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Reinforcing mechanism of anchors in slopes and numerical verification by FEM

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ABSTRACT: The reinforcing mechanism of anchors in slopes is studied. The effects of anchors on the safety factor of a slope are also predicted by 3D elasto-plastic shear strength reduction FEM (SSRFEM). The soil-anchor interaction is simulated with zero-thickness elasto-plastic interface elements. The results are compared with those obtained by Bishop's simplified method, where the anchors are considered only to supply an axial tension. The safety factor of SSRFEM is consistent with that of Bishop's simplified method. SSRFEM shows that the prestressed load has little influence on the safety factor. The better stabilizing effects can be obtained when the anchors are installed with a small angle between the anchor and the horizontal direction.

1 INTRODUCTION

The permanent grouted anchors have been extensively used to provide vertical and lateral support for natural and engineered structures during the past 50 years. The end type of anchorage has been used to stabilize the dangerous slopes, and as a preventive measure in stable slopes because of its significant technical advantages resulting in substantial cost savings and reduced construction period. The basic design concept consists of transferring the resisting tensile forces generated in the anchors into the ground through the friction mobilized at their interfaces. The loads are usually developed by the anchorage of the tendon within the soil mass and tensioning at the surface against a bearing plate or concrete pad. Some of the successful applications of this technique to stabilizing slopes have been reported (Tan et al. 1985, Hashimoto et al. 1986, Corona 1996).

The stability of slopes reinforced with anchors is commonly assessed using LEM, assuming that the anchor only supplies an axial tension to reinforce the slope. In this research, the 3D SSRFEM is used to evaluate the reinforcing mechanism of anchors. The soil-anchor interaction is simulated by zero-thickness 3D interface elements. The results of SSRFEM are compared with those of Bishop's simplified method. The effects of the prestressed load, direction angle on the safety factor of slopes are numerically studied. Some useful conclusions are obtained.

2 ANALYSIS METHODS

2.1 *Limit equilibrium method*

Bishop's simplified method of slip circle analysis is employed to determine the safety factor of slopes reinforced with anchors. The safety factor, F_s, of slopes reinforced with anchors is given by

$$F_{si} = \frac{\sum[cb + W\tan\phi]/m_\alpha + \sum P_{ei}}{\sum W\sin\alpha} \quad (i = 1, 2) \qquad (1)$$

The conventional vertical and novel normal approach is used for $i = 1$ and 2, respectively. P_{ei} is the effective stabilizing force supplied by anchor, and tangential to the base plane of the slice with the anchor located, and is given by

$$P_{e1} = \frac{F_{s1}P[\cos(\alpha+\theta) + \sin(\alpha+\theta)\tan\phi_m]}{1 + \tan\alpha\tan\phi_m} \qquad (2)$$

$$P_{e2} = F_{s2}P\left[\cos(\alpha+\theta) + \frac{\sin(\alpha+\theta)}{1+\tan\alpha\tan\phi_m}\tan\phi_m\right] \qquad (3)$$

where P is an axial resisting force supplied by anchors, θ is the angle between the anchor and the horizontal direction, ϕ_m is the mobilized friction angle on the slip surface.

The simplex reflection technique is used for locating the critical slip circle that has the lowest safety factor of a slope. When the slope is stabilized with the anchors, the critical slip surface is found with the safety factor calculated by Equation 1. Thus a smaller safety factor can be obtained than that considering the effect of the anchors with the original critical slip surface without anchors.

2.2 *Shear strength reduction FEM (SSRFEM)*

SSRFEM has been gradually used to analyze the stability of slope in 2D and 3D situations. The numerical comparison has shown that SSRFEM is a reliable and robust method for assessing the safety factor of slopes and the corresponding critical slip surface. One of the main advantages of SSRFEM is that the safety factor emerges naturally from the analysis without the user having to commit to any particular form of the mechanism *a priori* (Griffiths & Lane 1999). SSRFEM has been successfully used to determine the safety factor of the slopes improved with piles (Cai & Ugai 2000). SSRFEM can evaluate the stability of such slopes under a general frame for slopes, where the soil-structure interaction is considered with zero-thickness interface elements.

