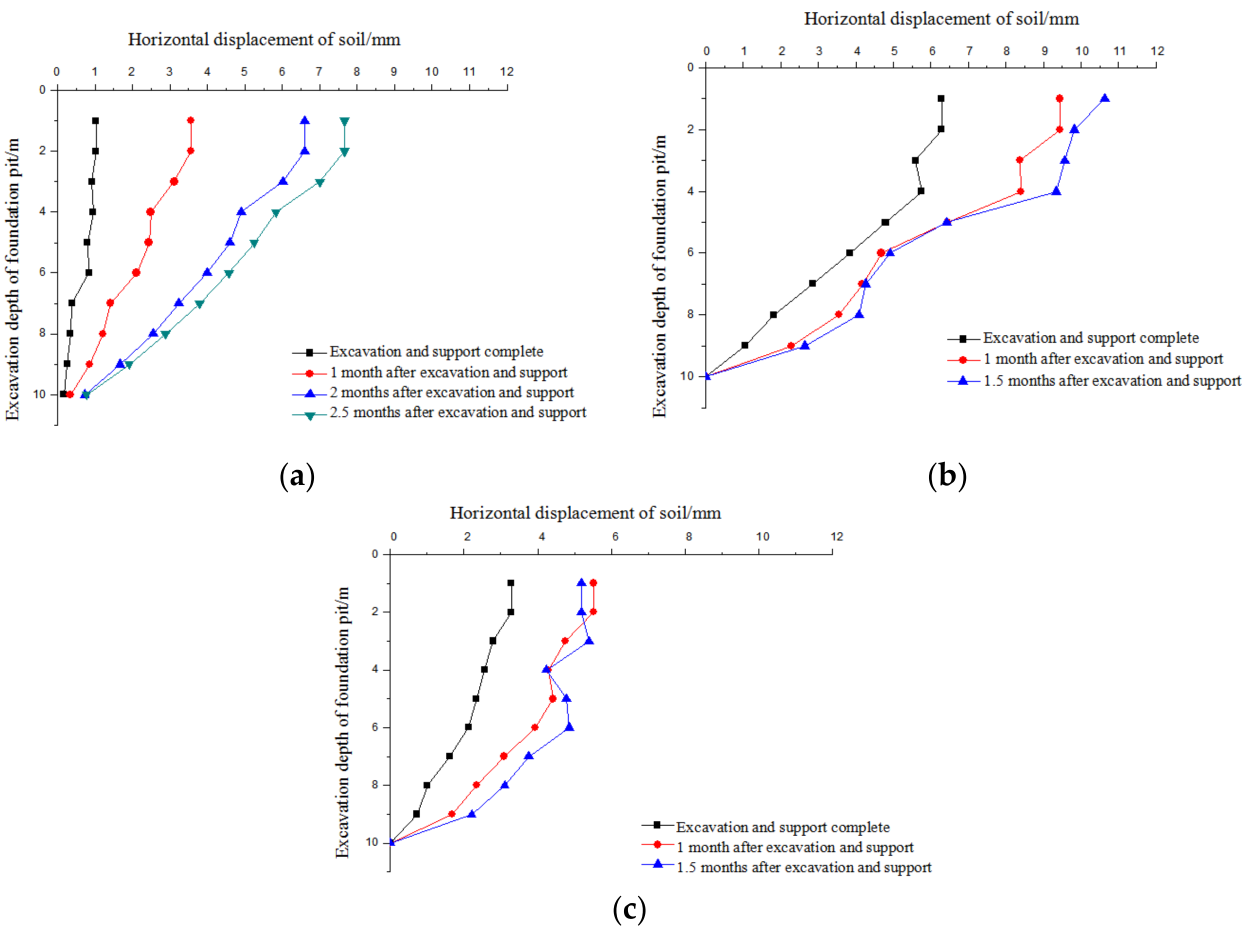


Figure 14. Time history curves for the deformation of No. 5. (**a**) Time history curve for deformation of No. 1 (**b**) Time history curve for deformation of No. 4 (**c**) Time history curve for deformation of No. 5.

During the excavation of the foundation pit, the deformation of the foundation pit mainly results from unloading. The increment in earth pressure caused by unloading destroys the original static equilibrium state of the support system, resulting in the displacement of the pit wall towards the foundation pit. The deformation of the pit wall mainly depends on two factors, one is the stiffness of the supporting structure itself, and the other is the earth pressure acting on the supporting structure. For soil nailing and prestressed-anchor-composite soil nailing, because there is no vertical advance support, only the concrete surface transmits the earth pressure, and the stiffness of the concrete surface is small. On the premise of meeting the design requirements, the earth pressure applied to the support structure is the main factor affecting the deformation of the supporting structure. During the intervals of foundation pit excavation, the properties of the foundation pit are mainly caused by soil consolidation and rheology. Accordingly, in the process of foundation pit excavation, the development of earth pressure goes through two stages. Stage I is a s follows: in the initial stage of excavation, the pit wall undergoes slight deformation under the acting earth pressure. With the passage of time, the deformation of the pit wall increases slowly, the earth pressure on the active side decreases gradually, and the bearing capacity of the soil begins gradually to play a role. When the earth pressure on active side decreases to the minimum, and the static earth pressure σ_0 converts into active earth pressure σ_a. Stage II is as follows: in the later stage of excavation, the deformation of the pit wall continues to increase, and the time effect caused by rheology is gradually highlighted, which makes the bearing capacity of the soil begin to decay, leading to a slight increase in the earth pressure on the active side, as shown in Figure 15.

