Analysis of Landslide Displacement and Stress under the Condition of Overturning Failure of Fully Buried Anti-slide Piles

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Abstract. In this paper, on the basis of proving the basic consistency between numerical experiments and on-site physical experiments, a three-dimensional model of push pile FLAC3D was established. Based on relevant engineering analogies, parameters were selected to simulate and analyze the overturning failure mechanism of fully buried anti-slide piles. The research results indicate that the displacement of sand filling in front of the pile is significantly smaller than that of sand filling behind the pile. When approaching the failure load, a large area of uplift phenomenon appears at the top of the sliding body behind the pile; Most of the sand filling above the sliding surface showed a positive displacement along the x-axis, and the maximum displacement occurred at the top of the bulldozer. As the load increases, the sliding and upwelling area behind the pile tends to expand, and the vertical displacement at each point increases to a certain extent. At this time, the pile body is subjected to a "pull-out" effect from the surrounding sand.

Keywords: fully buried anti-slide pile; stress analysis; landslide displacement; overturning failure; numerical simulation.

1. Introduction

The use of anti-slide piles for landslide control began in the 1930s abroad and began in the 1950s domestically[1]. Anti-slide piles transmits landslide thrust through the soil arch effect formed by the force bearing section of the pile and the frictional resistance between the soil behind the pile and both sides of the pile body. Its mechanism is to transfer the landslide thrust from the upper part to the stable rock layer in the lower part through the pile anchoring section, and stabilize the lateral constraints in the rock layer by relying on the anchoring section to balance the external load, thus achieving the goal of landslide control [2].

Anti-slide piles can be divided into three types according to their burial conditions: cantilever type, fully buried type, and embedded type[3]. Compared with cantilever type anti-slide piles, fully buried and embedded anti-slide piles bear less bending moment, consume less materials on the pile body, greatly improve the pile's load-bearing performance, and reduce engineering costs. Therefore, fully buried and embedded anti-slide piles are increasingly being applied. At present, the design of fully buried and embedded anti-slide piles mainly relies on engineering experience and industry standards. However, these experiences and standards use overly simplified calculation assumptions, complex calculation formulas, and arbitrary parameter values. Designers often increase the safety factor based on experience due to unclear working mechanisms of piles and soil. This approach either causes great waste or creates safety hazards[4]. Therefore, it is necessary to focus on the mechanism of the interaction between fully buried anti-slide piles and rock and soil based on previous research.

By comparing and analyzing the indoor model test results and numerical test calculation results of fully buried anti-slide piles, it can be found that[5-6], the calculation results using numerical analysis are in good agreement with the calculation results of indoor model tests.Therefore, on the basis of proving the feasibility of numerical analysis, further in-depth research can be conducted on the overturning failure of anti-slide piles.

2. Establishment of Model Experiments

2.1 Establishing the Grid of Landslide Mass model and Boundary Conditions of the Model

The calculation model for numerical analysis consists of sandy soil, artificially compacted gravel soil, and anti-slide piles. The size selection of the analysis model is based on the suggestions of Zhang Luyu, Zheng Yingren, et al. [7], that is, the distance from the front boundary of the landslide to the foot of the slope is equal to 1.5H (slope height), the distance from the top to the back boundary is equal to 2.5H, and the distance from the top to the bottom boundary is equal to 2H.

This model uses pile structure elements, and after grid division, there are a total of 6345 grid elements, 7520 grid points, 40 structural elements, and 44 structural nodes. After establishing the landslide anti-slide pile model and dividing the grid, it is shown in Figure 1.

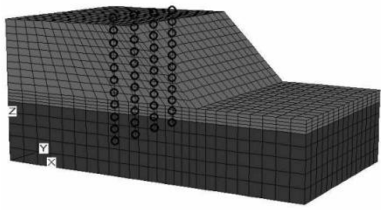


Fig.1 Model of FLAC3D numerical analysis

This numerical simulation constrains the velocity in the z-direction of the boundary nodes at the bottom of the model; Due to the constraints of baffles on both sides of the sand filling, the movement of the sand along the y-direction is limited, so the velocity in the y-direction is limited at the boundaries on both sides of the model; When calculating the initial stress under the action of gravity, the bulldozer plate has the effect of restricting the movement of the upper filling sand along the x-direction, and in addition, there is also a restriction on the movement of crushed stone soil along the x-direction at the forefront of the model pool.