The process of SSRFEM to predict the safety factor of a slope reinforced with anchors is simply described here. When the shear strength reduction factor, F, is less than unity, the slope completely consists of the soil. When F reaches unity, the materials of the solid elements within the extent of the anchor are changed from the soil into the tendon or the grouted body according to the position of the elements. The materials of the interface elements are simultaneously changed from the soil-soil interface into the soil-tendon interface or the soil-grout interface. The stress in the interface keeps unchanged when the materials are changed. This implies that the grouting pressure is the same as the normal stress in the interface, induced by the self-weight of soil. When F is unity, a pre-stressed load is applied. The prestressed load includes a drag load, applied at the anchor head, and a push load, applied on a circular rigid plate on the slope surface. The value of the two loads is the same, but their directions are opposite. The rigid plate is simulated by the identical deflections of the nodal points on the slope surface under the rigid plate. After the deflection under the prestressed load is finished, the tendon head is fixed to the rigid plate on the slope surface. Therefore, the deflection of the tendon head is the same as that of the rigid plate during the shear strength reduction from unity to the ultimate value. The detailed process for SSRFEM and properties of the interface element can be seen elsewhere (Cai & Ugai 2000).

3 RESULTS AND DISCUSSIONS

3.1 *Model slope*

An idealized slope with a height of 8m, a gradient of 1V:1H, and a ground thickness of 10m is analyzed with a 3D FE mesh, as shown in Figure 1. The diameters of the tendon and grouted body are 32mm and 90mm, respectively, and their lengths are 6m and 6m, respectively. The soil-tendon interface is assumed to be smooth, and the shear strength to be zero (Table 1). The shear strength of the soil-grout interface is assumed to be the same as the soil. Young's modulus of the grouted body is assumed to

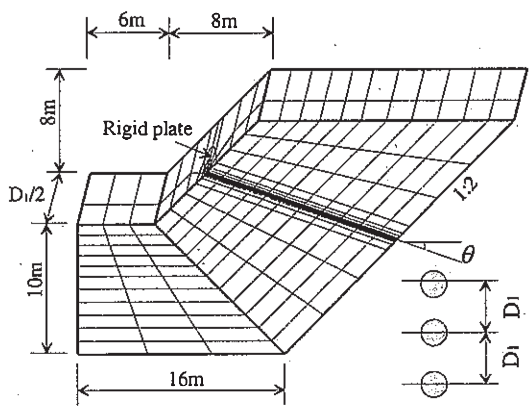

Figure 1. Model slope and schematic FE mesh.

Table 1. Material parameters.

Parameter	Soil	Soil-tendon interface	Soil-grouted body interface	Tendon	Grouted body
Young's modulus, E (MPa)	200	200	200	210000	24000
Poisson's ratio, ν(-)	0.25	0.25	0.25	0.30	0.20
Unit weight, γ(kN/m^3)	20.0				
Cohesion, c (kPa)	12.0	0.01	12.0		
Friction angle, ϕ (°)	20.0	0.0	20.0		
Dilatancy angle, ψ(°)	0.0	0.0	0.0		

be the same as the reinforced concrete. The rigid circular plate on the slope surface is with a diameter of 30cm. The anchors are installed with a horizontal distance between the slope toe and the anchor head, Lx=4m, and a center-to-center spacing, D_1 =1.5m, unless otherwise stated. The material parameters of the soil, soil-tendon interface, soil-grout interface, tendon, and grouted body are shown in Table 1.

When the slope is not reinforced with anchors, SSRFEM gives a safety factor of 1.09, comparing well with 1.084 of Bishop's simplified method. The failure mechanism of SSRFEM, agrees well with the critical slip circle of Bishop's simplified method.

