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Effects of additional excavation on critical slip surface of stabilized walls with soil nailing

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ABSTRACT: In recent years, soil nailing has been increasingly used, due to its low cost, high safety, workability and remarkable performance, to stabilize slopes and support excavations. Much research has been done on parameters affecting safety factor, stress, settlement and displacement. However, studies on the effects of additional excavation on excavation walls or, in other words, methods and mechanisms to preserve additional depth without compromising the whole wall stability while maintaining and controlling the initial slip surface are not many. Therefore, this paper aims at investigating the effects of 7m additional excavation on the 23m-deep excavation walls (totally 30 m) of the Twin Towers project in Shahr-e kord, Iran, retained by soil nailing systems. To retain the additional depth, use has been made of the 2D-FEM and anchorage method with in-situ concrete piles, and the results have been validated through a comparison between the calculated and measured wall displacements. The effects of seven key design factors (pile diameter, horizontal spacing, embedded length, anchor angle, prestressing force, bonded/unbonded length of the piles or anchors) have been discussed based on the results of FEM which is quite an efficient method for settlement predictions. Finally, a number of design charts have been prepared for in-situ concrete pile anchorage used in additional excavations.

1 INTRODUCTION

Nailing (started in mid 1980s in Hong Kong) has been widely used in deep excavations in recent years because of its safety, workability, and cost-effectiveness. In cases where excavation does not allow mere nailing walls, a combination with prestressed anchor cables can be quite effective. Nailed walls consisting of nailing and anchorage can be used effectively in reinforcing soil and controlling displacements in deep excavations. In recent decades, the combination has become a very popular method in Iran. So far, extensive research has been done on this method which is widely used in protecting deep excavations. Earlier, such research studies were based on limit equilibrium methods. Then, over time, and with the progress in FEM methods, many researchers used them to simulate nailed walls. Design and implementation of nailing is now several decades old and extensive research has been done.

Using the finite difference method for the analyses of composite nailed walls. Wang et al. concluded that

the maximum horizontal displacement occurs mostly at the anchor tip and, then, it decreases from top to bottom. Tang et al (2008). analyzed the displacement and stress in prestressed anchor cables of the composite nailed structures and showed that the wall displacements (vertical and horizontal) are controlled better when use is made of prestressed anchor cables with the nailing system. Jin et al. (2010) concluded, in their research, that a combination of nailing and prestressed cables is more appropriate for the protection of the walls of deep excavations. Yan combined Drucker-Prager's and tensile slip models, carried out the finite element analysis of the composite nailing, and concluded that better results are found (compared to using only Drucker-Prager's model). Ma et al.'s research results showed that a composite nailed structure has a better seismic performance than a simple one.

A point common in all the related studies is a constant excavation depth, but if, for any reason, e.g. when the design parameters are not found at the drill-hole bed, the excavation depth is to be increased and,

therefore, its wall protection system (designed based on the former depth) will not work properly; the depth increase will cause an increase in displacements, settlements, forces in different anchoring members, and, hence, a decrease in the factor of safety. Therefore, it is necessary that proper measures be taken to stabilize the additional depth, maintain the position of the initial slip surface, prevent the displacements to exceed the allowable limits, and, finally, preserve the stability of the whole implemented system. To achieve these goals, use has been made, in the present research, of a combination of in-situ concrete piles and prestressed anchor cables as a stabilization system for the additional depth. The effects of such parameters as the pile diameter, horizontal spacing and embedded length, and the anchor angle, prestressing force, and bonded/unbonded length on the critical slip surface have been studied and the results discussed in full details in the sections that follow. In general, past researches have shown that composite soil anchorage methods (using steel profiles, concrete piles or concrete blocks) are quite efficient in controlling displacements in excavation walls. Krabbenhoft et al., (2005), Tan and Paikowsky, (2008), Niroumand and Kassim, (2010), Ghareh, (2011), and Ghareh and Saidi, (2011) are only a few among many researches carried out on the subject.

