Numerical Simulation Study of the Load Sharing of an Arched Micropile Group in the Tizicao High-Position Landslide, China

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Abstract. This study presents a combined anti-sliding structural system of micropile groups, with an arched shape on the plane and cement paste between the micropiles, in the Tizicao high-position landslide study conducted in the Wenchuan seismic area, China. Improvements in the landslide’s stability as a result of the embedded micropile groups alone and in combination with long prestressed anchor cables are studied using FD-SRM and FOS contour analysis methods, respectively. The soil arching effect and the load sharing of the arched micropile group are analyzed using the numerical simulation method. Findings show that the arching effect is due to arc-shaped arrangements of the micropile groups. The design scheme of the embedded micropile groups improves the stability of this kind of thickly layered, high-position landslide. Moreover, its construction is convenient and the mechanism is clear, making it a good engineering reference for the treatment of similar landslides. The improvement in the landslide’s stability is even better than that achieved by the combination of micropile groups and long prestressed anchor cables. Furthermore, the arching effect of multiple rows of micropile groups is significant and can effectively block the movement of the sliding body. The load transfer involved in the micropile–soil interaction process is a new type of two-part load sharing pattern. The soil arching behind the micropile groups takes more than 80% of the total load. A tangential tension zone appeared along the top of the pile–group arc crown when the arch protruded upward, and a related structural performance design should be considered in the future.

1. Introduction
In recent years, catastrophic, high-position landslides have often occurred in seismically affected areas, such as the Wenchuan area in China. Such landslides often slide suddenly from the ridge crest or high
positions on steep slopes, impact and entrain a large volume of surface materials, and produce high-speed debris avalanches, which are then transformed into debris flows that accumulate and even block the frontal river valley (Yin et al., 2016; Wang et al., 2019). Although this kind of geological disaster appears to be small in scale, its concealment is strong, the risk of failure is great during rainfall events, and the impact force is significant. Thus, the investigation and prevention of these events should be a priority. On June 24, 2017, a catastrophic high-position, long-runout landslide-debris avalanche occurred in Xinmo, Maoxian, Sichuan Province. The initial landslide volume was only 390.6 $\times 10^4$ m$^3$, but the sliding distance exceeded 2.8 km due to the elevation difference of 1200 m between the leading and trailing edges of the landslide. The strong entrainment of the basement during the movement increased the accumulation volume of the debris avalanche, reaching a final volume of 1637.6 $\times 10^4$ m$^3$ (more than four times the original volume). This landslide destroyed Xinmo Village and killed 83 people. Numerous sites of potential high-position landslides are located near the Xinmo landslide. One such site is the Tizicao landslide in Maoxian County, which is only 20 km away (Fig. 1). This landslide is a giant ancient landslide, with a volume of about 1388 $\times 10^4$ m$^3$. It is presently still in a state of reactivation and directly threatens the safety of 113 people in the Shidaguan town government, primary school, and gas station on the other side of the Minjiang River.

The landslide is more than 60 m thick, and part of its front edge has disintegrated, resulting in an unstable state of continuous small-scale collapse. At present, about 60,000 m$^3$ of material from the landslide has fallen into the Minjiang River. Moreover, the front edge is located on a steep bedrock slope with an angle of nearly 70°, which is about 260 m away from the Minjiang River. Controlling this landslide is much more difficult than controlling many others (Fig. 2). At first, anti-sliding piles were considered as one of the most significant measures for controlling this landslide. However, this approach is neither economic nor feasible because the length of the pile would need to be more than 60 m, with an effective length of only about 30 m. Micropiles refer to bored piles formed by pressure grouting after pores are drilled with strong reinforcement. Generally, the diameter is less than 300 mm. Micropile groups are increasingly used in landslide treatment projects, particularly in landslide emergency rescue projects, because of their convenient and rapid construction, flexible pile placement, and small disturbances to landslides. On the basis of this idea, embedded arched micropile groups were proposed to control the Tizicao landslide, with a single pile diameter of 300 mm and an I-steel concrete structure. The column cavity from the top of the pile to the
surface, which was formed through mechanical drilling, was backfilled with mortar, and the pile groups were arranged in an arch pattern on the plane. The cost of embedded arched micropile groups may be about half that of laterally loaded piles.

