Analysis on the best position and the pile distance of anti-slide pile of reinforced soil slope

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Abstract. Regarding numerical calculation convergence and plastic zone through the slope as the criterion of slope instability, strength reduction method as calculating principle, the stability of soil slope was analyzed by using finite element software ABAQUS, and on the basis of analysis, the best position and pile distance of anti-slide pile of reinforced soil slope were studied. The numerical results showed that with the increasing of distance between anti-slide pile and toe position, safety coefficient raised firstly and then decreased, when the ratio between the horizontal distance of anti-slide to slope toe and horizontal distance of slope is around 0.6, which is the largest safety factor; The pile spacing had certain influence on the soil slope safety factor, with the different pile spacing, the safety factor was different. With the increase of the pile spacing, the safety factor decreased gradually.

1. Introduction

As to the studies on the anti-slide pile reinforcement slope, many scholars have done efforts for decades, which mainly focused on the aspects of theoretical analysis, numerical simulation scale model experiments and centrifugal experiments to study the effects of lateral soil movements on sliding pile and the interaction between pile and soil, as well as pile stress and deformation. Among them, the numerical simulation method is a convenient method to study the slope stability, especially the finite element method and the finite difference method based on the strength reduction method. Ugai and others have found that the strength reduction method is more stable, compared with the traditional limit equilibrium method, the safety factor and the location of the sliding surface are in good agreement. The calculation accuracy and influence factors of the finite element strength reduction method are studied in detail by Zheng Yingren. Lei Wengjie used finite element method to analyze the pile position of anti-slide piles. Based on the strength reduction method, Deng Jianhui et al. proposed a three-dimensional analysis method for slope stability analysis. Based on a water supply project, Liu Zuoqu et al. analyzed the stability and reinforcement of slope by strength reduction method. Zhang Jinghui et al. used the strength reduction method to analyze the stability of the landslide before and after reinforcement, and evaluated the reinforcement effect.

However, through the literature search, in author’s opinion, the best anti-slide pile position and the most reasonable pile spacing in reinforced soil slope have seldom been studied. Therefore, in this paper the stability of a soil slope were analyzed based on the finite element software ABAQUS by strength reduction method. On the basis of the above analysis, the stability of soil slope reinforced by anti-slide piles were further analyzed, and the most reasonable pile spacing and pile spacing are studied that could supply some reference for the project.
2 Theoretical analysis of strength reduction method

2.1 The principle of strength reduction method

Safety factor refers to the ratio of actual shear strength that soil slope can provide to resist and shear stress generated by the external load stress, when the constant external load keeps its role in slope and the slope reaches a critical state. Strength reduction refers to a reduction of the shear resistance of the soil under the limit condition, which is equivalent to a discount on shear strength. The implementation process: generally, the shear strength index \( c \) and \( \phi \) of soil are firstly reduced which are divided by a reduction factor of \( F \), and then the new \( c', \phi' \) value is obtained, a series of reduction is made according to this method. Secondly, input related parameters after reduction into the finite element software and carry out the calculation of reciprocating, until it reaches the end of the computation criterion, at the moment, the factor \( F \) is the safety factor of the slope stability.

The reduction formula of \( c \) and \( \phi \) is shown below:

\[
c' = \frac{c}{F} \quad (1)
\]
\[
\phi' = \arctan(\tan \phi / F) \quad (2)
\]

In formula: \( c, \phi, c', \phi' \) —cohesion, friction angle, cohesion and friction angle after reduced. \( F \) —reduction factor.

Special attention is paid to that when using of strength reduction method to calculate the stability of the soil slope, the reduction coefficient calculated from the beginning of the \( F \) is less than 1 so as to prevent the soil slope at the beginning of calculation from being destroyed and keep the soil in the elastic state. Compared with the traditional limit equilibrium method, the strength reduction method has many advantages\(^{[1]}\): ①it does not have to assume the position of the sliding surface; ②it can simulate the shape and position of the sliding surface and the dynamic change process; ③based on the nonlinear characteristics of soil, the stress-strain relationship of rock and soil is increased.

2.2. Strength reduction method and instability criterion

There are a lot of constitutive relations in the finite element method, but the elastic-plastic model is the most used one. The reason is that the calculated results are better than the traditional methods. What's more, in the calculation of rock and soil, we pay more attention to the size of the plastic zone of soil, not the relative displacement. Therefore, the elastic-plastic model was used in this calculation\(^{[12]}\), Mohr-Coulomb failure criterion was used as strength criterion, and its function formula\(^{[13]}\) was:

\[
f(I_1, I_2, I_3) = \frac{1}{2} \left[ 3(1 - \sin \phi) \sin \theta + \sqrt{3(3 \sin \phi) \cos \theta} \sqrt{I_2 - I_1 \sin \phi - 3c \cos \phi} = 0 \right] \quad (3)
\]

In formula: \( I_1, I_2, I_3 \) —the first, second and third stress invariants.