2 A BRIEF STUDY OF THE GEOTECHNICAL CONDITIONS OF THE PROJECT SITET

The project in question is situated in Shahr-e Kord, Iran, in a piece of land 7000 m² in area facing streets from three sides and a 1-storey building from the fourth; the site lies in Zagros Zone. Our studies started through drilling three 25m, two 30m, and two 45m deep boreholes none of which met the underground water level. The SPTs performed at different depths needed more than 50 blows showing the soil layers' high compactness. In addition, some pressure-meter tests were also carried out in some boreholes on undisturbed samples to study the horizontal displacement module for the profile of the soil being studied (Table 1).

Table 1. Soil properties used in the FEM simulation

Depth(m)	SoilType	ϕ (deg)	C (kPa)	γ (kN/m ³)	E (kPa)	BS*
0-4.5	GC	38	9.8	20	68600	250
4.5-12	SC	38	9.8	20	58860	250
12-16	GC	38	9.8	20	68600	250
16-21.5	GC	38	9.8	20	83380	250
21.5-45	SC	38	9.8	20	245250	250

* Bond stress.

The borehole depth was 23m, the excavation amounted close to 160000 m³, and stabilization was done by 11 rows of nails placed 2 meters apart (vertically and horizontally) at an angle of 150 (FIG. 1).



Fig. 1 A view of walls stabilized by nailing

3 THE ANALYSIS METHOD STABILITY ANALYSIS

To study the effects of different parameters on the slip surface, use was made of Slop/w section of Geostudio (a product of Geoslope Co.) which is based on the limit equilibrium relations and checks the safety factor and the condition of the slip surface.

4 DISCUSSION AND RESULTS

To validate the obtained results, a model was made based on the B. Xu et al.'s (2006) (Figure 2) and the safety factor and the slip surface conditions were studied. As shown in FIG. 3, the results conform to those of B. Xu et al.'s (2006) concluding that the proposed modeling has presented acceptable results.

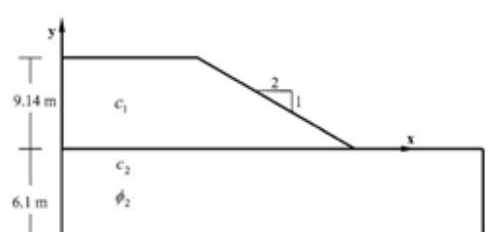


Fig. 2 Modeling for the validation of the results of Geoslope

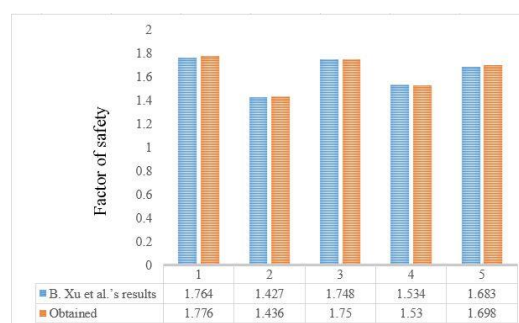


Fig. 3 Comparison of B. Xu et al.'s results with those obtained by the proposed modeling

If there is additional excavation, as shown in Figure 4, the initial slip surface will fundamentally change

and shift position to a lower level causing inefficient performance of the nails in previous levels and an increase in the displacements- hence the instability of the whole system.

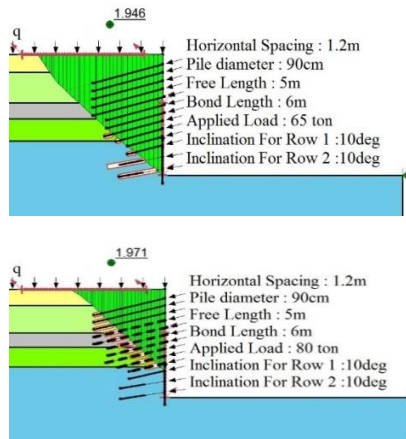


Fig. 4 The initial and secondary slip surfaces based on the limit equilibrium relations

Since the initial depth has been 23 m increasing to 30 m after 7 m of additional excavation, we are to take measures to anchor the additional depth and preserve the slip surface at its initial state and do not allow the displacements to exceed the permissible limits.