The landslide model is divided into two parts: the landslide body and the sliding bed, with the landslide body being sandy soil and the sliding bed being gravel soil. The main calculation parameters for sand and gravel soil are as follows, as shown in Table 1.

Table 1 Basic parameters of model materials

materials of the model	density （kg/m3）	bulk modulus （MPa）	shear modulus （MPa）	cohesive force （kPa）	internal friction angle （°）
Gravels	2200	13.3	8	10	39
Sand	1600	0.56	0.42	8	15

2.2 Establishment of Pile Structure Units

The pile structure unit needs to be defined through geometric parameters, material parameters, and coupling spring parameters. In addition to providing the structural characteristics of the beam, the pile element also provides mutual friction with the normal and shear directions of the solid element. Essentially, the pile is a combination of the beam and anchor cable, suitable for simulating pile foundations with friction in both normal and axial directions. In order to study the state of the cross-section at each position of the pile body under load, each pile unit is divided into 10 structural units. Therefore, there are a total of 40 structural elements and 44 structural nodes in the four pile units. See Table 2 for calculation parameters of pile unit.

Table 2 The calculation parameters of the pile element

Elastic modulus （GPa）	Dimension (m×m)	Poisson's ratio	xciy (m4)	xciz (m4)	xciz (m4)
32.5	0.1×0.1	0.2	8.3×10-6	8.3×10-6	1.67×10-5

The value of the elastic modulus of the pile unit should be calculated based on the actual reinforcement situation inside the supporting pile and the elastic modulus of the concrete and steel bars respectively. The calculation formula is as follows :

$$E = E_c \times (1 - \rho) + E_s \times \rho \qquad (1)$$

In the formula, E represents the elastic modulus of the reinforced concrete pile, Ec represents the elastic modulus of the concrete selected for the pile, and Es represents the elastic modulus of the steel bars inside the pile. After calculation, the elastic modulus of the pile is 32.5GPa. In the above table, xciy is the quadratic moment of the y-axis of the pile structure, xciz is the quadratic moment of the z-axis of the pile structure, and xcj is the polar moment of inertia of the pile structure.

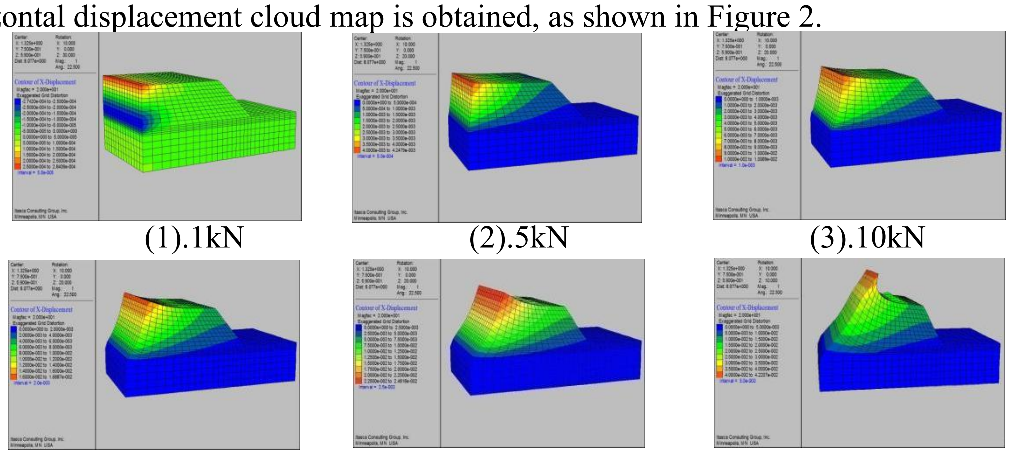
2.3 Establishment of Constitutive Model

FLAC3D has 12 built-in geotechnical constitutive models to meet various engineering analysis needs, including empty models, 3 elastic models, and 8 plastic models. The Mohr Coulomb criterion and Drucker Prager criterion are currently the most widely used yield criteria in geotechnical engineering. The Mohr Coulomb model mainly targets loose or cemented granular materials, such as soil, rock, and concrete. As a universal model of geotechnical mechanics, it is widely used in slope stability and underground excavation engineering. The Drucker Prager model is mainly used for limit analysis and low friction angle soft clay. This experiment used crushed stone soil and sandy soil, using the Mohr Coulomb model.

