

# **Research** Article

# Influences on Antislide Piles Used for Slope Reinforcement: Numerical Simulation Based on the Soil Arching Effect

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This study explores the pile-soil interaction mechanism and the optimal use of antislide piles for slope reinforcement based on finite difference numerical modelling. The force and displacement principles of slopes and antislide piles are analysed. The influences of various factors are investigated, such as postpile filling parameters, pile embedding methods, and pile cross-sectional shapes. Numerical modelling is used to determine the optimal layouts of antislide piles for push and traction landslides. The findings indicate that the cohesive force of the fill has a greater influence on the piles and slope than the friction angle and is the primary control factor. Fully buried antislide piles provide a better antisliding effect than semiburied ones. With fully buried piles, the best controlling effect is obtained when the ratio of the length of the pile's free section to the height of the sliding body is approximately 4/5. Moreover, stepped-cross-section piles provide better slope reinforcement than those with rectangular, *T*-shaped, or trapezoidal cross-sections. In practical applications, end-bearing arches can be utilized as the primary control structures, with friction arches used for secondary control to improve the soil arching effect as much as possible, thereby enhancing the stability of the piles and slope. To control landslides of various thrust forms, antislide piles should be set in the active section, the core sliding section, or both, as required. This paper provides guidance for improving the design of antislide piles.

# 1. Introduction

China has a vast territory with diverse geomorphological topographies and extensive mountainous areas. With the increasing coverage of the national road network and other infrastructures, it is imperative to construct road networks among complex landforms such as mountains. In this geological environment, high and steep slopes present a challenge to the safety and economic costs of road construction and operation [1]. Therefore, devising ways to reinforce high and steep slopes has important engineering significance.

Antislide piles have a strong antisliding ability and flexible positioning and are a targeted and cost-effective reinforcement method used in high, steep slope protection projects. To optimize their layout, there has been a considerable research on their influencing factors, such as pile spacing, soil properties, and anchor cable prestress parameters. For instance, Jiang et al. and Li et al. employed numerical simulation to analyze the stress and deformation of antislide piles with prestressed anchor cables. They found that the point of maximum stress and displacement is in the upper part of the pile initially and gradually moves downward as the anchor cable prestress increases [2, 3]. Chu and Wang [4] extended the prestressed anchor cable antislide pile-slope model and demonstrated that when the anchor cable tension coefficient is in the range of 0.22–0.42, the pile body bears the optimal force and the slope is more stable. This broke through the limitation of designing anchor piles based only on the form of landslide thrust distribution [5]. Zhang [6] indicated that there is an optimal anchorage depth for restraining the deformation of antislide piles.

In terms of pile spacing, Xin [7] and Hou [8] reported that as the pile spacing increases, there is a soil arching effect that increases and then decreases. At a pile spacing equal to 2–3.5 times the pile width, the soil arching effect is maximal. Hou et al. also found that as the width of antislide piles increases, the effect of soil arching first increases and then decreases [9]. Lu et al. [10] and Shen et al. [11] investigated the relationship between the spacing of double-row piles and the soil arching effect finding that when the row spacing is more than four times the pile width, soil arching between the piles disappears. The soil arching effect is greatest at a row spacing of 2.0–2.5 times the pile diameter.

For soil properties, Liu et al. [12] and Han et al. [13] determined the influences of soil cohesion, Poisson's ratio, and other mechanical parameters on soil arching. Also, they demonstrated that soil cohesion and Poisson's ratio are proportional and inversely proportional to the soil arching effect, respectively, while other soil mechanical parameters have no obvious impact. Wang et al. [14] built an antislide pile-slope particle-flow model by varying the soil particle parameters. This clarified the force transmission mechanism of anchor cable-pile systems under pile-soil interaction.