When the slip surface shifts position to a lower level, the nails in the first 23 m do not work efficiently and will not play a role in the stability of the system; therefore, effort has to be made to make the system work properly and, in the mean time, insure the stability of the additional depth. To achieve these goals, use was made, in this paper, of in-situ concrete piles with anchors, and the 7 key design parameters mentioned before were checked (results will be presented in the sections that follow). Figure 5 shows an overall picture of the wall after additional excavation.

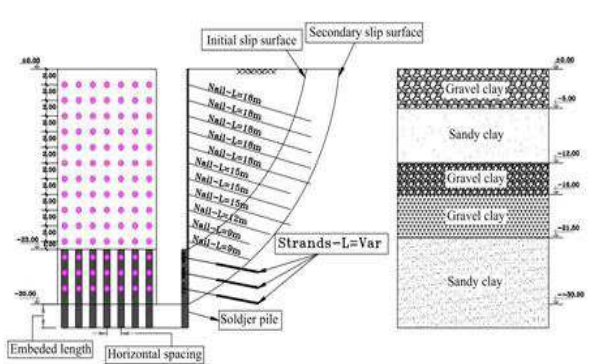


Fig. 5- An overview of the wall after additional

4.1 Effects of anchor angle

Effects of the anchor angle on the controlling situation of the initial slip surface were investigated for 2 and 3 rows of anchors at angles of 10, 15, 20, and 25°

(and also combinatorial angles according to Tables 2).

Table 2. Combinatorial angles

Number of row	Angle(deg)	Angle(deg)
1	10	15
2	15	20
3	20	25
View	Mixed Angle:1	Mixed Angle:2

Number of row	Angle(deg)	Angle(deg)
1	10	15
2	25	20
View	Mixed Angle:1	Mixed Angle:2

To check the effects of the anchor angle on the position of the initial slip surface (3 rows of anchors) some models were made with 80 cm diameter piles, for a prestressing force of 50 tons and a horizontal spacing of 1.2 m for different anchor angles; the results are shown in Figure 6a.

For 2 rows of anchors too, some models were made with 120cm-diameter piles, for a prestressing force of 80 tons and a horizontal spacing of 1.5 m for different anchor angles; the results are shown in FIG. 6-b.

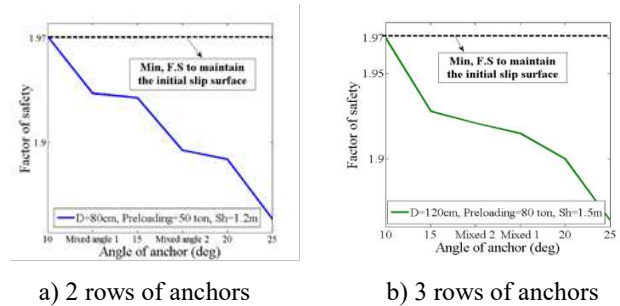


Fig. 6 Effects of anchor angle on the F.S and the initial slip surface

Figure 6 shows that the angle increase from 10 to 25° generally causes a decrease in the F.S and a position shift of the initial slip surface; the use of combinatorial angles is, by far, better than using 20 and 25° angles.

4.2 Horizontal spacing of piles and anchor members

Any change in this spacing directly affects the performance of the stabilization system; this is clearly shown in Figures 7 and 8. The initial slip surface too was checked (as the displacements were). Figure 7 shows the effects of the increase in the horizontal spacing for different angles for both 2 and 3 rows of anchors; the pile diameter is 90 cm and the prestressing force is 80 tons. As shown, for 2 rows of anchors,

the initial slip surface is maintained only when the spacing is 1.2 m; if this is increased, the F.S. is reduced considerably and the slip surface shifts position to a lower level. For 3 rows of anchors, the spacing can be increased up to 1.5 m.