Figure 2. Tizicao landslide in an unstable state.

The safety factor should be considered first in landslide control. Several methods can be used to evaluate the stability state of a landslide, such as the limit equilibrium method and the strength reduction method (SRM). The SRM of calculating the landslide factor-of-safety (FOS), which has been demonstrated to be convenient and valid for landslides with multiple slip surfaces, was originally proposed by Zienkiewicz (1975) and was extended by Griffiths (1999) and Dawson (1999). It is more often used to analyze slope stability with the rapid developments of finite element (FE), finite difference (FD), and other calculating methods (e.g., Zhao and Zheng, 2002, Ni and Wang, 2016). FE-SRM is recommended for locating potential slip surfaces by reducing the selected strength properties until failure occurs when finding the real slip surface is difficult. It can also be used to simulate the progressive failure and deformation processes of landslides (Eberhardt, 2008; Chen and Huang, 2013).

Cala et al. (2004) proposed a modified shear strength reduction technique for obtaining the location of the next critical slip surface after the identification of the first slip surface. It is useful for the design of complex slope stabilization projects (e.g., benched slopes and slopes with a berm). Cheng et al. (2007) concluded that the ability to calculate multiple minimum states and slip surfaces may be more important than calculating one global minimum stability state when obtaining the FOS by using FE-SRM or FD-SRM and FLAC (commercial finite difference package).

Research on pile–soil interactions has identified the soil arching effect as an important factor that is often considered to be the self-optimizing adjustment of the stress in the soil to resist external forces. The soil arching effect was proposed by Terzaghi (1943), and its transition state was validated by Chevalier et al. (2007). The new concept of the horizontal arching effect, which acts as a locked segment of a landslide, was proposed by Cheng et al. (2004). It is usually composed of two different stress arches, with the maximum principal stress arch protruding upward and the minor one dipping downward. With the fast development of numerical modeling technology, Martin and Chen (2005) and Li and Tang (2013) proposed the load sharing law of anti-sliding piles due to the soil arching effect under the horizontal movement of the slope (Qin and Ni, 2017; Ji and Ni, 2018). They also analyzed the related parameters, such as the pile spacing and shearing parameters, of the sliding mass, and the pile–soil interface. The soil arching effect also exists between adjacent micropiles, which are bored piles formed by pressure grouting after the pores are drilled with strong reinforcement. Generally, their diameters are no more than 300 mm. The soil arching effects are further weakened when the pile spacing gradually increases. Shi and Liang (2013) investigated the load sharing law of a
soil–micropile system and concluded that the back rows also gradually experience the soil arching effect as the ratio of the micropile spacing to the diameter increases. In addition, the best soil arching effect is achieved at a ratio of 7.5.

Therefore, the main purpose of this work is to study the load sharing law of an arched micropile group on the basis of the soil arching effect of the Tizicao high-position landslide in Maoxian County. Our results can be used to effectively improve the FOS value of the landslide by calculating the multiple minimum stability states with the use of SRM. On the basis of the mechanical analysis and numerical modeling conducted using the FD software FLAC$^2$D and FLAC$^3$D, this study provides a scientific basis for the design of an anti-sliding micropile group for high-position landslides.

2. Geological conditions of the Tizicao landslide

![Figure 3. Geologic map of the Tizicao landslide.](image)

The Tizicao landslide is a typical high-position landslide located on the right bank of the Minjiang River in Maoxian County, China. It is located in the west wing of the Daguan arc-shaped tectonic belt (103°40′51.12″, 31°53′14.89″N), where the Shidaguian fault extends along the east–west trending branch ditches on both sides of the Minjiang River, with an occurrence of NE$139°$–$78°$. The Devonian upper Weiguan group (Dwg$^2$) mainly outcrops in the slope area on both sides of the Minjiang River
Valley. It consists of metamorphosed gray-black, gray-yellow carbonaceous phyllite with an occurrence of NE195°–209° ∠71°–78°, and it intersects the slope’s strike at a large angle. This area is located in the middle of the famous South–North Seismic Belt, which has experienced frequent strong earthquakes throughout history. Since the 20th century, it has experienced the 1933 Diexi earthquake (Ms 7.5), the 1976 Songpan–Pingwu earthquake (Ms 7.2), the 2008 Wenchuan earthquake (Mw 7.9), and most recently the 2017 Jiuzhaigou earthquake (Ms 7.0).