Yi et al. [15] designed an antislide pile section from a mechanical perspective by reducing the tensile zone and increasing the compression zone, which enhanced the bending resistance of antislide piles to a certain extent. Pile stiffness and flexural bearing capacity alter the interaction mechanism between piles and soil and enhance the soil arching effect. Zhu [16] proved that the antisliding effect of a rectangular-cross-section antislide pile is better than that of one with a circular cross-section and that the diameter of the circular cross-section has almost no effect on the antislide effect. Zhu et al. found that *T*-shaped piles provide a greater bending stiffness, more uniform stress on the pile body, and better antisliding effect than rectangular piles [17].

Abroad, there are also many experts to carry out relevant research. For example, Wang and Sassa conclude the characteristics of landslide movement and dribs flows [18]. The essence of landslide stability is that the push load is transferred to the antislide pile, which forms the soil arching effect [19-22]. Some papers reveal the essence of shear resistance of antislide piles: the shearing resistance acts to keep the yielding mass on its original position by reducing the pressure on the yielding part and increasing the pressure on the contacting stationary part [23-26]. Some factors influencing the control effect of antislide pile are studied in some paper: antislide piles reinforce the slope through soil arching effect, which depends on soil properties, pile-spacing-todiameter ratio, and relative movement between the soil and the pile [27, 28]. Uzuoka et al. used different kinds of numerical simulation method to study the response regularity of the antisliding pile under the case of slope horizontal movement [29]. Kanagasabai et al. established multi-threedimensional numerical models to study the control effect of antislide pile on the slope [30].

From the previously mentioned review, it can be seen that the current research on antislide piles with anchor cables has mostly focused on single influencing factors. Hence, it has failed to fully grasp the pile-soil mechanism so that antislide piles can be optimally designed. Further effective economic and engineering guidance is, therefore, needed. This paper uses the numerical simulation software FLAC3D to investigate the factors affecting the effectiveness of antislide piles and their responses to the main control parameters, which include the *c* and  $\phi$  values of the filler behind the pile and the pile embedding method, cross-sectional shape, and layout under two types of thrust. Thus, we reveal the mechanism of pile-soil interaction for the optimisation of slope reinforcement plans.

#### 2. Construction of an Antislide Pile-Slope Model

2.1. Numerical Model of a Slope without Antislide Piles. A numerical model of a slope was created based on the actual size of the slope's rock and soil (Figure 1). This constitutive model adopts the Moore-Coulomb model. The mechanical parameters of bedrock, slippery body, and contact surface between the landslide body, bedrock, and antislide piles are shown in Tables 1 and 2, respectively [16, 31]. The sliding surface (surfaces 1, 2, and 3) and underside of the landslide are free, and the rest of the landslide side surfaces are fixed. Four sides and undersides of bed rock are fixed. To verify whether the initial slope is stable, the maximum sliding position of the model under gravity exceeds 10 m without any reinforcement measures; a displacement cloud is shown in Figure 2. Therefore, slope reinforcement is very necessary in this situation.

2.2. Initial Antislide Pile Design. The initial antislide pile was designed following reference [32]. The constitutive model of slip mass and bed rock adopt the Moore-Coulomb model. The constitutive model of the antislide piles adopt elastic model. The sliding surface (surfaces 1, 2, and 3) and the underside of the landslide are free, and the rest of the landslide side surfaces are fixed. Four sides and undersides of bed rock are fixed. The interface between the sliding mass and antislide piles, bed rock, and antislide piles are free. The corresponding physical and mechanical parameters are shown in Table 3 and the pile layout plan is shown in Figure 3. To analyze the pile-soil interaction process in detail, the paper extracted displacement and stress data of 15 points on each pile, as shown in Figure 4.

Cable elements are employed to simulate the mechanical behavior of prestressed anchor cables. The anchor cable arrangement scheme is illustrated in Figure 5. The cross-sectional area of the anchor cable in the slope model is  $5 \times 10^{-2}$  m<sup>2</sup>, the tensile strength is 1960 MPa, the elastic modulus is  $2 \times 10^5$  MPa, the cement slurry stiffness is  $1 \times 10^4$  MPa, and the other parameters of the anchor cables are as shown in Table 4.