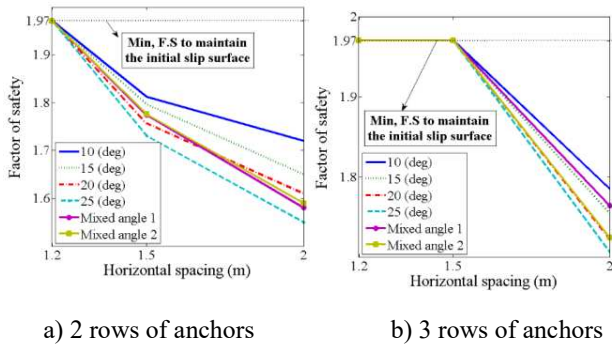


Fig. 7 Effects of horizontal spacing on the F.S. and the position of the initial slip surface

Figure 8 shows that if the stabilization system stiffness is increased and 120cm-diameter piles are used, in no case will the initial slip surface be maintained if the spacing is increased to 2 m; for 2 rows of anchors, the initial slip surface will be maintained only when the angle is 100 and the spacing is 1.5 m; therefore, it can be stated that the maximum possible horizontal spacing is 1.5 m (considering other conditions as well).

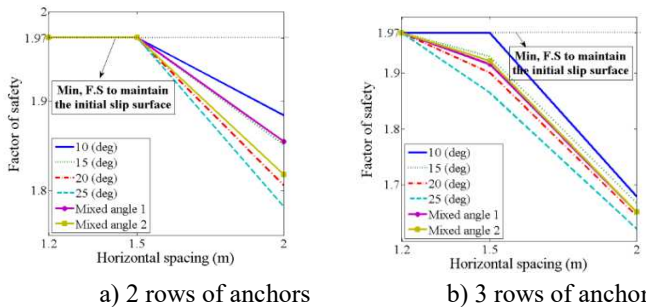


Fig. 8- Effects of stiffness variations on the F.S. and the position of the initial slip surface

4.3 Effects of pile diameter on displacements

One of the parameters that cause a change in the initial slip surface is a change in the pile diameter; such effects were studied once for 2 rows of anchors, 80 tons prestressing force, and 1.5 m spacing, and again for 3 rows of anchors, 65 tons prestressing force (same spacing). Results are shown in FIG. 9 for anchor angles of 10, 15, 20, and 25°.

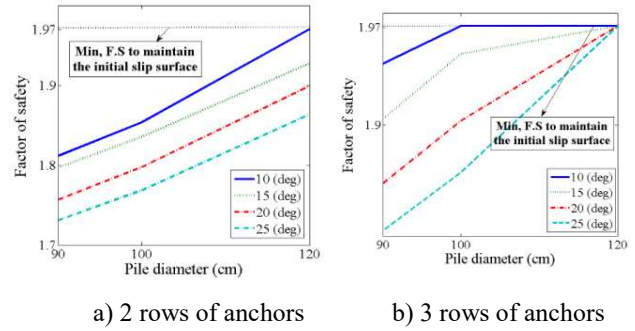


Fig. 9- Effects of pile diameter on the F.S. and the initial slip surface

Both figures show that the pile diameter increase can be an effective parameter in maintaining the position of the initial slip surface.

4.4 Effects of prestressing force

To check the effects of the anchors' prestressing force, different combinatorial forces were studied according to the values in Tables 3 and 4.

