Full-Scale Field Test On Retaining Structure Enhanced With Soil Nails And Prestressed Anchors

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Abstract

Retaining structure enhanced with soil nails and prestressed anchors is found good at constraining the horizontal displacement and therefore ensuring the stability of the foundation pit during excavation. Based on these advantages, such retaining structure is widely used in foundation excavation practice. This paper presents results of a series of in-situ tests conducted to investigate the mechanical behaviors of retaining structure enhanced with soil nails and prestressed anchors. Behaviors of three different retaining structures enhanced with i) soil-nails; ii) soil-nails and prestressed anchors without unbonded part; iii) soil-nails and prestressed anchors with a 2.5m unbonded length, were monitored during staged excavation to investigate the influences of i) the prestressing force and ii) unbonded length of the prestressed anchors on the performance of the entire retaining system. It was found that the affecting the stress and deformation of composite retaining system, which is in agreement with the other published results in the literature. The variation of the magnitude and distribution of soil nail force responding to the anchor prestressing force however showed no systematic trend. The unbonded length of anchors, which is suggested to be the main factor affecting the structural stability in dense materials in the literature, is found to have little influence in loose fill materials used in this study. Studies presented in this paper are useful for the rational design and serviceability analysis of the composite soil-nailed retaining structure enhanced with prestressed anchors.

1 Introduction

Soil-nailed retaining structure is broadly used in slope supporting, tunnel retaining, and bracing structure for foundation pit, to limit deformation and improve safety. The advantages of soil-nailing include its simple structure, flexible operation and high cost-effectiveness (FHWA 1996; Qin et al. 2005; Davies 2010). Soil nails have a high ratio of the circumference to the cross-section area, and therefore rely essentially on friction resistance for the load transfer. The soil nail force is transferred to the surrounding soils through soil-grout interface friction, which arises from the relative displacement between the soil and the grout. The shear strain required to mobilize the nail force is typically very small, therefore, soil nails usually start to function soon after the excavation when deformation occurs.

Pullout resistance of soil-grout interface is a critical parameter in the design and analysis of the soil-nailed slope. Extensive researches have been conducted to investigate pullout behaviour of pressure-grouted soil nails through either in-situ or laboratory tests (Zhang et al. 2009; Zhu et al. 2011; Jeon 2012; Hong et al. 2013). In addition, numerical studies were also carried out to explore the contribution of soil nails towards the slope stability (Chu et al. 2005; Huang et al. 2009; Zhou et al. 2009; Su et al. 2010). However, in certain circumstances such as downtown areas where deformation of foundation pit is strictly limited, the soil nail–prestressed anchor composite retaining structure is preferable. This is because the additional prestressed anchors can assist, in addition to the soil nails, to limit the displacement of the slope surface. Typical layout of the soil nail–prestressed anchor composite retaining structure is shown in Fig. 1.

In such a composite retaining structure, the combined contribution of soil nail and prestressed anchor is expected to provide higher resistance against rainfall or overload- induced failure. In the existing literature, interaction mechanism between soil nail and prestressed anchor is investigated mostly based on numerical studies (e.g. Dong et al. 2009). Very limited model and in-situ test results (e.g. Wang 2012; Wang 2008; Zhang 2011) and analytical theories and methods were reported despite the widespread use of such retaining structure. This is due to i) model and in-situ tests are expensive, complicated and time-consuming to conduct. For example, many delicate instruments are needed, such as stress and strain gauges which are prone to damage during testing and installation; ii) in-situ tests may disturb the scheduled construction process and the in-situ soil layers. In addition, previous studies were mainly focused on the behavior of such retaining structure installed in dense materials; the corresponding behaviors in loose fill materials need to be further investigated.

In this paper, a full-scale in-situ test on a composite soil-nailed retaining structure enhanced with prestressed anchors installed in loose materials is carried out to investigate the mechanical behavior of soil nails and prestressed anchors during excavation. Great precaution was taken during the in-situ tests to avoid possible damages to the instruments and ensure the survival ratio of gauges as high as 99%. A total of 90 strain gauges were installed, and only one was damaged. The effects of prestressing force and unbonded length of prestressed anchors on the nail forces are investigated. Different from the previous literature, it was found that the magnitude and distribution of soil nail force responding to the anchor prestressing force was governed by tensioning methods. For the other main factor, the unbonded length of anchors, was found to have little influence on the structural stability in loose fill materials, which showed no systematic trend with the existing results. Studies presented in this paper are useful for the rational design and serviceability analysis of the composite retaining structure.