3. Analysis of landslide displacement

3.1 Horizontal displacement

Under the action of horizontal thrust load, the landslide mainly exhibits displacement and deformation in the horizontal direction. In order to visually observe the deformation trend of the landslide model under various levels of load, the deformed grid diagram is used to represent the deformation results.The magnification factor magf is 20, and a deformation grid diagram displaying the horizontal displacement cloud map is obtained, as shown in Figure 2.



(1).1kN (2).5kN (3).10kN

(4). 15kN (5).20kN (6). 25kN

Fig.2 Deformation grid image of horizontal displacement

The following conclusion can be drawn from Figure 2:

① When the horizontal thrust load is small, the lower part of the landslide body shows displacement in the opposite direction along the x-axis, while the upper part of the landslide body shows displacement along the thrust direction.

② When the thrust is 5kN, most of the sand filling above the sliding surface shows a positive displacement along the x-axis, and the maximum displacement occurs at the top of the bulldozer plate, with the maximum displacement as the center of the circle. As the radius increases, the displacement along the x-axis decreases in the positive direction. In addition, a circular sliding surface with an angle of 20 degrees to the xoy plane appears in the sand filling.

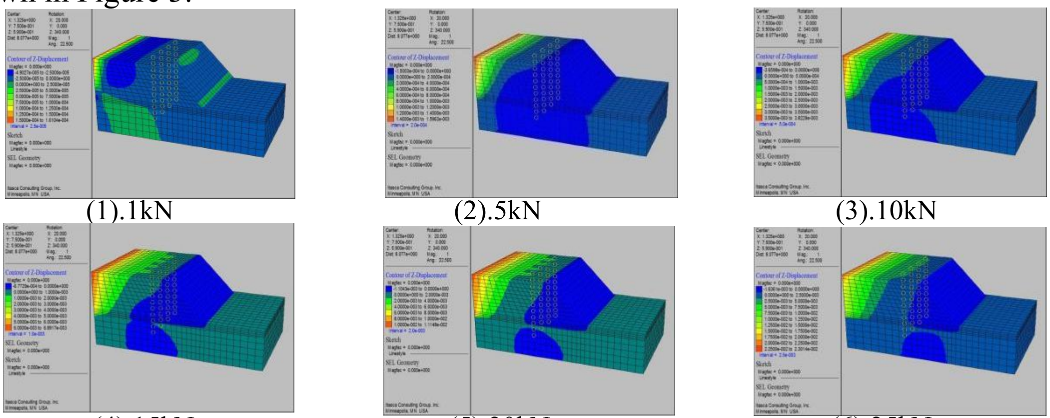
③ As the horizontal thrust load increases, the sand filling behind the pile shows an increasing displacement along the x-axis, and the top of the sand filling in contact with the bulldozer also shows a clear upward trend.

④ The displacement of sand filling in front of the pile is significantly smaller than that of sand filling behind the pile, indicating that the anti slip pile has played a good blocking role.

⑤ As the failure load approached, a large area of uplift appeared on the top of the sliding body behind the pile.

3.2 Vertical displacement

From the above deformation grid diagram, it can be seen that the landslide mass undergoes horizontal displacement while also experiencing varying degrees of vertical displacement at different parts of the landslide. Therefore, the vertical displacement cloud map of the landslide mass was obtained by studying the vertical displacement of the landslide mass under different loads, as shown in Figure 3.



(1).1kN (2).5kN (3).10kN

(4).15kN (5).20kN (6).25kN

Fig.3 Vertical displacement contour of landslide

The following conclusion can be drawn from Figure 3:

①When the thrust load is first applied, due to the small load, except for the sand that is close to the bulldozer plate showing upward displacement, all other parts have a downward movement trend.