Table 3. Anchors' prestressing forces (2 rows of anchors)

Number of row	Preloading(ton)				
1	80	80	65	65	50
2	80	65	65	50	50
View	80,80	80,65	65,65	65,50	50,50

Table 4. Anchors' prestressing forces (3 rows of anchors)

Number of row	Preloading(ton)			
1	80	80	80	80
2	80	65	65	50
3	80	65	50	50
View	80,80,80	80,65,65	80,65,50	80,50,50

Regarding the relation between the prestressing force and the condition of the initial slip surface, FIG. 10 shows that it can be maintained with 3 rows of anchors, piles of 90 cm diameter, and a prestressing force of 65 tons (spacing and angle are considered to be constant); with 2 rows, the prestressing force is 80 tons.

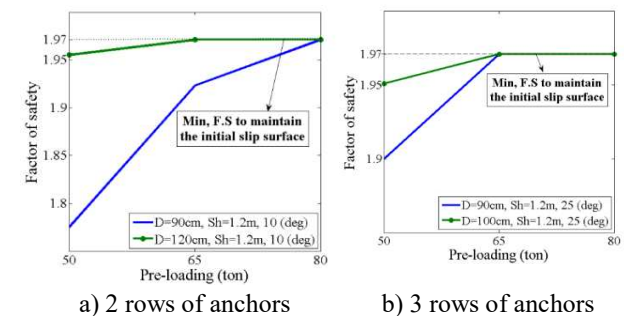


Fig. 10 Effects of prestressing force on the F.S. and the initial slip surface

4.5 Effects of bonded and unbonded lengths

Figure 11 shows that the bonded/unbonded anchor length does not affect the position of the initial slip surface.

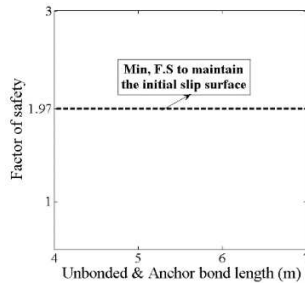


Fig. 11 Effects of bonded/unbonded anchor length on the F.S and the initial slip surface

4.6 Effects of embedded pile length

The embedded pile length, in this research, was found to have no considerable effects on the F.S and the position of the initial slip surface (Figure 12).

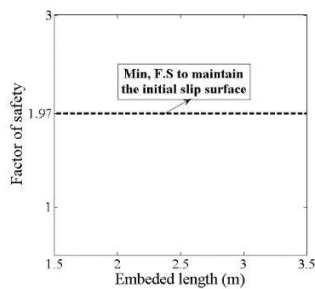


Fig. 12 Effects of the embedded pile length on the F.S and the position of the initial slip surface

Figure 13 shows the effects of pile spacing, pile diameter, anchor prestressing force, and anchor angle on the F.S and the position of the initial slip surface for 3 rows of anchors.

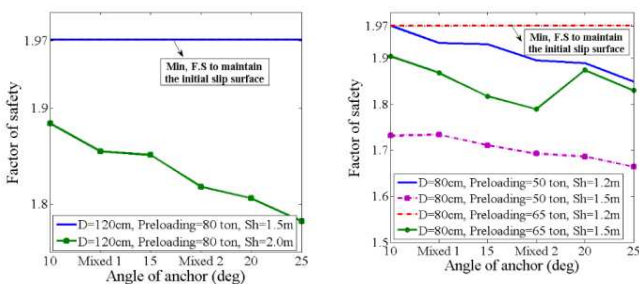


Fig. 13 Effects of pile spacing, pile diameter, anchor prestressing force, and anchor angle on the F.S and the position of the initial slip surface for 3 rows of anchors

As shown, an increase in the anchor angle from 10 to 25° will cause a decrease in the F.S and the position shift of the initial slip surface to lower levels; the use of combinatorial angles is by far better than 20 and 25° angles.