# 3. Impact of Postpile Filler on the Antislide Piles' Controlling Effect

This section chiefly investigates the influences of factors such as the cohesive force of the filler behind the pile and angle of



FIGURE 1: Slope model size (unit: m).

Table	1:	Mec	hanical	parameters	of s	slope	rock	and	soi	l.
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Parameter Rock and soil	Internal friction angle $\phi$ (°)	Bulk modulus $\mu$ (MPa)	Shear modulus E (MPa)	Cohesion C (kPa)
Bedrock	37	$2 \times 10^4$	$1.2 \times 10^4$	$1 \times 10^4$
Slippery body	30	30	50	30

TABLE 2: Mechanical parameters of the pile-soil interface.

Parameter Contact surfaces	Tangential stiffness ks (kN/m)	Internal friction angle $\phi$ (°)	Cohesion C (kPa)	Normal stiffness kn (kN/m)
Bedrock, sliding body	$1 \times 10^{7}$		_	$1 \times 10^{7}$
Sliding body, antislide pile	$1 \times 10^{7}$	30	_	$1 \times 10^7$
Bedrock, antislide pile	$1 \times 10^7$	37	$1 \times 10^{3}$	$1 \times 10^{7}$



FIGURE 2: Original slope displacement cloud map (unit: m).

TABLE 3: Physical and mechanical parameters of the antislide piles.

Antislide pile	Pile length (m)	Pile anchorage section (m)	Free section of pile (m)	Pile spacing (m)	Pile cross- section (m <sup>2</sup> )	Bulk modulus (Mpa)	Shear modulus (Mpa)
Parameter	15	5	10	6	$2 \times 2$	$5 \times 10^3$	$5 \times 10^3$



FIGURE 3: Layout of antislide.

internal friction on the antisliding effect of the antisliding pile and reveals its response law. On the basis of summarizing the response law of various influencing factors, this paper analysed the primary and secondary controlling factors of the mechanical parameters of the filler behind the pile. And these mechanical parameters of the filler behind the pile can affect the antislide effect of the antislide pile.

*3.1. Cohesion.* After setting up the pile, the filler was set to have cohesive forces of 10, 15, 18, 20, 25, 30, 60, and 100 kPa. As shown in Figure 6, at a cohesive force c of 10 kPa, the displacement between the sliding body and antislide pile is large, the slope is still unstable, and the reinforcement effect of the antislide piles is poor. The pile displacement and z-direction stress curves are as shown in Figures 7 and 8 for c = 15, 18, 20, 25, 30, 60, and 100 kPa.

Figure 7 indicates that the displacement of the pile body decreases with increases in the cohesive force of the filler. The displacement of the pile body is 33% lower when c = 100 kPa compared with when c = 15 kPa. We used the *z*-direction stress of the pile to characterize its bending moment. Figure 8 shows that the pile body's *z*-direction stress variation is consistent with its displacement evolution principle. In particular, the anchoring position of the anchor cable and the bending moment at the top of the pile body's anchoring section diminishes considerably with increases in cohesion. This suggests that the bending moment of the dangerous section of the antislide pile decreases as the pile body force increases.



FIGURE 4: Anchorage section of antislide piles and location of monitoring points.

3.2. Internal Friction Angle. Based on the previously mentioned conclusions, the filler cohesion was set to 30 kPa and the friction angles were varied from  $15^{\circ}$  to  $50^{\circ}$  in  $5^{\circ}$  steps. As shown in Figure 9, at a friction angle of  $15^{\circ}$ , the landslide is broken. As the friction angle of the fill rises, the maximum displacements at the middle and top of the antislide pile gradually decrease (Figure 10). As the friction angle gradually increases from  $20^{\circ}$  to  $25^{\circ}$ , the rate of decrease in displacement at the top of the pile is perceptibly greater compared with when the friction angle increases from  $25^{\circ}$  to  $50^{\circ}$ . This is because, in the process of increasing the friction angle to  $25^{\circ}$ , the soil arch progressively becomes stable, and the soil arching effect becomes stronger. More sliding force is transmitted to the entire pile-anchor system through the soil arch, which makes the pile-anchor



FIGURE 5: Anchor cable layout diagram.