1.1 Site Conditions

The tested foundation pit is design for Zhengzhou University Science and Technology Building which consists of a 20-story tower building, a 3-story skirt building and 1-story basement. The depth of the foundation pit is 6.53m. Soil nail–prestressed anchor composite retaining structure is used to support the north wall of the foundation pit where underground pipelines concentrate and therefore strict deformation control is required. Soil-nailed retaining structure is used to support the south wall of the foundation pit. Field investigation showed the ground water table is stable and beneath the foundation pit, which locates in a depth ranged between 10.1 and 10.9m. Due to this reason, the influence of ground water on the retaining structure could be safely ignored. The layout of the foundation pit is shown in Fig. 2.

There are a series of testing sites noted as C1 through C6. C1 and C2 are soil nail retaining structure located in the south; C3 through C6 are soil nail–prestressed anchor composite retaining structure located in the north, among which there are no unbonded parts in the anchors in C3 and C4 whereas there are 2.5m unbonded parts in the anchors in C5 and C6. For C2, there was massive cement near the testing site, therefore unloading of cement and vibration of the cement mixer may affect the development of soil nail force during staged excavation. In addition, there were two deserted holes near the north wall, left for determing the actual position of the gas pipelines before excavation. For C3 and C6, which were right located near the two holes, previous disturbance may change the magnitude and distribution of soil nail force. For revealing more actually the mechanical behavior of composite soil-nailed retaining structure, testing results derived from C2, C3 and C6 testing sites are discarded, and the other data from C1, C4 and C5 are taken for analysis.

1.2 Soil Properties

The in-situ soil layers from top to bottom are i) silt, 2.20m; ii) silty clay, 2.30m; iii) silt, 1.10m; and iv) silty clay, 2.30m, separately. The properties of every soil layer are listed in Table 1.

Table 1. The mechanics parameters of the soil layers

Soil nail	Depth (m)	Length (m)	Inclination(°)	Spacing(m)
1	1.20	9.00	10^{o}	1.50
2	2.70	9.00	10^{o}	1.50
3	4.20	9.00	10^{o}	1.50
4	5.70	7.00	10^{o}	1.50

Note. D is thickness, γ is unit weight, c is cohesion, φ is shear stress of soil/grout interface and τ is internal friction angle.

1.3 Construction of the retaining structure

For the soil nail–prestressed anchor composite retaining structure, soil nails and prestressed anchors were distributed in a “square” layout with an equal vertical and horizontal spacing of 1.4m. Boreholes with a diameter of 120mm 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. In stage one, conventional gravity grouting process was used to seal the annular space between the steel bar and the hole with cement grout. In stage two, a predefined length of the soil nail was grouted using a grout pressure of approximately 1.5MPa. The objective of the pressured grouting was to fabricate the annular cement grout and permeate the surrounding soil. The two staged grouting has been used successfully to reinforce cut slopes, excavations, tunnels etc. to increase the performance of soil nails and therefore reduce in the number of required soil nails, in many countries and areas.(Pooranapillai et al. 2010; Kummerer et al. 2003; Tosen et al. 2010)

Each soil nail used in the experiment consists of a ribbed steel reinforcement bar of 18/22mm diameter, the elastic modulus of which is 200GPa. The soil nails were embedded in a grout mixture with a water/cement ratio of 0.5. The facing was made up of 200mm by 200mm grid thin steel meshes (6mm in diameter). The facing was enhanced with two reinforcement bars (12mm in diameter) in both horizontal and vertical directions. The detailed enhancement configuration of facing is shown in Fig. 3.

The concrete slurry, the thickness of 80mm and the compression strength of 20MPa, was sprayed to fill the gap between the steel mesh and the soil behind and form the retaining wall. Steel plate, which is 200mm in length, 200mm in width, and 20mm in thickness, was installed at the conjunction between the prestressed anchor and the retaining wall to reduce the possible stress concentration. The designed value of prestressing force of the anchor was 50kN. The design parameters of soil nails and prestressed anchors in different retaining structures are summarized in Tables 2 and 3.