There are three main judgement standard for judging the failure of the soil slope to the critical state: ①whether finite element calculation is convergent; ②the displacement changes at the special site; ③whether plastic zone is through. The study of Zhou Yuanfu\(^{[14]}\) and Pei Lijian\(^{[15]}\) showed that the three judgement standards are consistent, so the first and the third article was used as the judgement standard of instability in this calculation model.

3. Example

In this paper, two examples are simulated, and the example one was used to calculate the stability of homogeneous slope. Then, on the basis of the example 1, the anti-slide pile was simulated and the most reasonable pile position and the optimal pile spacing are analyzed with the example 2. It was proved that the ABAQUS software based on the strength reduction method was suitable for the stability analysis of soil slope. The specific dimensions of the model involved in this example and the materials
used in the numerical experiments were shown in Figure 1 and table 1.

**Table 1.** Numerical test parameter.

| Material      | Density/(kg/m³) | Adhesion c/(kpa) | Internal Friction Angle φ(°) | Elastic Modulus E/(Mpa) | Poisson Ratio ν |
|---------------|-----------------|------------------|-----------------------------|------------------------|----------------|
| Soil          | 18×10³          | 15               | 27                          | 90                     | 0.25           |
| Anti-slide    | 22              | —                | —                           | 32000                  | 0.2            |
| Pile          |                 |                  |                             |                        |                |

**Figure1.** Dimension of numerical model(unit: m).

### 3.1. Example1

#### 3.1.1. Parameter selection of model

Two dimensional model was built by using non associated flow rule, the four node plane strain unit (CPE4) and uniform mesh in this calculation example. The model with mesh was as shown in figure 2. The boundary conditions were that the horizontal displacement was restrained on both sides of slope and horizontal and vertical displacement were restrained in the bottom of slope[15].

**Figure2.** Mesh model of example.

#### 3.1.2 Calculation Result Analysis

According to the judgement standard whether the numerical analysis is convergent and plastic zone is through which decides whether the slope was failure or not, the safety factor was 1.09 after several iterations. The safety factor calculated by traditional slice method is 1.06, which is close to the result calculated by numerical analysis. The result showed that the safety factor obtained by ABAQUS is within the allowable range, and it had a good applicability in slope stability analysis.
3.2. Example 2
On the basis of example 1, the reinforcement treatment with anti-slide pile was carried out in example 2. In example 2, the influence of different pile positions and pile spacing on the safety factor is calculated in order to determine the best pile position and pile spacing.

3.2.1. Parameter selection of model. This model was three dimensional calculation model that was built by using the 8 node hexahedron element (C3D8) and uniform mesh with sweep technique. The boundary conditions were that the horizontal displacement on both sides of model, the displacement of three directions in the bottom of the model and the displacement of Y direction in front of and behind the model was restrained.

3.2.2. Analysis of numerical simulation results. In this model, the anti-slide piles are buried in different positions of the slope. The position of toe of slope was as the origin of coordinate and X was defined as horizontal distance from the toe of slope. The maximum horizontal distance D of slope was 11.5m, and the buried position of piles were located at X/D = 0.3, 0.4, 0.5, 0.6 and 0.7.

(1) Analysis of the optimum pile position of anti-slide pile to reinforce soil slope
(1) Influence of different pile positions on the position and shape of sliding surface

(1) The pile is located at X/D = 0.3
(2) The pile is located at X/D = 0.4
(3) The pile is located at X/D = 0.5
(4) The pile is located at X/D = 0.6
The pile is located at X/D = 0.7

Figure 3. Position and shape of sliding surface at different positions of pile.

The results showed that the position of the pile produced some influence on the position and shape of the sliding surface. With the position of the pile changing from the toe to the top of the slope, position and shape of the sliding surface changed. The position of the sliding surface became gradually shallow and the shape of sliding surface changed from non-through to the run-through of plastic zone, then changed to the sliding surface crossing over the top of the pile which led to failure before pile.

When the pile was located at X/D = 0.3, the plastic zone of soil slope does not transfix, but the soil slope of pile top cracked and the crack was large. At the same time, the upper soil slid with extrusion; When the pile was located at X/D = 0.3, the anti-slide pile was bent at the position of the sliding surface due to be sheared. Moreover, the plastic zone was the largest in the middle of the slope, which accords with the law that the plastic zone increases from surface to interior of slope; When the pile was located at X/D = 0.5, the plastic zone of the soil slope reached the maximum, and the transfixion phenomenon occurred. At this time, the pile had a serious instability phenomenon, and the reinforcement effect was less than that of X/D = 0.4, but the safety factor was 1.328 and still met the design requirements; When the pile was located at X/D = 0.6, the plastic zone was small. But at the same time, the position of the sliding surface has changed and was damaged before the pile. When the pile is located at X/D = 0.7, the position and shape of the sliding surface is similar to that of X/D = 0.6. However, the plastic zone became larger, and the transfixion phenomenon happened.