TABLE 4: Anchor cable parameter table.

Anchor rope	Anchor rope Total length (m)	Free segment length (m)	Anchor section length (m)	Anchor rope inclination (°)	Layout position away from pile top	Prestress (kN)
1	17	12.5	4.5	15	2/15 pile length	800



FIGURE 6: Displacement cloud diagram of the model with a 10 kPa cohesive force of the filler behind the pile (unit: m).

system more reasonable and decreases the displacement at the pile top. The change in the middle of the pile is small because the pile displacement is primarily limited by the anchor cable and anchor section, while soil arching has little effect.

Figure 11 shows that, with the fill friction angle increasing, the z-direction stress of the pile body slowly increases. It occurs at a fill friction angle of 50°. The other fill friction angles correspond with small changes in stress.



FIGURE 7: Pile displacement curve for backfills with various cohesive strength.



FIGURE 8: Pile z-direction stress curves for backfills with various cohesive strengths.



FIGURE 9: 15° friction angle displacement cloud diagram.

While the angle of  $50^{\circ}$  is interesting for theoretical research, in actual engineering, such working conditions are rare. Thus, the filler friction angle can be considered to have little effect on the bending moment of the pile.

In Figures 7 and 10, as the cohesive force of the filler increases from 15 kPa to 60 kPa, the maximum displacement of the antislide pile is reduced by approximately 6 mm, and the maximum z-direction stress is abridged by about 900 kPa. It can be seen from Figures 8 and 11 that if the internal friction angle increases from 20° to 40°, the maximum pile displacement decreases by only about 3 mm, and the maximum z-direction stress is lowered by about 600 kPa. From the previously mentioned analysis, it can be seen that,



FIGURE 10: Pile body displacement variation at different fill friction angles.



FIGURE 11: Variations in pile z-direction stress at various fill friction angles.

at typical values of fill cohesion and internal friction angle, the cohesion has a greater influence on the displacement and bending moment of an antisliding pile than the friction angle. Consequently, the fill cohesion should be considered the chief control parameter in actual engineering.

# 4. Impact of Antislide Pile Embedding Method on Its Controlling Effect

By comparing the advantages and disadvantages of fully buried and semiburied antislide piles in slope strengthening, fully buried piles were selected to determine the relationship between the embedding method and slope control effect. This section improves the free section of a fully buried antislide pile and establishes ratios of free section length (l) to sliding body height (h) as 2/5, 3/5, 4/5, and 5/5. The threedimensional numerical model is partially shown in Figure 12.

Figure 13 shows that when l/h = 2/5, the landslide is in instability and the antislide pile design is unreasonable. Figures 14–16 show that the fully buried embedding method (l/h = 1) with a given pile length has greater concentrated displacement, shear stress, and *z*-direction stress than the semiburied pile, and the maximum displacement is about 7 mm lower. For completely buried antislide piles, as the length of the pile increases, the pile displacement, shear stress, and *z*-direction stress first decrease and then increase. This means that the fully buried antislide pile is not as long as possible, but there is an optimal pile length.

The reason is that the soil in front of a fully buried antislide pile can stop it sliding to a certain extent, so the free section has a certain anchoring effect. Thus, the force of the pile is more reasonable, and its displacement, shear stress, and z-direction stress are smaller. Besides, if the body of a fully buried antislide pile is too short, it will not be able to bear the thrust of a landslide and may even be damaged. If the pile body is too long, the sliding force on the pile body will increase since the free section is too long and the soil in front of the pile cannot exert its full antisliding effect, which will cause the pile shear stress and bending moment to increase, thereby increasing pile displacement. Therefore, a reasonable setting of the *l/h* ratio of fully buried antislide piles used in a slope reinforcement project not only increases slope stability but also reduces project costs. From the previously mentioned results, we suggest that the ratio of the optimal free section length of the antislide pile to the height of the sliding body should be about 4/5.