② As the load continues to increase, according to the distribution trend of vertical displacement, it can be divided into three areas: the sliding upwelling area behind the pile, the passive upwelling area before the pile, and the settlement area affected by the pile. The passive upwelling zone in front of the pile is a slight upwelling phenomenon in the gravel soil layer caused by the blocking effect of the model pool, under the premise of the overall movement of the landslide towards the thrust direction.

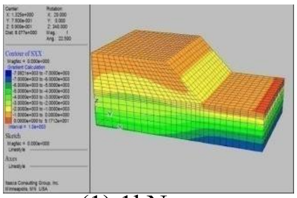
③ As the load increases, the sliding and upwelling area behind the pile tends to expand, and the vertical displacement at each point increases to a certain extent. At this time, the frictional resistance of the sand behind the pile to the vertical upward direction of the pile body is continuously increasing, and the pile body is subjected to a "pull-out" effect of the surrounding sand.

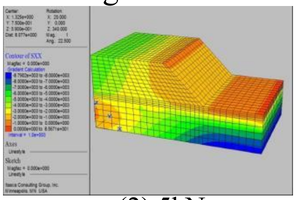
④ When the load reaches 15kN, there is a significant uplift phenomenon on the top surface of the sliding body behind the pile. As the load approaches the failure load, the upwelling area between the pile and the soil between the piles tends to form a whole.

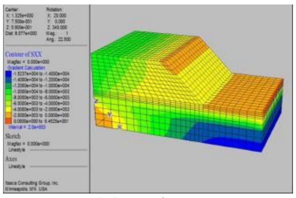
4. Stress analysis of landslide

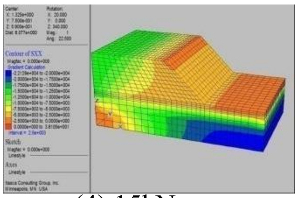
4.1 Stress analysis of sliding direction of landslide

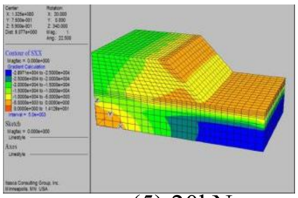
In order to visually observe the changes in soil pressure distribution along the thrust direction of the landslide under horizontal loads, the stress distribution cloud map in the X direction under different loads is obtained, as shown in Figure 4.


(1).1kN


(2).5kN


(3).10kN


(4).15kN


(5).20kN

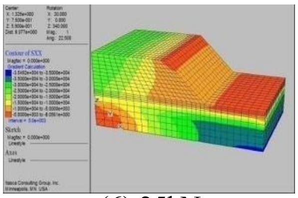

(6).25kN

Fig.4 The stress contour of X direction

From Figure 4, it can be seen that during the loading process, the soil pressure above the sliding surface gradually decreases along the loading direction, with the maximum soil pressure occurring at the bulldozer plate; The soil pressure below the sliding surface is exactly opposite to that on the sliding surface. Due to the frictional thrust of sand filling on the anchoring section of the gravel soil and the blocking effect of the model pool on the gravel soil, the maximum soil pressure appears at the bottom of the gravel soil far from the bulldozer plate; As the load increases, the soil pressure in each region increases to varying degrees, but the magnitude of the increase will vary. The increase in soil pressure in the area before the pile is significantly smaller than that in the area after the pile.

In order to visually observe the effect of anti-slide piles on reducing the soil pressure in the area before the pile under load, two observation points were taken at two locations located in the midpoint plane of the middle two piles, 0.2m away from the surface of the anti slip pile behind the pile and 0.3m deep in front of the pile, respectively. The soil pressure values of the two points behind the pile and in front of the pile under various levels of load were extracted, and Figure 5 was obtained.