3.2 *Effect of prestressed load*

When the anchors are installed with Lx=4m, $\theta = 15°$, and D_1=1.5m, SSRFEM indicates that the safety factor of the stabilized slope is not influenced by the prestressed load (Table 2). This is because the ultimate axial tension is almost the same for various prestressed loads. Table 2 shows that the safety factor of the stabilized slope, predicted by SSRFEM, is almost the same as that by Bishop's simplified method. The reinforcing effect of anchors can only come from the increase in the shearing resistance along the slip surface in SSRFEM, and then FEM calculation diverges under a larger safety factor. Thus SSRFEM gives a larger safety factor of the slope reinforced with anchors. Therefore, the reinforcing mechanism in SSRFEM is identical to that in Bishop's simplified method. The failure mechanism in SSRFEM is represented using the vectors of the nodal displacement increments induced by the shear strength reduction. The failure mechanism in Bishop's simplified method is shown in Figure 2 by the critical slip circle, which has the lowest safety factor of the slope reinforced with anchors. Figure 2 shows that the failure mechanisms, predicted with SSRFEM and LEM, agree well with each other. The prestressed load is assumed to be zero in the following analyses because it has little influence on the safety factor of a slope.

Figure 3 shows the influence of the prestressed load, P_i, on the axial deflection, cross deflection, initial axial tension, and ultimate axial tension of the anchor at the axial distance, L, from the anchor head. When F=1.00, the axial tension is the initial axial tension, which is induced by the prestressed load. When F=1.21, and reaches the ultimate value, the axial tension is the ultimate axial tension, P_u. The ultimate axial tension includes the two parts, induced by the prestressed load, and by the shear strength reduction from unity to the ultimate value, as shown by the solid line in Figure 3. It is indicated that the

Table 2 Safety factor for various prestressed loads.

Prestressed load P_i (kN)	Safety factor SSRFEM	Safety factor Bishop	Ultimate axial tension P_u (kN)
0	1.21	1.195	59.30
25	1.21	1.196	60.09
35	1.21	1.198	60.75
45	1.21	1.197	60.66

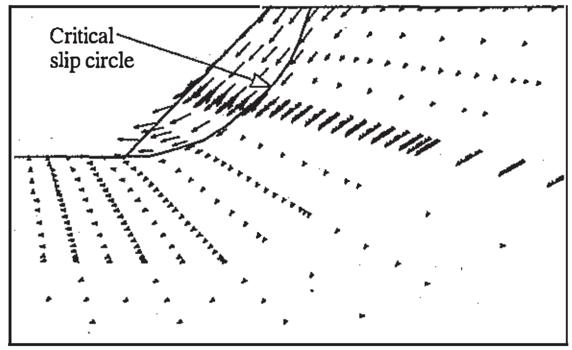

Figure 2. Failure mechanism of slope with anchors.