Table 2 Design parameters of soil-nailed retaining

Soil nail / anhcor	**Depth(m)**	**Length (m)**	**Bonded length(m)**	**Spacing(m)**
1	1.20	9.00	-	1.50
2	2.70	12.00	**12.0/9.5**	1.50
3	4.20	9.00	-	1.50
4	5.70	7.00	-	1.50

Table 3 Design parameters of composite soil-nailed retaining

soil layer	**D (m)**	**γ (kN/m^3)**	**c (kPa)**	**φ (º)**	**τ (kPa)**
▯	2.20	18.1	14.0	20.0	52.0
▯	2.30	17.9	20.0	15.0	50.0
▯	1.10	18.2	15.0	21.0	60.0
▯	2.30	18.2	21.0	16.0	56.0

1.4 Fabrication of testing instrumentations

In the in-situ tests, the soil nails were instrumented with vibrating wire strain gauges (labelled JMZX-416A), which were attached to the steel tendon of each soil nail. Readings were obtained and stored in a data logger labelled JMZX-3001. During the installation of the strain gauges, great cautions were undertaken to protect the gauges and ensure their survivability. The fixed strain gauge consists of four parts: sensor, connecting rod, wire and plug. Details of the strain gauge are illustrated in Fig. 4.

Before gauge installation, their initial readings are brought to a prescribed range. Gauges are then mounted to the blocks used for fixation and wrapped with a plastic cover to isolate and protect them from subsequent grouting. A typical installation procedure of the strain gauge is specified as follows. First, the steel bar is cut into the predesigned size and length. Then, the fixed part of the strain gauge, as shown in Fig. 4, is welded to the steel bar. It is noted that the overall length of soil nail remains unchanged after the installation of the strain gauge. Afterward, wires are arranged along the length of soil nail and fixed on the soil nail with waterproof tapes. Finally, wires are collected to the top of the slope and connected to data loggers. It is worth noting that care must be exercised during welding to avoid sensor damaged, and the part where sensor and connecting rod is combined should be covered with wet cloth and moisturized constantly to avoid overheating. Afterwards, fiber optic sensors are fixed onto the soil nail according to the circuit of U. The soil nail, with centralizers at 2.0 m interval, is placed in the borehole and followed by the two staged grouting (i.e. gravity and pressure grouting). Figure 5 shows details of the instrumented soil nails for tests.

Different from soil nail, each anchor (25 mm ribbed high yield steel bar) was instrumented with a vibrating wire load cell labelled MJ-101 at the head to monitor the anchor force, with the exception of strain gauges. Figure 6 presents the details of a load cell.

Due to that the anchor tendons are made of steel bars instead of steel strands or wires, the main difference between soil nail and anchor is the processing of the unbonded part. Depending on the designed unbonded length, after grease was spread, PVC corrugated pipe was used to wrap the steel reinforcement bar. The connection between unbonded and bonded part was fastened with fine steel wires. Figure 7 presents the manufactured testing anchors.

To investigate the mechanical behaviour of composite soil nailing, a series of tests were carried out under different conditions. The measured results from the testing profiles of C1, C4 and C5 were analyzed to study the effects of two important characteristics, namely, prestressing force of the anchor and unbonded length of the anchor, on the soil nail force. For the first parameter, it is worth noting that loss of prestressing force should be avoided as possible. For the second parameter, it can be expressed in terms of the length ratio L_u / L, where L_u is the length of unbonded part and L is the entire length of anchor. Testing results of profiles C1, C4 and C5 were simplified with No.1, No.4, and No.5 in the following analyses. As shown in Table 3, two different unbonded lengths of anchors were used. No.1 represents a simple soil-nailed retaining structure; No.4 represents a composite soil-nailed retaining structure enhanced with prestressed anchor without unbonded part; and No.5 represents a composite retaining structure with a 2.5m unbonded length. The layout of instruments is shown in Figs. 8 ~ 10. As can be seen from these diagrams, load cells were installed at the anchor heads to monitor the anchor force and strain gages which were adhered on the steel bars were used to measure the axial strain of the soil nails at different locations. It is important to note that the connection between the soil nails and the facing is robust enough to function properly throughout the entire processes of excavation.