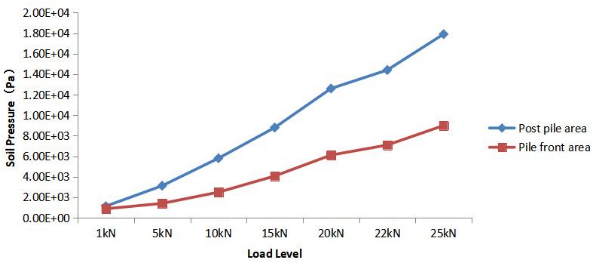
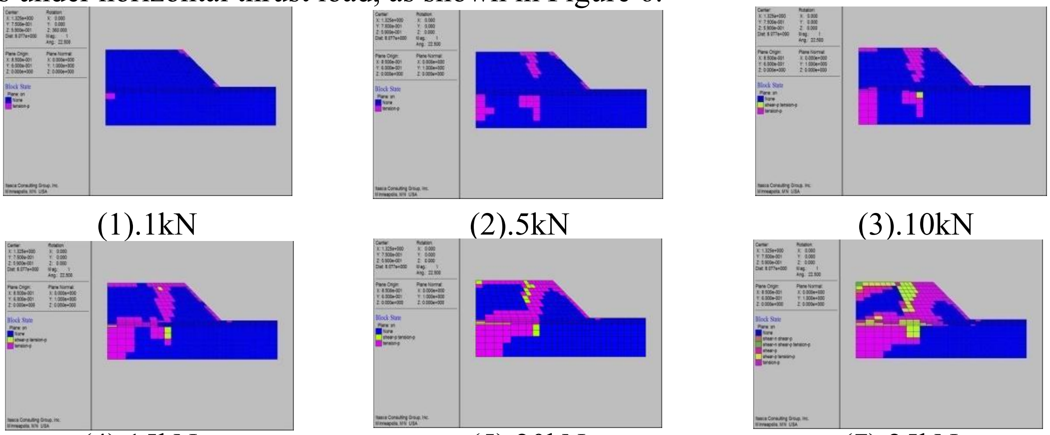


Fig.5 Earth pressure curves in front of and behind piles under different load levels

From Figure 5, it can be seen that due to the blocking effect of the anti slip pile, the increase in soil pressure before and after the pile varies under various levels of thrust loads. The increase in soil pressure after the pile is significantly greater than that before the pile, and the anti slip pile plays a good role in blocking the transmission of thrust loads.

4.2 Development of plastic zone of landslide mass

By displaying the distribution of plastic zones in the landslide mass, the elastic-plastic deformation that occurs during the loading process can be observed. Therefore, a profile parallel to the long side direction is established through the middle pile to obtain the distribution map of plastic zones under horizontal thrust load, as shown in Figure 6.



(1).1kN (2).5kN (3).10kN

(4).15kN (5).20kN (7).25kN

Fig.6 Distributions of plastic zone

From Figure 6, it can be seen that when the load reaches 10kN, tensile and shear yield units begin to appear in the anchoring section of the pile body. As the load increases, the tensile and shear yield units in the upper area of the pile body and the anchoring section increase and connect into one piece. In addition, tensile and shear yield units also appear at the sliding surface near the bulldozer plate. When the load reaches 25kN, the range of tensile and shear yield units at the above multiple locations further increases and there is a trend of connecting into a continuous yield surface, At this point, the anchoring section has lost its restraining effect on the pile.

5. Conclusion

The main analysis was conducted on the displacement changes of the landslide body under the thrust of the landslide, the stress changes along the thrust direction, and the distribution of the plastic zone. Combined with the value of the spacing between anti-slide piles and the influence of landslide rock and soil parameters on the soil arching effect, the following results were achieved:

① The displacement of sand filling in front of the pile is significantly smaller than that of sand filling behind the pile, indicating that the anti slip pile has played a good blocking role. When approaching the failure load, there is a large area of uplift at the top of the sliding body behind the pile; Most of the sand filling above the sliding surface showed a positive displacement along the x-axis, and the maximum displacement occurred at the top of the bulldozer plate, with the maximum displacement as the center of the circle. As the radius increased, the displacement became smaller and smaller. In the sand filling, a circular sliding surface with an angle of 20 degrees to the xoy plane appeared.

② As the load increases, the sliding and upwelling area behind the pile tends to expand, and the vertical displacement at each point increases to a certain extent. At this time, the frictional resistance of the sand behind the pile to the vertical upward direction of the pile body is continuously increasing, and the pile body is subjected to a "pull-out" effect of the surrounding sand.

③ When the failure load is reached, the range of tensile shear yield units further increases and there is a trend of connecting to the yield surface. At this time, the anchoring section has lost its constraint on the pile, and continuous tensile shear yield units appear in the sand before and after the pile.

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