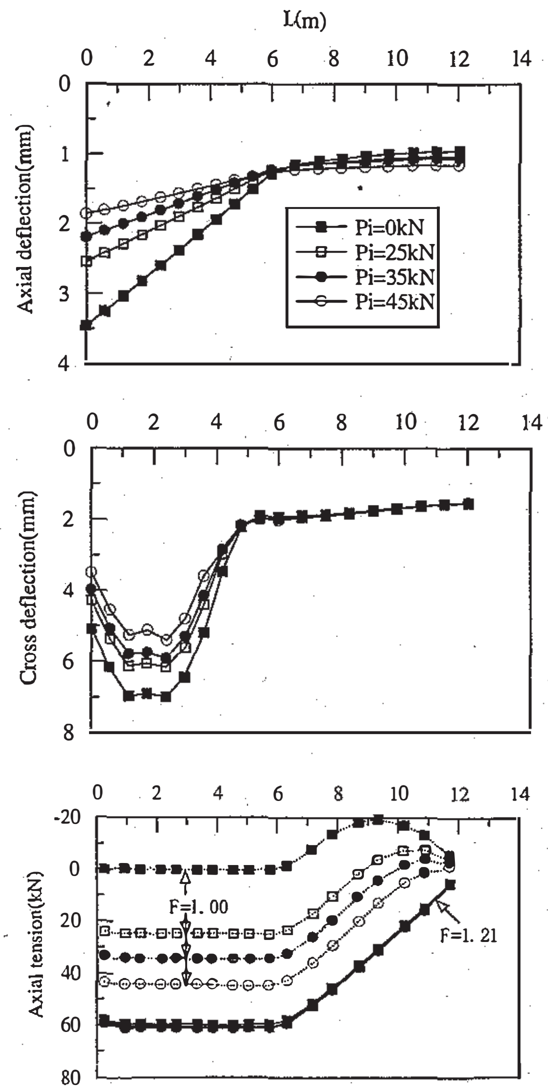

Figure 3. Response of anchor for various prestressed loads.

prestressed load can decrease the axial and cross deflections of the anchor when the slope failure takes place. This implies that the prestressed load can decrease the movement of the slope when the slope failure takes place. The axial tension in the free tendon is the same along its axial direction because of the smooth soil-tendon interfaces. Therefore, the resisting force of the anchor completely comes from the friction between the grouted body and the soil. The distribution of the ultimate axial tension along its axial direction is almost the same for various prestressed loads, although the initial axial tension increases with the increase in the prestressed load.

3.3 *Effect of direction angle*

When the anchors are installed with Lx=4.0m and D_l=1.5m, the direction angle of the anchor has significant influence on the safety factor of the slope reinforced with anchors, as shown in Figure 4. Despite the fact that the relative error between the safety factor of SSRFEM and F_{s1} is smaller than 3%, F_{s2} is better consistent with that of SSRFEM. Figure 4 indicates that there is an optimized direction angle of the anchor for the safety factor of the slope reinforced with anchors. The influence of the direction angle of the anchor on the safety factor comes from its influence on the ultimate axial tension, and the angle between the anchor and the slip surface. For the anchors installed horizontally, the normal stress in the soil-grout interface is smaller because of the smaller vertical soil pressure on the grouted body. The normal stress in the soil-grout interface increases with the direction angle due to the self-weight of soil. The experimental results also indicated that the ultimate reinforcing effects are mobilized under a more shearing displacement for a larger angle between the reinforcement and the sliding surface when the angle is less than 90° (Edirisinghe et al. 1996).

Figure 5 indicates that the direction angle of anchor has influences on the ultimate axial tension, P_u, and on the angle between the anchor and the critical slip surface, $\alpha+\theta$. Such influences can be indicated comprehensively with the effective stabilizing force, as indicated in Figure 5. The larger the direction angle of the anchor, the smaller P_e/P_u, the ratio of the effective stabilizing force to the ultimate axial tension, because the angle, $\alpha+\theta$, increases with the increase in the direction angle of the anchor. Comparing Figures 4 and 5, one knows that the relationship between the safety factors versus direction angle is identical to the relationship between the effective stabilizing forces versus direction angle of the anchor. This suggests that the reinforcing effect of anchors is the increase in the shearing resistance along the slip surface, and completely dependent on the effective stabilizing force under various direction angles of the anchor.

3.4 *Effect of anchor position*

When the anchors are installed with $\theta=15°$ and D_l=1.5m, the influence of the anchor position, Lx, as shown in Figure 1, on the safety factor of a slope stabilized with anchors is shown in Figure 6. The safety factor of SSRFEM is consistent with that of

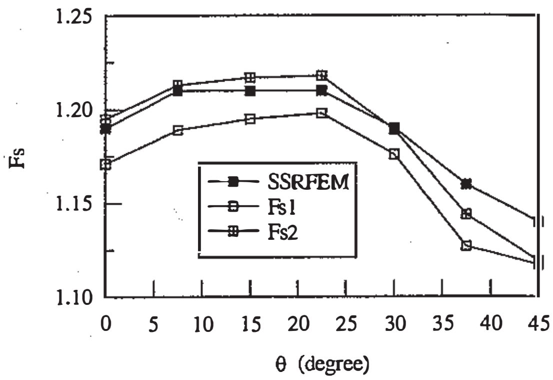

Figure 4. Safety factor vs. direction angle.