1.5 Test results

1.5.1 Stresses of soil nails

After excavation and installation of the soil nails and prestressed anchors, the data acquisition system was established. The mechanical behavior of the soil nail-prestressed anchor retaining system was monitored for about three months. Figures 11 ~ 15 reveal the stress-date relationship obtained from the in situ tests during the period of three months, in which Tij presents the stress value of the jth strain gauge calculated from the nail head in the ith row of soil nail.

(i) As shown in Fig. 11, it presents stresses of the first row of soil nails for No.1, No.4 and No.5 sections during excavation process. It is evident that there is an non-linear increase in the nail force for No.1 section with each excavation step. The nail force tends towards a stable value when excavation is completed. This means that there are effects of time and excavation on the internal force of soil nail. This is consistent with the result reported in the literature (Wang et al. 2008). Compared with No.1 section, the effect of excavation is less significant for No.4 and No.5 sections. The overall stress level monitored from the tests is relatively low. Corresponding to the excavation of the foundation pit, increments of earth pressure due to unloading are transferred to soil nail through shear stress of soil-grout interface. For this testing project, the foundation pit is adjacent to Fengchan Road in the north, under which a gas pipeline is buried paralleling to the foundation wall. The pipeline lays 1.0m in depth and about 1.5m away from the side of the foundation pit. Due to this reason, the upper soil layers north of the foundation pit for No.4 and No.5 sections have been previously disturbed, which is considered looser compared to the undisturbed soil for No.1 section. Therefore, the friction resistance of soil/grout interface for No.4 and No.5 sections is lower, and earth pressure increment transferred to soil nail is less. According to the above analysis, a conclusion can be drawn that the stress distribution is affected by the density of the soil. Stress level and concentration is higher when the soil is dense; Stress level and distribution is uniform and lower when the soil is loose. The obtained results are consistent with observations reported in the literature (Barley 1995; Woods and Barkhordari 1997).

(ii) As can be seen from Fig. 12, the stress levels of soil nails for No.1 section decrease due to unloading, which is only manifest that the first and second rows of soil nails close to the ground surface are affected a lot, however, the third and fourth rows less influenced. This is because that the soil for No.1 section is dense and the mechanical property is close to undisturbed soil, and the unloading effect from the ground surface can not achieve the range of the lower two rows.

(iii)Fig. 13 presented the stress history curves of No.4 and No.5 sections, the stress distribution and level are less affected by rainfall which continuously lasted for 48This is because that infiltration rate of the rainfall in the clay or silty clay is extremely slow, for example, in clay soil, initial infiltration rate is 2.21mm/min and steady infiltration rate is 0.62mm/min according to the test results(Liu et al. 2012). Accordingly, the depth of infiltration is relatively low. In addition, the actual location of the first low of soil nails are moved down to keep off the gas pipeline, and the exact location for the two test profiles is -2.0m and – 2.2m, separately.

(iv) As can be seen from Fig. 14, the stresses of soil nails in the lower two rows decrease a lot compared to the stressses of the upper two rows(as shown in Fig. 13). Based on the technical specifications, the bonded tendons can be tensioned effectively when the stress exceeds 15However, in fact, next layer was removed away followed by the second excavation as a result of arranged rapid construction, after that tensioning is Consequently, the soil mass influenced by prestressing is the lower parts instead of the upper parts of the foundation A conclusion can be drawn, that is the stress magnitude and distribution of the soil nails are affected by different prestressing periods: the upper rows are influenced significantly when applying earlier; the lower rows will change greatly when applying later.
(v) As can be seen from Fig. 14, the influence of prestressing on the stress of the third and fourth rows of soil nails is only manifest as a part of nails forces changed, which is close to the slope surface, comparatively, another part, which is away from the slope surface along the longitudinal axis of the nail, almost is not affected, which shows that influencing range of prestress is very limited.

(vi) As mentioned before, No.4 and No.5 sections are different retaining strucutres enhanced with i) soil-nails and prestressed anchors without unbonded part; ii) soil-nails and prestressed anchors with a 2.5m unbonded length, when comparing the measured results, the influence of unbonded length on nail forces can be investigated. As can be seen from Fig. 15, the main difference lies in the distribution of nail forces of the first row. For No.4 section, without unbonded part, the distribution of nail forces is consistent with the documented results, which presents an inverted saddle shape, that is “small in the end and big in the middle”. However, for No.5 test profile, with a 2.5m unbonded length, the distribution is manifested as “double peaks”, which shows there may be more than one popential slip surface in loose fill materials. For No.4 section, due to anchor fixed in the overall length, there is deformation of steel reinforcement bar to transfer the load from anchor head to the slope, accordingly, anchorage effect can not be functioned adequately. In other words, it amounts 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.

