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Theme 1: Analysis and numerical modeling of deep excavations

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Optimization design of composite soil-nailing in loess excavation

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ABSTRACT: The loess excavation has its unique characteristics compared with the others due to its structural property and collapsibility. In order to acquire the work mechanism and design methods of composite soil-nailing in loess excavation, a reasonable finite element analysis model is selected. The optimization design methods are introduced based on the results of finite element analysis conducted to determine the regularity of deformation, the safety factor and the endogen force of the structure along with the change of design variable. Finally, the optimization design methods are validated contrasted with the data measured in an actual project.

1 INTRODUCTION

Composite soil-nailing combined soil nails with other forms of supporting measures has avoided the soil-nailing technology from excessive dependence on the soil and expanded its application field. Among the different kinds of composite soil-nailing forms, the anchor composite soil-nailing support method is widely applied for its powerful location adaptability, easy construction, low cost and reducing the pit deformation remarkably. However, its work mechanism and design method, especially the Loess Pit anchor composite soil-nailing research, fall behind the project practice by far. In the first instance, this paper aims at studying nail design parameter selection in plain soil-nailing on the premise of maintaining soil-nailing total length, and then replacing a anchor for a soil nail to research the parameter value of anchor composite soil-nailing structure and optimization design under the circumstances of maintaining plain soil-nailing design parameters a more optimal value.

2 PARAMETER ANALYSIS

The overall stability and working performance of excavation supporting is closely related to the design parameters. Understanding and grasping the relations of the overall stability safety factor with the change of these design variables, particularly this kind of sensitivity degree that variety, have special and important meaning for guiding engineering practice.

2.1 *Hypothesis*

To simplify the calculations, we make the following assumptions when carry on the numerical analysis to the composite soil-nailing numerical analysis:

1 Composite soil-nailing problems are plane strain problems;
2 Soil-nailing and assistance reinforcement materials are elastic materials;
3 The soil is presumed as the elastic-plastic material.

2.2 *Computation diagram and parameter of material*

2.2.1 *Computation diagram*

Engineering experience shows that the influence of excavation width is about 3 to 4 times of the excavation depth, influence depth is about 2 to 3 times of excavation depth. The case assumes that the excavation depth is 9.5 m, the total length of the finite element model is 45 m, the total height is 25 m and the slope gradient is 1:0.1 (Fig. 1).

2.2.2 *Boundary conditions and loads*

On the left and right boundary of the model, we set the X-direction displacement to zero and allow the Y direction deformation; the X and Y direction displacement of the bottom boundary are zero; the top is a free surface. Initial stress field is gravity stress field; the value of Gravitational Acceleration is 9.8 m/s^2. Since composite soil-nailing is usually constructed after precipitation, the impact of groundwater is not considered.

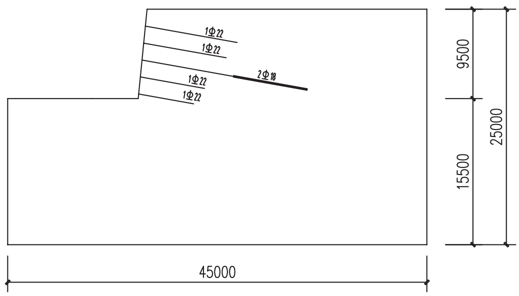

Figure 1. Finite element analysis model (Anchor at middle).

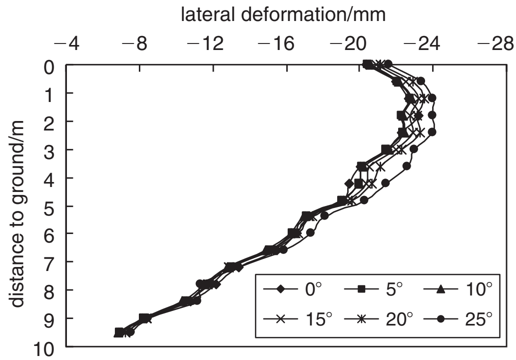

Figure 2. Relations of soil-nailing angle and pit displacement.