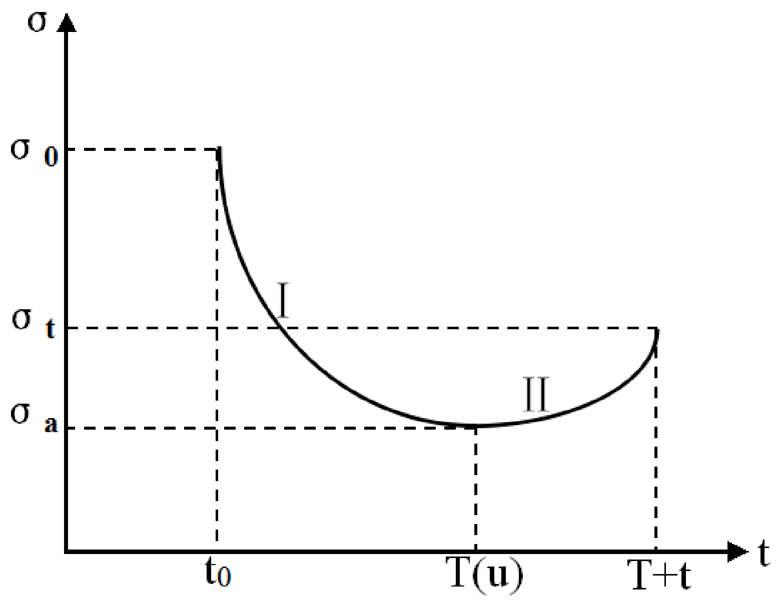


Figure 15. Time-varying characteristics of earth pressure.

5. Summary and Conclusions

In this investigation, three types of different retaining structures were investigated through an in situ test. Test results on the evaluation of mechanics behaviors were reported. The influences of external adverse disturbances on stress and deformation were analyzed. The effects of parameters such as prestress and unbonded length were discussed. The results obtained will assist practicing engineers in designing soil nails and anchors for applications in civil engineering. Through numerical simulation and comparison with ideal working conditions, the construction mechanics behaviors of composite support structures were analyzed considering the time-varying effect. In particular, it was found that:

(i) The interface stress is affected by the density and hardness of the soil around the soil nail: the interface stress is higher when soil is dense and hard, which is characterized by serious stress concentration; the interface stress is lower and uniform when soil is loose and soft, which is consistent with the theoretical hypothesis;

(ii) In all kinds of designs of bolt supports, it is generally assumed that the interfacial shear stress is evenly distributed along the length of the rod when the pull-out test is carried out on-site to determine the bonding strength between the anchor and the geotechnical medium. The average bond strength $\overline{\tau}$ is calculated by the simplified formula $P = \pi DL\overline{\tau}$ and is regarded as the ultimate bond strength τ_{ult};

(iii) The influence of prestress on the internal force of the soil nail is governed by the tensioning schedule: when the anchor is tensioned synchronously, the function of limiting deformation is obvious and the upper soil nails are affected; when the anchor is tensioned later, the lower soil nails are influenced;

(iv) Connection along all maximal nail forces along the longitudinal axis of nails is regular for soil-nailed retaining structures, which is matched with the assumed sliding surface; while for soil-nail–prestressed-anchor-composite retaining structures, prestress changes the distribution of the stress field, and there is an obvious “breakpoint” in the connection;

(v) The effect of unbonded length, which is considered to be the main reason for slope stability in dense materials, is mainly manifested as the change in stress distribution of the first row of soil nails, and the influence on the other rows can even be negligible in loose fill materials;

(vi) External adverse factors cause great disturbance to the construction process, which should be fully considered in theoretical analysis and numerical simulation, and reasonable suggestions should be put forward for design.

6. Analysis and Discussion

Construction of a foundation pit is a dynamic and gradual process, and stress and deformation are affected by construction steps and sequences. With the progress of each step, such as the installation of soil nails or anchors and the filling or digging of soil, the calculation system continues to evolve, and the load conditions and mechanical response change accordingly. From the perspective of construction mechanics, the stress analysis of the whole structural system should be formed by the successive superposition of a series of different initial strain conditions. The research shows that analysis results based on the idea of construction mechanics are very different from analysis results of one-time loading on a given complete structural system from the perspective of structural mechanics. The impacts of construction procedures and interference factors are rarely taken into account in technical specifications for retaining and protection of building foundation excavations (JGJ 120-2012) and specifications for soil nailing in foundation excavations (CECS: 96:97), which are technical specifications for foundation excavations in China and are used to guide site construction. Although these two technical specifications are not international, they have been verified by a large number of engineering practices in China and proved to be scientific and reasonable and are often used to guide engineering practice. But these impacts really exist, which results in differences between field monitoring data and theoretical analysis results. This is an urgent problem to be solved. These research results provide a theoretical basis and practical experience for the design and use of soil nailing combined with prestressed anchors for the construction of support structures and puts forward reasonable suggestions for the current situation of nonstandard construction.

Author Contributions: J.C.: writing—original draft preparation, writing—review and editing; L.G.: software; H.W.: data curation; Z.D.: investigation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by (1) the National Natural Science Foundation of China, grant number U1810203, and (2) the Doctoral Program Foundation of Henan Polytechnic University, grant number B2018-67.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Acknowledgments: The writers wish to acknowledge the financial support of this research by the Comprehensive Design and Research Institute, Zhengzhou University. The kind assistance and valuable contributions of the staff of the School of Civil Engineering at Zhengzhou University, and the generosity of the Henan No. 7 Building Engineering Group who provided the site for the test, are gratefully acknowledged.

Conflicts of Interest: All authors declare that they have no conflict of interest.

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