1.5.2 Distribution of maximal nail forces

The distribution of maximum nail force along the longitudinal axis of the soil nail for No.1 and No.4 sections are shown in Fig. 16, in which the broken lines only represent the positions of soil nails not the lengths, the below is same.

Figure 16(a) shows the distribution of maximum nail force along the longitudinal axis of nails for No.1 section. From the viewpoint of qualitative analysis, this distribution curve of maximal nail force matches with the most critical failure plane of slope. However, the distribution profile of maximal nail forces for No. 4 section is different, as can be observed from Fig. 16(b). There is an obvious breakpoint which indicates that stress distribution is affected by the prestressing. After prestressing, compressive stress zone arises at the end of the anchor, meanwhile, tensile stress zone appears at the tip of the anchor, where stresses of adjacent soil nails increase according to superposition principle (Fig. 17). In this testing project, the tensile force on anchor is relatively low, in addition, there is not a reaction frame to transfer the load to the slope. Consequently, the anchoring effect cannot function adequately, which makes the effective compressive stress zone limited. Furthermore, the stress zone is isolated instead of connected. The peak stress is not evident for No.5 section, the distribution of maximal axial forces of soil nails of the testing profile is not provided. According to Fig. 15(b) mentioned before, the distribution of maximal nail stresses of the first row for No.5 section features an obvious characteristic of “double peaks”, which indicates that more than one critical failure plane exists. However, one month after excavation finished, the performance of “double peaks” weakens gradually since the creep characteristic of loose fill materials. Therefore, it can be concluded that the development of stress of a single soil nail is not uniform nor stable, which may be caused by uniformity of soil layers.

1.6 Interaction between soil nails and prestressed anchors

Soil nails are designed according to reinforcement theory, prestressed anchors are designed as per anchoring mechanism, and composite soil-nailed retaining enhanced with prestressed anchors should therefore designed considering superposition principle. When anchors are tensioned, excessive stress concentration arises at the tip of the anchor. Compression stress reduces gradually along the longitudinal axis of anchor to the top of the anchor. Effective compressive stress zone forms within the range of half-length of the anchor approximately. Keeping away from the end continuously, there appears to be a zero-stress zone as the result of weak anchoring effect; when close to the tip of the anchor, the tensile stress zone appears. With increasing prestressing force, the range of effective compressive stress zone becomes larger according to the simulated results (Kang et al. 2007), sometimes even connected and become a whole. Meanwhile, the zero-stress zone becomes smaller gradually until it eventually disappears. According to the superposition principle, the nail force affected by compressive stress will decrease, meanwhile, the stresses of soil nails which are adjacent to the tensile stress zone will increase. However, due to the smaller tensile stress, the influence of which is limited, the effect of prestressing is only manifest as decreasing of internal forces of soil nails.

The disturbed soil due to pipe line construction encountered in this testing project is more compressible compared to undisturbed soil. The diffusion effect of prestressing is not well developed. Due to this reason, the anchoring effect cannot be adequately realized. In particular, for the circumstances where there is no unbonded part in condition of low prestress (50kN), deformation of slope is mainly controlled by loose fill materials. In case there is unbonded part in the anchor, load from anchor head can be transferred to bonded part through free deformation of steel bar of unbonded part, which will resist the deformation of loose fill materials. The function of prestressing in loose disturbed soil need to be discussed further.