2.2.3 *Material parameters*

This research was completed against the loess excavations and the soil parameters were provided from a engineering investigation report in Xi'an City. Because the soil distributes in certain scope are uneven, it is discommodious to carry on the Numerical Calculation and take the soil strength average value of each level. Soil nails and anchors take the form of the commonly used procedure in Xi'an: Soil-nailing 110 mm diameter bored, steel bar 1 ϕ 22; the anchor hole diameter 150 mm, steel bar 2 ϕ 18, surface 100 for C25 thick concrete, reinforced with distribution steel bar network. Soil nail and anchor were made of steel bars that wrapped with cement slurry composition. Slurry tightly wrapped the external part of steel bars, and occluded with the soil in dogtooth. In order to simulate the mechanical behavior of soil-nailing and anchors correctly and simplify finite element analysis process, we regard the steel bar and the cement paste body as a kind of compound material. Materials geometric and mechanical parameters, as follows:

Soil: $c = 30$ kpa, $\varphi = 18°$, gravity $\gamma = 18$ KN/m^3, deformation modulus $E_0 = 1.8 \times 10^7$ Pa, Poisson's ratio $\mu = 0.3$; Soil-nailing: diameter 0.11 m, sectional area is 0.0094985 m^2, moment of inertia 1.8324×10^{-6} m^4, equivalent modulus of elasticity $E_{eq} = 2 \times 10^{10}$ Pa, Poisson's ratio $\mu = 0.3$;

Anchor: the sectional area of free segment is 5.0868×10^{-4} m^2, moment of inertia is 1.030077×10^{-8} m^4, elastic modulus $E_s = 2 \times 10^{-11}$ Pa, the sectional area of anchorage segment is 0.0176625×10^{-4} m^2, moment of inertia is 2.483789×10^{-5} m^4, equivalent elastic modulus $E_{eq} = 2.03 \times 10^{10}$ Pa. Poisson's ratio $\mu = 0.3$; Surface (unit length) : The sectional area is 0.1 m^2, moment of inertia is 8.33333×10^{-5} m^4. Equivalent elastic modulus $E_{eq} = 2.1 \times 10^{10}$ Pa, Poisson's ratio $\mu = 0.3$.

Contact surface friction: According to the research of reference (Chen, 2000, Wang, 1997), the soil-nail contact surface and the soil-anchor contact surface friction value is 60 kPa.

Table 1. Relations of soil-nailing angle and safety factor.

Soil-nailing angle	0	5	10	15	20	25
Safety factor	1.593	1.623	1.654	1.615	1.568	1.53

2.3 *Soil-nailing support*

2.3.1 *The angle of soil-nailing*

Concerning with the construction method, the angle of soil-nailing has great influence on the pit displacement, the safety factor and the surface subsidence. Taking the total length of soil-nailing is 40 m, establishing five rows of soil-nailing, taking the soil-nailing level and the vertical spacing takes 1.8 m, the first row of soil-nailing depth of burying is 1.8 m. Dividing five steps excavates, the first step of excavation depth is 2.3 m, and the other step of cutting depth is 1.8 m each. Soil-nailing obliquities are calculated by inclination of 0°, 5° , 10° , 15°, 20° and 25° respectively.

Figure 2 and Table 1 show that the horizontal displacement is gradually increasing and changing at an increasingly rapid pace as soil-nailing angle from 0 degrees to 25 changes gradually. When the pit design requires strict control of the horizontal displacement, they should use a smaller angle. Safety factor in soil-nailing angle reduces 10 degrees at the largest and declines rapidly with the angle increases after 10 degrees.

On the other hand, Soil-nailing angle is related with construction methods and soil-nailing construction usually adopt the self grouting methods, in the hope of soil-nailing has more inclination to make the cement grout fill soil-nailing holes under the weight easily.

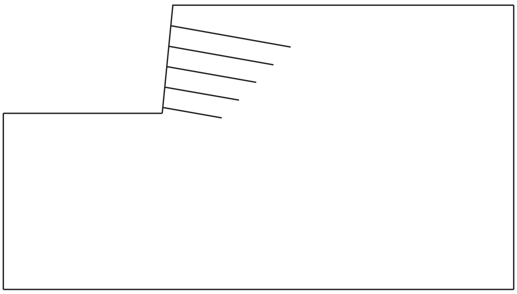

Figure 3. Long at upper row and short at lower row.