Influence of different pile positions on the safety factor of soil slope

With the calculation model considering the interaction between pile and soil, the anti sliding effect of pile position on the slope safety factor was analyzed. The results were shown in Figure 4 and table 2. The position of pile in table 2 was horizontal distance from pile to toe of slope.

Table 2. Safety factor of soil slope under different pile positions.

| Pile Position/m | 3.45 | 4.6 | 5.75 | 6.9 | 8.05 |
|-----------------|------|-----|------|-----|------|
| Safety Factor/$F_s$ | 1.16 | 1.23 | 1.33 | 1.67 | 1.56 |

Figure 4. Relation curve between pile positions and safety factor.
Figure 4 and table 2 showed that with the changes of pile positions buried in slope, safety factor of soil slope was different, and after the reinforcement with anti-slide pile, safety factor was greater than 1.06, that of the soil slope unreinforced. The results also showed that with the increase of distance from anti-slide pile to toe of slope, safety factor of soil slope increased first and then decreased. Moreover, the safety factor was largest when the distance reached near 6.9m.

Based on the analysis of the influence of pile spacing on the sliding surface position and safety factor, it could be obtained that the best pile position was when the ratio between distance from pile to toe of slope and horizontal distance of slope was 0.6, the reinforced effect of anti-slide pile was best.

(2) Analysis of the optimum pile spacing of anti-slide pile to reinforce soil slope

In order to study the influence of different pile spacing in soil slope on slope stability, take pile position of 6.9m from toe of slope as an example, the stability of soil slope under 4 times of the pile diameter (4D), 6 times of the pile diameter (6D) and 8 times of the pile diameter (8D) was calculated.

① Position and shape of slip surface of soil slope under different pile spacing

![Image](image1.png)

(1) The position and shape of the sliding surface at 4D

![Image](image2.png)

(2) The position and shape of the sliding surface at 6D

![Image](image3.png)

(3) The position and shape of the sliding surface at 8D

**Figure 5.** Position and shape of slip surface of soil slope under different pile spacing.
As can be seen from Figure 5, the pile spacing had some influence on the position and shape of the sliding surface. With the increase of pile spacing, position of sliding surface was gradually close to the unreinforced soil slope, the reinforcement effect weakened. When the pile spacing was 4 times of the pile diameter, the sliding surface damaged with transfixion in front of the pile and the largest plastic zone was located near the top of the pile. When the pile spacing was 6 times of the pile diameter, the pile was bent, sliding zone was extended to the top of the slope, the reinforcement effect weakened. When the pile spacing was 8 times of the pile diameter, phenomenon of secondary sliding of the slope appeared and phenomenon of soil tympanites appeared at pile bottom. At this time, the reinforcement effect was poor and safety factor was similar to unreinforced soil.

2. Safety factor of soil slope under different pile spacing

In order to show the influence of different pile spacing on the safety factor of soil slope, Table 3 and Figure 6 show the safety factor of soil slope under different pile spacing.

| Pile Spacing | 4D | 6D | 8D |
|--------------|----|----|----|
| Safety Factor/ $F_s$ | 1.67 | 1.28 | 1.0 |

Note: D is 0.8m.

Figure 6. Curves of pile spacing and safety factor.

As can be seen in Table 3 and Figure 6, the safety factor was different with different pile spacing. With the pile spacing increasing, the safety factor decreased and presented linear change. When the pile spacing is 8 times of the pile diameter, the safety factor is 1.0, smaller than unreinforced soil. The reason was that the pile spacing is sparse which leads to the pile functioning badly. At the same time, because of the anti-slide pile, the disturbance to the slope soil aggravated the failure of slope. Considering the sliding surface and safety factor under different pile spacing, the optimal pile spacing of anti-slide pile was near 4 times of the pile diameter.

4. Conclusion

1. ABAQUS software has good applicability for calculation of soil slope stability and its accuracy and applicable scope can meet the requirements.

2. The stability of slope reinforced by anti-slide pile is greatly improved. Take distance of 3.45m from anti-slide pile to toe of slope as an example, the safety factor is increased by 6.4%.

3. The pile position of anti-slide pile has some influence on the stability of soil slope. With the increase of distance from anti-slide pile to toe of slope, safety factor of soil slope increased first and then decreased. When the ratio between distance from pile to toe of slope and horizontal distance of slope was 0.6, the safety factor was largest.

4. The pile spacing had some influence on the safety factor of soil slope. The safety factor was different with different pile spacing, and with the pile spacing increasing, the safety factor decreased. It was recommended optimal pile spacing was 0.4D.
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