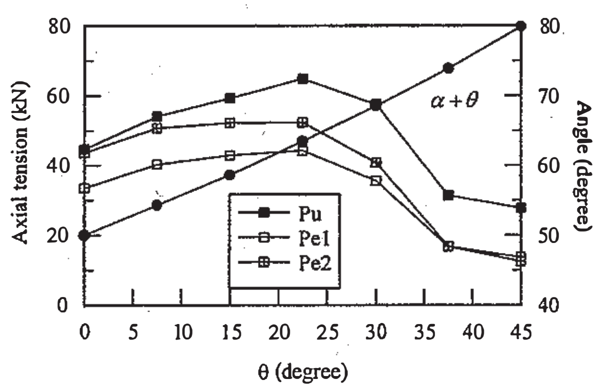

Figure 5. Axial tension and stabilizing force vs. direction angle.

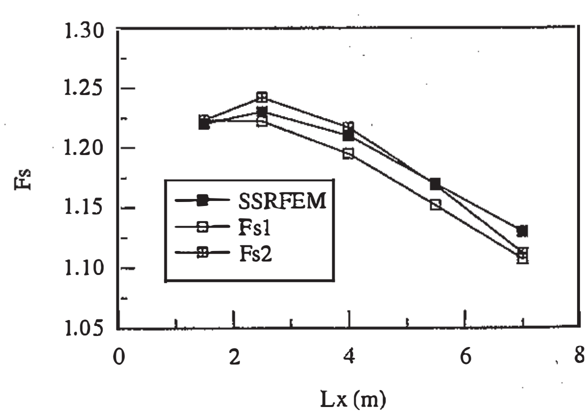

Figure 6. Safety factor vs. anchor position.

LEM, and generally the consistency is better between the safety factor of SSRFEM and F_{s2}. When the position is closer to the top of the slope, the ultimate axial tension in the anchor is smaller, though the shear strength of the soil-anchor interface has been mobilized. The reason lies in that the normal stress in the soil-anchor interface is smaller because of the smaller vertical soil pressure induced by the self-weight of soil. The numerical results of SSRFEM and LEM show that the positions of the anchor have significant influence on the safety factor of the slope even when the ultimate axial tension is the same. For example, the ultimate axial tension of Lx=1.5m is almost the same as that of Lx=5.5m, and the ultimate axial tension of Lx=2.5m is almost identical to that of Lx=4.0m, as shown in Figure 7. However, when the anchors are closer to the toe of the slope, the effective stabilizing force is larger because the angle between the anchor and the slip surface is smaller. Therefore, the safety factor of the slope stabilized with anchors is larger when the anchors are closer to the toe of the slope. Comparing Figures 6 and 7, one knows that the relationship between the safety factors versus direction angle is identical to the relationship between the effective stabilizing forces versus direction angle of the anchor. The results suggest that the reinforcing effect of anchors is the increase in the shearing resistance along the slip surface, and dependent on the effective stabilizing force under various anchor positions.

The ultimate axial tension under Lx=1.5 is smaller than those under Lx=2.5m and Lx=4.0m although the normal stress in the soil-grout interface under Lx=1.5m should be larger than those under Lx=2.5m and Lx=4.0m. This is because the slip surface under Lx=1.5m is significantly different from those under $Lx > 1.5\text{m}$, as shown in Figure 8.