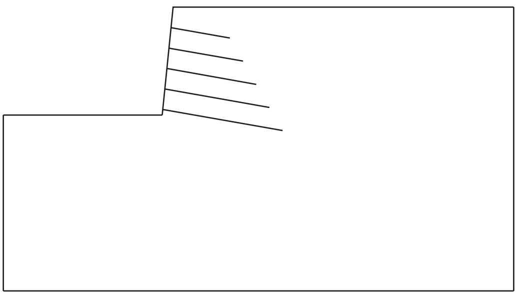

Figure 4. Long at middle row and short at upper and lower row.

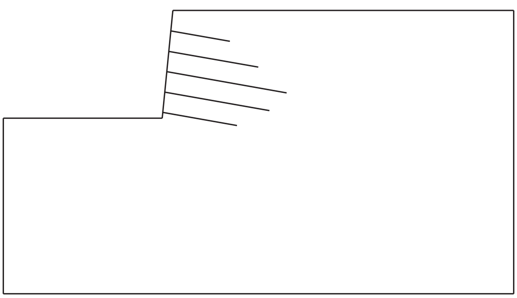

Figure 5. Short at upper row and long at lower row.

So after considering the pit displacement, the safety factor and construction factors, the angle should be about 10–15 degrees.

2.3.2 *Scheme of soil-nailing layout*

Other researchers do more about the schemes of soil-nailing layout (Hu & Song, 1997, Li & Zhang, 1999). But their studies focus more on comparison between long at upper row and short at lower row scheme (long-short scheme) and short at upper row and long at lower row scheme (short-long scheme). But in practice, we often use long at mid row and short at upper and lower row scheme (mid-long scheme), especially when the soil-nailing is used with anchor together (Figs. 3–5).

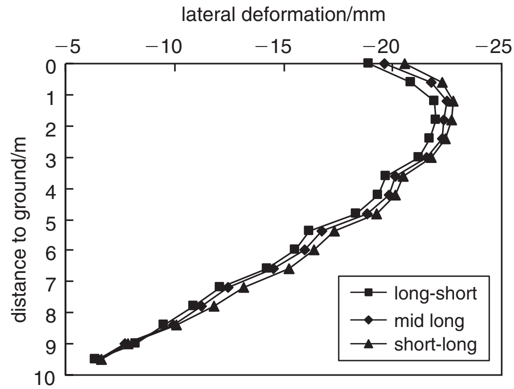

Figure 6. Relations of soil-nailing layout and displacement.

Table 2. Relations of scheme of soil-nailing layout and safety factor.

Scheme of layout	Long-short	Short-long	Mid-long
Safety factor	1.478	1.447	1.376

Selecting nail angle is 10 degrees then calculates and analyzes on three different layouts, we get the results Figure 6 and Table 2 below.

From Figure 6 and Table 2 we can find that there are smallest displacement and largest safety factor when using long-short scheme. On the contrary, there are largest displacement and smallest safety factor when using short-long scheme. As the same conclusion with our forerunners, displacement and safety factor that use short-long short scheme are between the other two modes and we can see that when using plain soil-nailing support a long-short scheme should be adopted.

2.4 *Anchored soil-nailing support*

At present, the application of prestressed anchor in composite soil-nailing design is often used empirically and there has not a determinate calculative method to set the anchor position, the length of anchorage, prestressed value.

Based on previous studies, we chose the nails angle of 10 degrees and long-short layout scheme to research the anchored soil-nailing support.

2.4.1 *Location of prestressed anchor*

After replacing the 1st and 3rd rows and the fifth row of soil nails with anchor, let us study the influence of blot location on the pit's level displacement and safety factors. Diagrams shows in Figures 7–8, 1, and the results are shown in Figure 11 and Table 2 below.

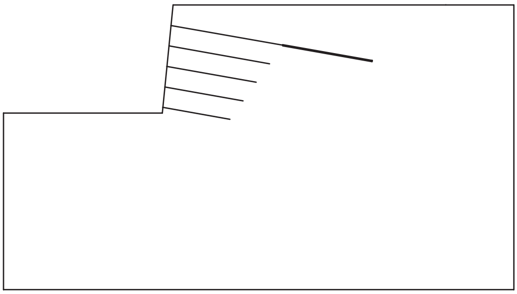

Figure 7. Anchor at upper row.

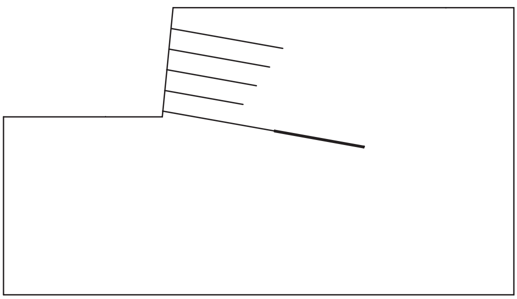

Figure 8. Anchor at lower row.