### 5. Influence of Antislide Pile Embedding Method on Its Slope Control Effect

Commonly used antislide pile cross-section shapes include rectangular, *T*-shaped, and trapezoidal [33, 34]. This section investigates the effect of a novel step-shaped cross-section that can theoretically form a larger end-bearing arch and friction arch. We modelled the previously mentioned four cross-sectional shapes, all with the same cross-sectional area (Figure 17). The layout of the stepped cross-section in the model is shown in Figure 18, and the calculation results are shown in Figures 19 and 20.

It can be concluded from Figures 19 and 20 that the displacement of the free section of the pile body follows the order of rectangular, *T*-shaped, trapezoidal, and stepped-cross-sections: from the top to the bottom of the pile, the displacement of the pile body increases first, then decreases, and then increases. The maximum pile displacement occurs in the middle at the weak position of the two wings.

Evidently, the displacement of a prestressed anchor cable antislide pile has nothing to do with its cross-sectional shape. The pile displacement is limited by the anchor cable. From the top of the pile anchoring section to the anchor cable position, it first increases and then decreases. The displacement above the cable position gradually increases with height. Based on Table 5, the maximum lateral displacement of the sliding body is significantly affected by the shape of the pile body. The maximum lateral displacement of the slope is 54.8% lower with the stepped-cross-section pile than with the rectangular-cross-section pile.

The rectangular-cross-section pile produces the worst antisliding effect, lowest pile body displacement, worst soil arching effect, and lowest landslide thrust due to soil arching. As a result, the pile displacement is the least and the soil between the piles overflows, so the landslide displacement is the greatest. The sliding body displacement of the T-shaped-section pile is less than that of the rectangular-section pile. The reason is that although the T-shaped section has no friction arch, the endbearing arch on the soil-facing surface is larger than that of the rectangular section, and the soil arching effect is enhanced. This conclusion also indicates that the soil arching effect of the endbearing arch is stronger than that of the friction arch. The endbearing surfaces of the T-shaped, trapezoidal, and stepped cross-sections are equal, and the pile-side friction surface increases successively, while the pile body and landslide body displacements show gradual decreases. This is because a stronger pile body friction arch bears more force. Under greater landslide thrust, part of the sliding force on the end-bearing arch is shared, the pile body is more rational, and the interception effect on the sliding body is more obvious. This reduces both pile displacement and movement of the sliding body.

To sum up, pile bodies with different cross-sectional shapes cause different forms of soil arching, which, in turn, affect the displacements of the pile body and sliding body. Thus, to enhance the stability of piles and slopes in actual projects, end-bearing arches should be applied as the primary form of control, with friction arches for secondary control of the soil arching effect.

# 6. Best Positions for Antislide Piles to Control Landslides of Various Thrusts

According to their thrust form, landslides can be categorized as push landslides and traction landslides [35]. To establish the optimal antislide pile positions for controlling push landslides and traction landslides, this section constructs three-dimensional numerical models of four layouts of fully buried antislide piles as an example. The specific pile positions are shown in Figures 21 and 22. To enhance calculation efficiency, the size of the model is scaled down. The length of the model along the route is 4.5 m. The remaining dimensions are shown in Figures 21 and 22. The design dimensions of the antislide piles are shown in Table 6.

Research has demonstrated that the maximum stress in an ordinary antislide pile body occurs at the top of the anchoring section. The maximum displacement occurs at the top of the pile and decreases from there to the top of the anchoring section [4]. Thus, this section mostly investigates stress and displacement at the top of the anchor section and the top of the pile.



FIGURE 12: Three-dimensional numerical models of fully buried antislide piles with different l/h ratios. (a) l/h = 2/5. (b) l/h = 1.



FIGURE 13: Numerical model cloud diagram at various l/h ratios.