3.5 *Effect of anchor spacing*

When the anchors are installed with Lx=4.0m and $\theta = 15°$, the effect of the spacing between the anchors, D_1, as shown in Figure 1, on the safety factor of the slope stabilized with anchors is shown in Figure 9. It is indicated once again that the safety factor of SSRFEM is better consistent with F_{s2}. The safety factor approximately linearly increases with the anchor spacing becoming smaller and smaller because the ultimate axial tension and the failure mechanism are almost the same regardless of the anchor spacing.

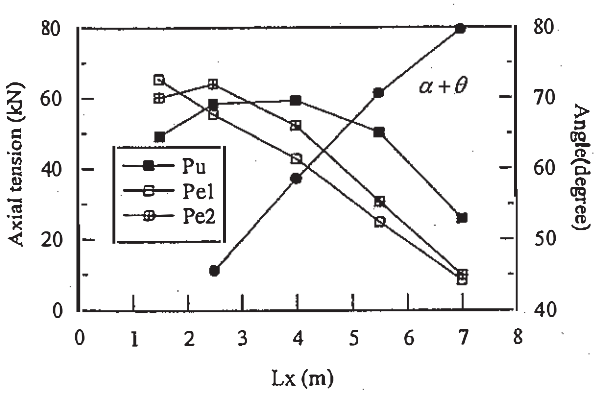

Figure 7. Axial tension and stabilizing force vs. anchor position.

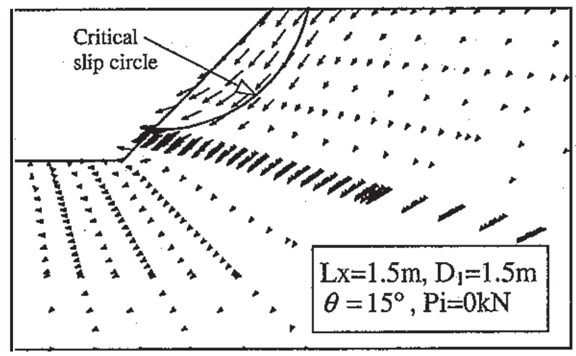

Figure 8. Failure mechanism of slope with anchors.

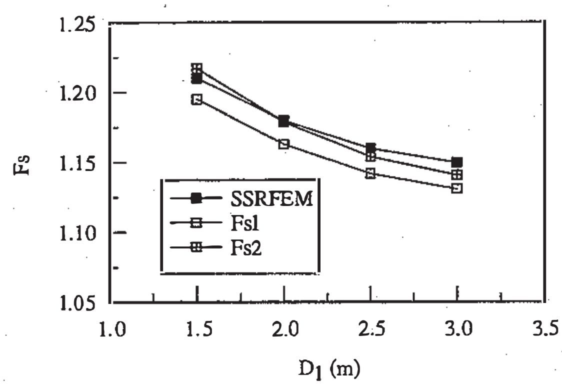

Figure 9. Safety factor vs. anchor spacing.

4 CONCLUSIONS

The reinforcing mechanism of anchors in slopes is analyzed in this research. The 3D SSRFEM is used to evaluate the stability of a slope reinforced with anchors, and to verify the reinforcing mechanisms of anchors in slopes. The soil-anchor interaction is simulated by the 3D zero-thickness elasto-plastic interface elements. The numerical results are compared with those of Bishop's simplified method. Based on the numerical results, the following conclusions are reached:

(1) The reinforcing mechanisms of anchors in slopes are to increase the shearing resistance on the slip surface due to the axial tension.

(2) SSRFEM shows that the prestressed load has little influence on the safety factor though it can decrease the movement of the slope stabilized with anchors when the failure takes place.

(3) The safety factor of the proposed LEM is better consistent with that of SSRFEM. This consistency is independent of the prestressed load, direction angle, position, spacing, and shear strength of the soil-grout interface for the analyzed homogeneous slope.

(4) The better stabilizing effects can be obtained when the anchors are installed with the angle between the anchor and the horizontal direction within the range of 7.5°-22.5° for the analyzed slope, and slightly closer to the slope toe.

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