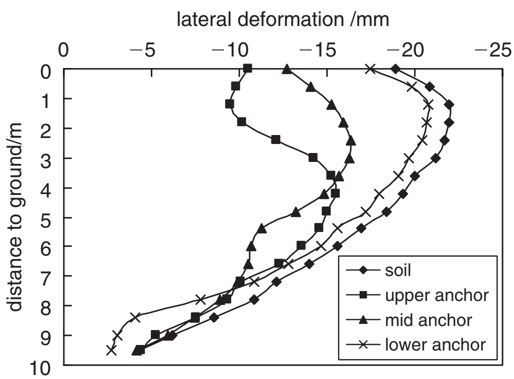

Figure 9. Relations of anchor locations and displacement.

Table 3. Relations of anchor locations and safety factor.

Anchor locations	Upper	Middle	Lower
Safety factor	1.496	1.546	1.511

Figure 9 and Table 3 show that add prestressed anchor into soil-nailing can significantly reduce the maximum horizontal displacement, especially in and near the anchor location. In addition, compared with

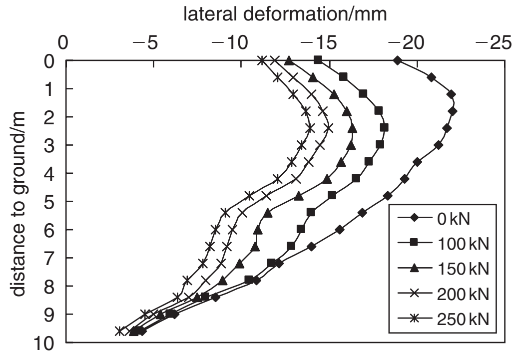

Figure 10. Relations of prestressing and displacement.

Table 4. Relations of prestressing and safety factor.

Prestressing value/kN	0	100	150	200	250
Safety factor	1.546	1.597	1.617	1.624	1.628

plain soil-nailing, it can significantly reduce the level of surface displacement through adding prestressed anchor, particularly the top-anchor scheme and bottom-anchor scheme have the most obviously effect on the surface of the horizontal displacement control. Anchor locations also affect the safety factor. It has the biggest safety factor when anchor at the central pit.

Therefore, to control the pit deformation, the angle of anchor would favor the upper-anchor scheme; the mid-anchor scheme is the most beneficial to improve the safety factor. However, in the engineering practice, because excavations concentrate more and more on urban areas and the anchor may into the pit slope outside more distance, there may affect anchor construction for the adjacent buildings when used the top anchor scheme.

2.4.2 *Level of prestressing value*

Used prestressed anchor replace with the 3rd soil-nail, taking the anchor free segment length is 10 m, anchorage segment length is 8 m, prestressing value is 0 kN, 150 kN, 200 kN and 250 kN respectively for calculating. The results calculated from the horizontal displacement and the safety factors are shown in Figure 10 and Table 4.

Figure 10 and Table 4 show that the impact of prestressing value on the horizontal displacement is greater. When the magnitude of prestressing is 100 kN, horizontal displacement decreases more than plain soil-nailing from the maximum displacement of 23.1 mm to 17.6 mm lower. If prestressing value

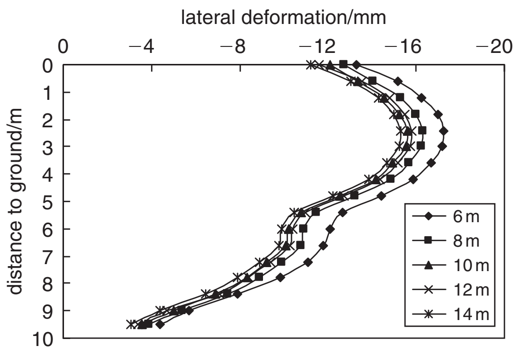

Figure 11. Relations of anchorage segment length and displacement.

Table 5. Relations of anchorage segment length and safety factor.