6.1. Optimal Layout of Antislide Piles for Controlling a Push Landslide. Table 7 shows that when antislide piles are set at two of the pile positions, the z-direction and shear stresses of the piles are greater, while the reinforced slope displacement is smaller than that when the piles are set at position 1. This is because when the piles are set at position 1, the soil in the antislide section in front of the piles shares part of the sliding force, leading to a reduction in the force on piles. The slope of the section is far away, and the consequence of strengthening the sliding section is poor, causing a large maximum displacement of the landslide. In contrast to position 2, when piles are installed at position 4, the stresses in all directions are lower and the maximum displacement point moves down to the chief sliding section. If piles are mounted to strengthen the sliding body at position 3, the slope displacement is the smallest. At position 3, the sliding thrust is sensibly distributed by the piles and the antislide section. The previously mentioned findings indicate that piles have the greatest reinforcement effect when installed in the middle part of the primary sliding section of a push landslide.

6.2. Optimal Antislide Pile Layout for Controlling a Traction Landslide. It can be seen from Table 8 that when the antislide piles are set at position 1, the maximum displacement of the slope occurs in the middle of the main slide



FIGURE 14: Pile displacement curves when l/h = 2/5 at different l/h ratios.



FIGURE 15: Pile shear-stress curves at various l/h ratios.

body. If the antislide piles are installed at Positions 2, 3, and 4, the greatest displacement of the slope body occurs in the lower part of the active section. This is because installing piles at Positions 2, 3, and 4 only provides indirect reinforcement, which decreases the overall sliding force but does not directly reinforce the active section. Hence, the sliding body of the active section can slide as it is not reinforced. Relative to the maximum displacements of all sliding bodies shown in Table 8, it can be concluded that when the piles are

set at position 2, the sliding body displacement of the slope is the lowest, suggesting that piles at the foot of the primary sliding section provide the best slope reinforcement. The previously mentioned outcomes demonstrate that there are two approaches to mitigating traction landslides: (1) burying antislide piles with prestressed anchor cables at the slope toe of the active section and (2) installing antislide piles in the main sliding section and active section to reinforce the slope in blocks.



----- Buried antislide pilel/h = 1

FIGURE 16: Pile z-direction stress variations at different l/h ratios.



FIGURE 17: Four pile cross-sectional shapes and sizes.



FIGURE 18: Layout of stepped-cross- section antislide piles.



FIGURE 19: Displacement cloud diagram of the free section of an antislide pile.



FIGURE 20: Displacement curve of the free section of an antislide pile.

TABLE 5: Maximum lateral displacement of a slope reinforced by antislide piles with different cross-sectional shapes.

Cross-sectional shape	Rectangular	T-shaped	Trapezoidal	Stepped
Maximum lateral displacement of landslide body (mm)	102.35	65.01	58.96	46.26



FIGURE 21: Schematic of the push landslide model with pile layout.



FIGURE 22: Schematic of the traction landslide model with pile layout.

TABLE 6: Design dimensions of antislide piles used in the model.

Antislide pile parameters	Pile length (m)	Free section length (m)	Embedding depth (m)	Pile spacing (m)
Size	3.5	2.5	1	1.5

TABLE 7: Maximum forces and sliding body displacements with piles installed at different positions to control a push landslide.

Pile position	Maximum shear stress on pile (kPa)	Maximum <i>z</i> -direction stress on pile (kPa)	Maximum displacement of pile (mm)	Maximum displacement of sliding body (mm)	Location of maximum displacement of the sliding body
1	257	1583	22.1	112	Upper part of main slide
2	277	1664	23.6	57.8	Active section toe
3	382	1371	19.1	16.9	Lower part of active section
4	284	1007	11.4	34.7	Lower part of main slide

TABLE 8: Maximum pile forces and sliding body displacements with piles installed at different positions to control a traction landslide.