The use of 80cm-diameter piles with prestressing forces of 50 and 65 tons, and horizontal spacing of 1.2 and 1.5 m was also investigated; the position of the initial slip surface will be maintained when only 1.2 m spacing is used for piles. If the prestressing force decreases from 65 to 50 tons, the position of the initial slip surface will be lowered and, in this case, the position will be maintained only when the anchor angle is 10°; if the prestressing force is 65 tons, the position will be maintained for all the angles. If the pile diameter and the prestressing force are increased to 120 cm and 80 tons respectively, the position will be maintained if the horizontal spacing is 1.5 m.

For 2 rows of anchors, if the spacing and the prestressing force are 1.2 m and 65 tons respectively, the position of the initial slip surface will change with an increase in the pile diameter. If the latter is 120 cm, the position will be maintained for all the defined angles, and if it decreases to 100 cm, the position will be maintained for anchor angles of 10, 15, and 20°, and if it decreases to 90 cm, the F.S necessary to maintain the position will not be sufficient (for all the defined angles) and the initial slip surface will shift position to a lower level (FIG. 14).

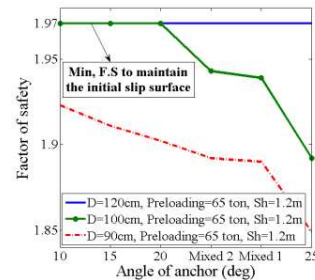


Fig. 14 Effects of pile diameter and anchor angle on the F.S and the position of the initial slip surface

Figure 15a shows (for constant pile diameter of 120 cm and prestressing force of 80 tons) the combined effects of the F.S and the position of the initial slip surface due to changes in the anchor angle and the horizontal pile spacing. Decreasing the pile diameter to 100 cm (other parameters remaining unchanged), the conditions will be more critical (compared to the previous case) if the spacing is increased (FIG. 15-b); the F.S will be reduced and the initial slip surface will shift position to lower levels for all the defined angles.

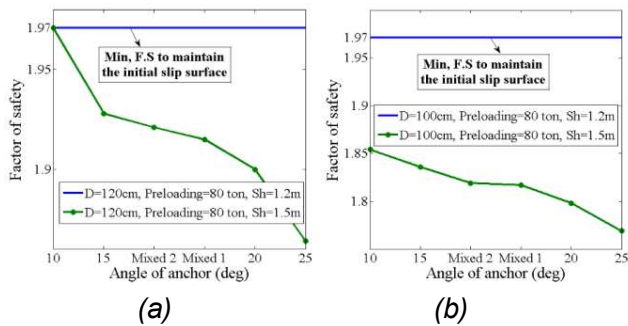


Fig. 15 Effects of anchor angle and horizontal pile spacing on the F.S and position of the initial slip surface

5 CONCLUSIONS

In this case study, we investigated a 23 m deep excavation wall stabilized by soil-nailing and a 7 m deep additional excavation stabilized by a combinatorial system of in-situ concrete piles and anchorage (based on the FEM) using limit equilibrium relations for the stability analyses; results are as follows:

- Effects of the 7 key design parameters (pile diameter, horizontal spacing, embedded length, bonded/unbonded length, anchor prestressing force, anchor angle) on the initial slip surface were studied and the results are as follows:

- It can be stated, considering the condition of the initial slip surface, that for both 2 and 3 rows of anchors, an angle of 10° can be optimal.

- Pile diameter variations affect the position of the initial slip surface; an increase in the pile diameter from 80 to 120 cm (for 3 rows of anchors) or from 90 to 120 cm (for 2 rows of anchors) increases the F.S and maintains the position of the initial slip surface.

- An increase in the anchors' prestressing force from 50 to 80 tons will lead to an increase in the F.S to maintain the position of the initial slip surface.

- An increase in the bonded/unbonded anchor length and the concrete piles' embedded length does not considerably affect the position of the initial slip surface.

- It is worth mentioning that the key design parameters studied in this research are somehow interrelated; a change in any one of them will affect the main conditions governing the design; hence, for an optimum design, use can be made of the graphs of this research to check the combined effects of the parameters that affect the design.

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