The landslide has a circular chair-like shape, i.e., high in the west and low in the east, with a slope direction of 44°–78°. It features a straight-line steep slope with a slope angle of about 70° from the bank of the Minjiang River to an elevation of 2000 m. The terrain is slightly flat between the rear edge of the landslide and has an elevation of 2000 m due to the adjustment of the sliding process and the artificial cultivation with a slope angle of only 20°. However, the terrain continues to exhibit a steeper angle of 45° at the scarp of the landslide (Figs. 3 and 4). The gullies in the slope have large vertical gradients and are usually dry. However, they easily fill with water during rainstorms, creating short-term floods.

Fig. 4 shows that the sliding body is composed of two layers: the loose surface accumulation body and the lower fragmented rock mass identified from the drilling data. The thickness of the loose surface soil is generally 3–10 m, and it mainly consists of gray-yellow silt with gravel and soil. The lower part is a fragmented rock mass composed of gray-black, black carbonaceous phyllite. This stratum is distributed throughout the landslide area with a thickness of 10–50 m. The materials can be interpreted as an early toppling rock mass. The soil slip zone is mainly composed of gray or yellowish-brown silty clay containing gravel and rock fragments, which is in a dense, hard plastic state that is consistent with the upper and lower parent rocks. Visible striations were observed in this area, and the thickness of the soil slip zone is 1.2–3.0 m. Furthermore, the weathering degree of the bedrock is generally lower than that of the sliding body, which is a moderately to weakly weathered rock mass. The cores mainly exhibit a columnar structure, and the maximum length of a single core is about 1.5 m.

**Figure 4.** Geological profile of section I-I’ in the Tizicao landslide.

### 3. Numerical simulation comparison of the design schemes

Two schemes are proposed In accordance with the above described design idea. The first is the use of embedded arched micropile groups alone. The second is the use of embedded arched micropile groups combined with long cables, in which the upper part of the landslide is stabilized by cables, and the arched micropile groups are installed in the middle and lower parts. A numerical simulation comparison of these two designs was conducted as follows.

#### 3.1. Numerical computation method for multiple slip surfaces
Most of the implemented landslide stability procedures are based on 2D cross sections. A 2D cross-section of the Tizicao landslide was directly input into the FLAC\textsuperscript{2D} code, where the SRM is often presented as the following formulas:

\begin{align}
C' = C / F & \quad (1) \\
\tan \phi' = \tan \phi / F & \quad (2)
\end{align}

where $C$ and $\phi$ are the original cohesion and friction angle of the rock mass, respectively, and $C'$ and $\phi'$ are the new cohesion and friction angle, respectively. $F$ is the reduction coefficient, and if the given critical condition is reached, then the corresponding $F$ is called the minimum FOS. In addition, by setting the limiting velocity threshold and monitoring the velocities, the FLAC\textsuperscript{2D} code developed by the Itasca Consulting Group (2011) can draw the regions of unstable grid points by using different strength factors and can produce an FOS contour plot.

The main parameters involved in the model calculation for the embedded arched micropile groups and the sliding soil mass according to the site investigation and laboratory tests conducted on the Tizicao landslide are presented in Table 1. The soil–micropile interface is modeled with a normal stiffness of $1.3 \times 10^6$ kN/m and a shear stiffness of $1.3 \times 10^7$ kN/m. The internal friction of the soil–micropile interface is set as 30°. The soil–cable interface of the anchored section is modeled with a bond stiffness of $6 \times 10^6$ kN/m and bond stress of 2000 kN.