2 Summary And Conclusions

In this paper, in-situ tests were conducted to investigate the mechanical behavior of soil nail and prestressed anchor enhanced retaining structure. Three types of different retaining structures, including i) soil-nails; ii) soil-nails and prestressed anchors without unbonded part; iii) soil-nails and prestressed anchors with a 2.5m unbonded length, were investigated. The effects of different factors, such as prestressing and unbonded length were discussed. The results obtained would assist practicing engineers in the design of nails and anchors for civil engineering application. In particular, it was found that:

(i) The interface friction stress of the soil nail is affected by the density of surrounding The friction stress is higher when soil is denser and harder, which is characterized by manifest stress concentration; the friction stress is lower and uniform when soil is looser and softer, which is consistent with theoretical hypothesis;

(ii) Influence of prestressing on internal force of soil nail is governed by tensioning When the anchor is tensioned synchronously, its ability to limit the deformation is obvious; meanwhile the upper soil nails are When the anchor is tensioned later, the lower soil nails are affected;

(iii) The distribution of the maximum nail forces is regular for soil-nailed retaining structure, which matches the assumed sliding surface; while for soil nail–prestressed anchor composite retaining structure, prestressing changes the distribution of stress field and there is an obvious “breakpoint” in the distribution;

(iv) The unbonded length, which is considered to be the main factor affecting the slope stability in dense materials, is only manifest as the change of stress distribution of the first low of soil nails, the influence on the other rows is negligible in loose fill materials.