Anchorage length/m	6	8	10	12	14
Safety factor	1.586	1.617	1.629	1.637	1.641

increases to 150 kN, the maximum horizontal displacement will decrease to 15.3 mm. If the prestressing value is more than 150 kN, such as 200 kN, 250 kN, horizontal displacement will continue to decline, but the reduction range is insignificant. As the value of the prestressing increases, the Pit safety factor will gradually increase in a limited extent, which means the value of prestressing has no significant impact on safety factor.

2.4.3 *The length of anchorage segment*

Selecting a middle-anchor scheme, the prestressing value is 150 kN, taking the length of anchorage for 6 m and 8 m, 10 m, 12 m, 14 m to calculate, the results are shown in Figure 11 and Table 5.

Figure 11 and Table 5 show that the horizontal displacement of Pit gradually diminishes as the anchorage length increases, but the reduction is modest. Pit safety factor would increase as the length of anchor increased either, but not markedly.

3 ANCHOR AND SOIL-NAILING WORKING TOGETHER MECHANISM

Plain soil-nailing support is a passive support system and soil-nailing would have a role only when the soil generates sufficient deformation. Anchor belongs to the initiative support system and through prestress to control soil deformation. Anchored composite soil-nailing is a special kind of support, which between plain soil-nailing and prestressed anchoring support. It has the advantages of both the plain soil-nailing support and the prestressed anchor support simultaneously.

3.1 *Anchor and soil-nailing working together*

It is at the initiative stressful condition as anchor support construction completed because of the existence of prestressing. As a result of the anchor prestressing reaction, the soil is caused to be at the pressed condition, reduced soil lateral deformation. On the other hand, anchor is wrapped in the cement paste, and adhibited with cement paste. Because of the holes, pores and crannies existed in soil; the cement and the soil assume the zigzag linking. After anchor tension deformation, there will have a shear stress due to elastic deformation and retraction in the anchor-soil interface, which direction on the soil deformation under shear stress is the contrary. It reduces soil internal tensile stress, and will also limit the deformation of soil. The axial force of soil-nailing is related with the deformation of the earth. Because stress reduces the soil deformation, soil-nailing internal force is reduced more remarkably than plain soil-nailing .The closer the anchor approaches the soil nails, the more the axial force decreases. Therefore, the role of restrictions pit deformation is the base of anchor and soil-nailing working together.

3.2 *Anchor contribution to resistance moment*

When the Pit Slope in the event of damage, the slip surface have too much plastic deformation to make slide mass along for destruction under sliding. Generally, the sliding moment entirely depends on the depth of excavation and the soil gravity. For a certain pit, the soil depth and its weight usually are constant and its sliding moment can be seen as a constant. Meanwhile resistance moment is provided by the undisturbed soil, shear strength, soil nails and anchor.

The contribution of soil nails performance lies in three main aspects: soil-nailing presence gives the slip surface place to the post-transfer slip, improves the sliding area and increases the friction of slip surface. Uplift role of the soil-nailing that outside the slip surface, and the bending resistance role of soil-nailing.

The contribution of anchor main features (Chang, 2007):

1. The anchor's anchorage is long in general and extends into the steady soil mass in central slip away from the excavation surface to provide a stronger uplift capacity.
2. The anchor's prestressing makes slide and stability soil mass tightly squeezed each other to improve the friction resistance to sliding and increase the resistance moment.

3 When the slip surface crosses the anchorage segment, the anchor resistance to bending has some contribution, but the contribution is weak in general.

3.3 *The impact of prestressing to soil-nailing axis force*

There are many studies about the impact of prestressing to soil-nailing axis force and the conclusions are the same. Generally, the prestressing will significantly reduce soil-nailing forces and the greater the value of prestressing, the smaller the soil-nailing internal force. And moreover, the closer the anchor, the greater the internal force reduction (Zhang & Liu, 2002, Zhen et al. 2005).

4 DESIGN OPTIMIZATION

1. Soil-nail design. Recommending taking the soil-nailing's long-short layout and it is advisable to select 10–15 degrees.
2. Loess has strong structure, which should be used as much as possible.
3. Anchor should be installed close to the central vertical part of the pit, which can achieve a higher safety factor and restrict the pit deformation.
4. It does not provide a greater safety factor and better control deformation even the anchor length is too long. So it had better be about 8–12 m.
5. Since the anchor prestressed reaction limits soil lateral deformation, reduces the lateral displacement of composite soil-nailing retaining and axial force of the-soil-nailing near the anchor. On the premise of meeting deformation control request, we can shorten the length that several soil-nailing top of the pit appropriately in long-short scheme, long-short-long scheme while forming to reduce project cost. However, in order not to reduce safety factor, it is not recommended to shorten the length of soil nails in the lower side.
6. The fixing on the prestressed value must be according to the soil shear strength values, it will be about 100 kN to 200 kN as well. Due to the prestressed value has no obvious influence on project cost, we can incline safety to choose the values greater. But too much prestressed has no significant impact on pit retaining performance.