Pile position	Maximum shear stress on pile (kPa)	Maximum <i>z</i> -direction stress on pile (kPa)	Maximum displacement of pile (mm)	Maximum displacement of sliding body (mm)	Location of maximum displacement of the sliding body
1	869	3542	51.3	91.1	Middle of main slide
2	614	2336	31.5	41.2	Lower part of active section
3	412	1668	20.8	77.2	Lower part of active section
4	297	1082	12.1	122	Lower part of active section

### 7. Discussions

It can be seen that current research on antislide piles with anchor cables has mostly focused on single influencing factors. Hence, it has failed to fully grasp the pile-soil mechanism so that antislide piles can be optimally designed. This paper uses the numerical simulation software FLAC3D to investigate the factors affecting the effectiveness of antislide piles and their responses to the main control parameters. In addition, we also investigated the following aspects.

7.1. Simulation Study of the Influences on Antislide Piles Used for Slope Strengthening. A self-designed antislide pile anchoring mechanism model was used to investigate the soil arch effect. The influences of various parameters on the soil arch effect and antislide pile bodies were studied to reveal the antislide piles' mechanical characteristics and reinforcement mechanism. Figure 23 shows a schematic diagram of the soil arching effect test. 7.2. Numerical Simulation of Factors Influencing the Soil Arching Effect of Antislide Piles in a Slope. The PFC software was used to establish a particle-flow calculation model. We further analysed the soil arching effect and forces on the pile bodies. For single-row antislide piles, changes in cross-sectional shape and surface roughness were investigated to determine the relationship between the soil arching form and the soil stress between the piles. For double-row piles, we varied the pile row spacing, layout, and soil stress between piles to reveal the soil arching mechanism. Figure 24 shows a schematic diagram of the displacement and contact forces of antislide piles as modelled in PFC software.

Thus, we reveal the mechanism of pile-soil interaction for the optimisation of slope reinforcement plans. However, in this paper, the design of antislide piles with prestressed anchor cables was only optimised under the influence of a single variable, and not multiple ones. Thus, the systematic optimisation of these piles need further study.



FIGURE 23: Diagram of soil arching effect test.



FIGURE 24: Diagram of displacement and contact force of antislide pile in PFC.

#### 8. Conclusions

This paper used FLAC3D numerical simulation software to build models of a slope with antislide piles. We investigated the influences on the piles' slope control ability, such as the *c* and  $\phi$  values of the filler behind the piles, and pile embedding type and cross-sectional shape. The ideal pile positions for controlling sliding and traction landslides were determined and the primary findings are summarised as follows.

- (1) With gradual increases in the cohesion and friction angle of the fill, the shear stress, bending moment, and displacement of an antislide pile have correspondingly slow decreases. Relative to the friction angle, the cohesive force of the fill has a greater impact on the controlling effect of an antisliding pile.
- (2) Fully buried antislide piles are more effective for slope reinforcement than semiburied ones, as they exhibit lower bending moments, displacements and shear stresses. When the ratio of the free length of a fully buried pile to the height of the sliding body is close to 4/5, the best control effect is obtained.
- (3) Because of the combined effect of the end-bearing arch and friction arch formed by a stepped-crosssection antislide pile, the shear stress and bending moment of the pile body are minor and the slope reinforcement effect is better compared with other cross-section types. Different cross-sectional shapes produce various forms of soil arching effects. In practical projects, end-bearing arches should be applied as the core controlling structure, and friction arches should be utilized as secondary structures to improve the soil arching effect as much as possible and enhance the stability of the pile and slope.
- (4) To reinforce a slope at risk of a sliding landslide, antislide piles should be installed in the middle of the primary sliding section. At this location, the piles are safer and more stable, and sliding of the slope is minimised. When dealing with traction landslides, one approach is to install antislide piles with prestressed anchor cables at the toe of the active section, and the other method is to arrange antislide piles at the toe of the primary sliding section and the active section to strengthen the slope in two parts.

Consequently, based on numerical simulation, we determined the main control parameters to be the *c* and  $\phi$  values of the filler behind the piles. The effects of the pile embedding method and cross-sectional shape, as well as other factors, were also investigated. This study reveals the mechanism of pile-soil action, providing a significant reference for the optimisation of slope reinforcement schemes in mountainous areas.

#### **Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

#### Disclosure

Guojian Zhang and Sifeng Zhang are the first and second corresponding authors, respectively.

# **Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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