Declarations

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Figures

Figure 1

Vertical Section of Soil nail – prestressed anchor composite retaining structure

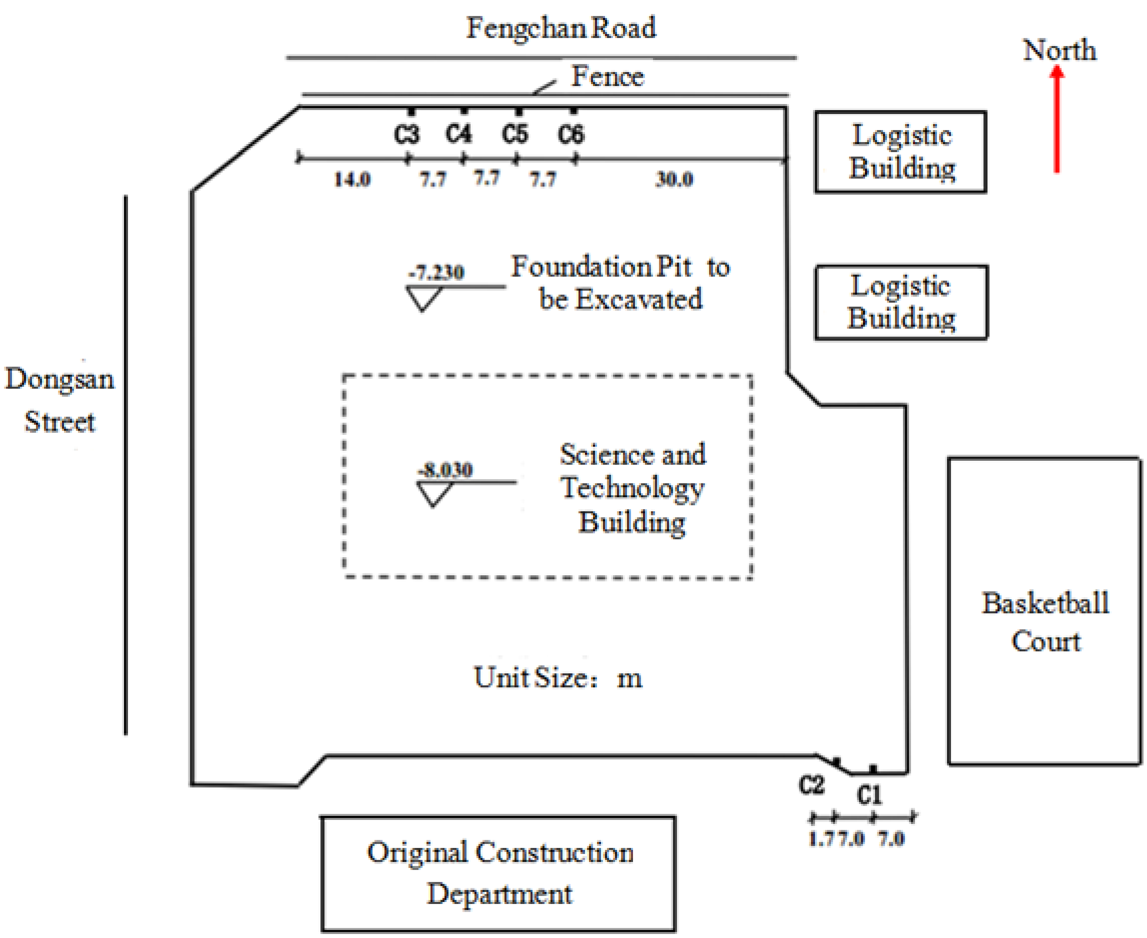

Figure 2

The layout of foundation pit

Figure 3

The enhancement configuration of facing

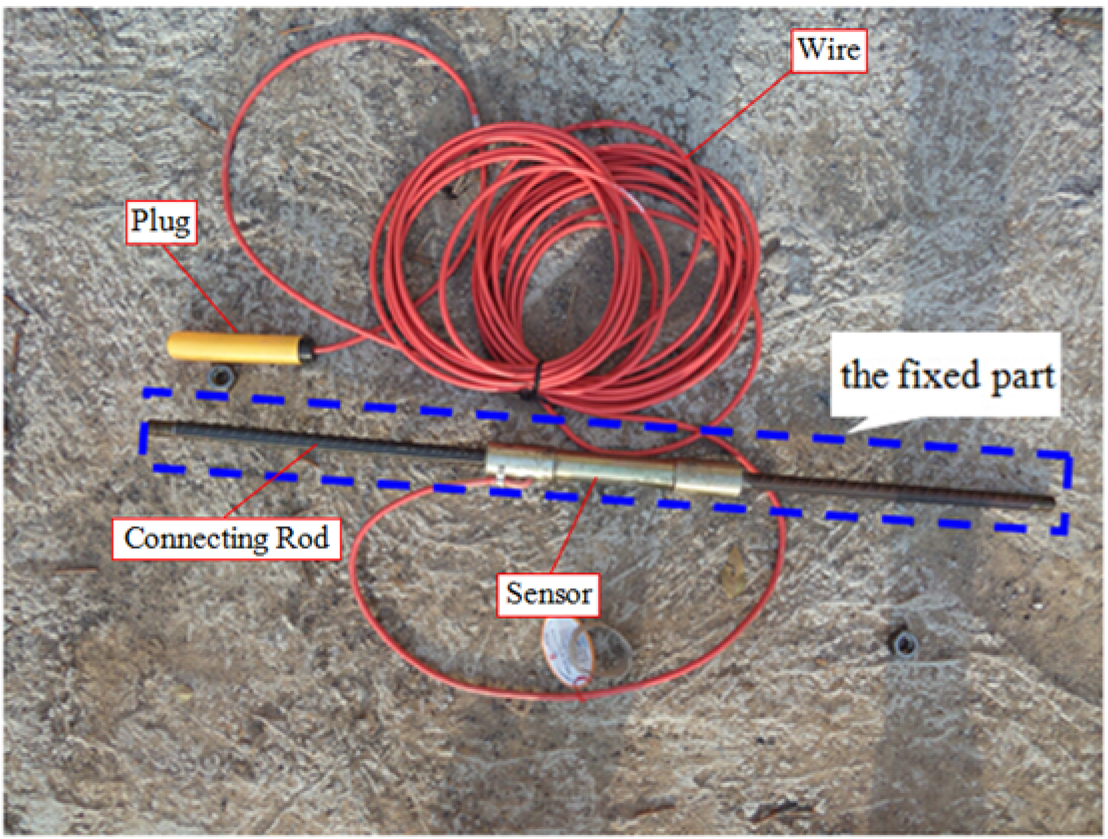

Figure 4

The details of the strain gauge

Figure 5

The manufactured testing soil nails

Figure 6

The details of the load cell

Figure 7

The manufactured testing anchors

Figure 8

Loaction of instruments for No.1 testing set

Figure 9

Loaction of instruments for No.4 testing set

Figure 10

Loaction of instruments for No.5 testing set

Figure 11

Stress-date relationship of the first row of soil nails for testing sections

Figure 12

The influence of unloading on stress of soil nails for No.1 section

Figure 13

Stresses of the upper two rows for No.4 and No.5 sections

Figure 14

Stresses of the lower two rows for No. 5 section

Figure 15

The distribution of nail forces of the first row for No.4 and No.5 sections

Figure 16

The distribution of maximal nail forces: (a) No.1 Section; (b) No.4 Section