5 ENGINEERING ANALYSIS

5.1 *Project overview*

A project in Xi'an , the excavation depth is 11.0 m, both the Pit's length and width are about 100 m. In the east by north from the pit 6.3 m is a seven-storey masonry structure residential buildings, the lime soil foundation depth is about 3 m.On the south-east there is a 18-storey high-rise building with one-storey basement which depth is 6 m, reinforced concrete pile foundations are 36 m long, from Pit 9.10 m, and the adjacent side of the project pit used soil-nailing in the construction; north of the seven-storey residential building masonry structure, and roughly parallel to pit edges, buildings length is 42 m and the width 13 m, the nearest to excavation is 5.3 m; the west side of the South and an adjacent hotel podium which is a two storeys building with an underground layer from the edge of pit 4 m, framework and infrastructure end elevation is −7.13 m; the south side is close to a main road, there are water and gas pipelines under the sidewalks.

Table 6. Site layer structure and geotechnical characteristics.

Soil class	Thickness/ (m)	Unit weight (kN/m3)	Cohesion/ kPa	Angle of internal friction/°
Miscellaneous	0.90	18.20	25.00	18.00
LoessQ3^{2EOL}	6.60	16.20	28.00	18.00
LoessQ3^{2EO}L	1.70	18.00	26.80	18.10
Ancient soilQ3lal	3.40	18.90	32.20	17.60
LoessQ3^{al+PL}	8.00	19.50	20.00	18.00

5.2 *Engineering geological conditions*

According to geotechnical engineering investigation report that the project site geomorphic units belong to the Loess beam-swamp landscape. Proposed site layer structure and geotechnical characteristics are in range of 30.0 m deep in Table 5.

5.3 *Retaining design*

The design of anchored composite soil-nailing adopts the methods proposed in part 4 of this paper, which is the excavation depth was 11.0 m and the slope was 1:0.1. The basic design parameters were shown in Table 6. There are six layers of soil nails and the layout is cinquefoil. We also set a prestressed anchor at the depth of −6.0 m to reduce the lateral displacement and ensure the high-rise buildings in safety and stability. Using two 18 mm diameter grade 60 bars in anchor (10 m free, 8 m anchorage); Using one 22 mm diameter grade 60 bar in soil-nailing with 1.5 m spacing and inclination of 15 degrees, prestressing value is 150 kN. (Fig. 12).

5.4 *Monitoring results*

This project was constructed since March 20, 2006 and lasted 75 days. Monitoring results showed the greatest

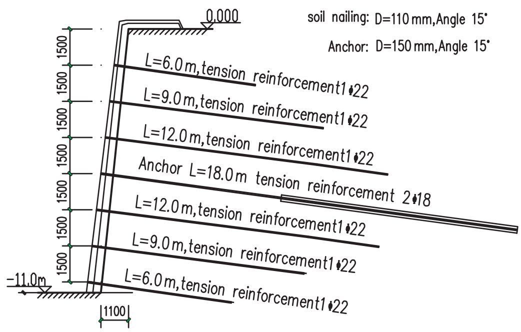

Figure 12. Composite soil-nailing support diagram.

lateral displacement occurred in the east central pit and the largest displacement was 16 mm. It was no excessive lateral deformation and earth surface subsidence and surrounding buildings were no greater settlement.

6 CONCLUSIONS

In this paper, the author analyzed the parameter sensitivity of composite soil-nailing in loess excavation using the finite element method. The optimization design methods are introduced based on the results of finite element analysis. The writer believes that anchor should be installed in the pit in the central vertical, which can achieve a higher safety factor and restrict the pit deformation obviously.

We can shorten the length that several soil-nailing top of the pit appropriately in long-short scheme, mid-long scheme while forming to reduce project cost. Anchor length should not be too long and prestressing also should not be too large. Practical project proved that this optimization method in loess pit is applicable.

ACKNOWLEDGMENT

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