\begin{table}[h]
\centering
\caption{Parameters of the material properties used in the calculation model}
\begin{tabular}{|l|c|c|c|c|c|}
\hline
Material & Deformation modulus & Poisson’s ratio & Unit weight & Cohesion & Internal friction angle \\
(kPa) & & & (kN/m\textsuperscript{3}) & (kPa) & (°) \\
\hline
Slip zone & $1.0 \times 10^4$ & 0.25 & 19.0 & 21.3 & 25.3 \\
Fragmented rock & $1.5 \times 10^4$ & 0.25 & 20.0 & 28.7 & 20.9 \\
Gravel & $4.0 \times 10^4$ & 0.25 & 16.0 & 16.3 & 24.4 \\
Bedrock & $1.1 \times 10^7$ & 0.29 & 27.0 & / & / \\
Micropile & $2.0 \times 10^7$ & 0.2 & 25.0 & / & / \\
Cable* & $2.0 \times 10^8$ & 0.2 & 77.8 & / & / \\
\hline
\end{tabular}
\end{table}

*The prestressed anchor cable with a prestress of 2000 kN.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fos_contour_plot}
\caption{FOS contour plot of cross-section I-I’ in the Tizicao landslide under natural conditions.}
\end{figure}
The FOS contour comparison was also used to analyze the effect of the different design schemes. In Fig. 5, the red area corresponds to FOS = 0.90–0.95, the orange area corresponds to FOS = 0.95–1.00, the yellow area corresponds to FOS = 1.00, the light green area corresponds to FOS = 1.05–1.10, the green area corresponds to FOS = 1.10–1.15, the light blue area corresponds to FOS = 1.15–1.20, and the blue area corresponds to FOS > 1.20. Fig. 5 shows the FOS contours of cross-section I-I’ in the Tizicao landslide under natural conditions. Below Point A*, a significantly unstable area is disintegrating through continuous small-scale collapse events, which is consistent with the placement of the red zone. An orange zone is located between Points C* and A*, a yellow zone is found between Points C* and D*, and a green zone is present between Points D* and E*. This finding indicates that the FOS of the entire landslide is about 1.05–1.10, and the local frontal area falls between 0.90 and 0.95, making it an unstable area.

Fig. 6 shows that the red zone still exists below Point A* after the preventative measures were taken because the embedded micropile groups were installed above Point A* to improve the FOS of the zone above Point A* and the FOS of the entire landslide to more than 1.20. The upper part of the orange zone is located between Points A* and B*, the yellow zone is located close to Point B*, the light green and green zones almost overlap just above Point C*, the light blue zone just reaches Point D*, part of the blue zone extends to Point E*, and the slip zone is located near the embedded micropile groups. We conclude that the overall stability of the landslide improved, and the FOS reached about 1.20.

![Figure 6. FOS contour plot of cross-section I-I’ when only arched micropile groups are employed.](image-url)
Figure 7. FOS contour plot of cross-section I-I’ when arched micropile groups and cables are employed.

Fig. 7 shows the FOS contours after the micropile groups and the long cables were installed. The upper parts of the red, orange, and yellow zones have the same distribution as in Fig. 7. However, the FOS did not significantly improve in the cable-reinforced area, as demonstrated by the fact that the green zone replaced the blue zone between Points D# and E#. Only a small blue zone is found near the slip zone where the micropile groups were installed. This finding also demonstrates that the embedded arched micropile groups have a better reinforcement effect on high-position landslides.

4. Numerical simulation of load sharing pattern
Aside from the reinforcement effect described above, the soil arch effect should also be considered by the numerical simulation method due to the micropile–soil interactions and the arc-shaped arrangements of the micropile groups. The landslide mass is assumed to be an elastic–plastic material, and the coordinates are updated in each step. An isotropic elastic model was used for the micropile group, and the related material properties are presented in Table 1.

4.1. Numerical model
The Z direction in the model presented in this study is assumed to have a unit thickness. In the XY plane, the meshing space for the sliding mass is 1.0 m (0.06 m for a micropile unit). Therefore, the total number of meshing nodes was 230,001, and the total number of meshing elements was 45,726. The micropile spacing and the spacing between the front and rear rows were both S = 2.0 m. The micropile groups were arranged in the form of an arch, and the cross-sectional diameter of a single pile was 300 mm. A uniform stress Q (50 kPa) was applied to the upper boundary along the Y direction (Fig. 8), i.e., the direction of the driving force’s movement, in this analysis to represent the driving force of the sliding mass. The left and right boundaries of the model were constrained in the X direction to prevent lateral displacement due to the sliding mass, and the front and rear boundaries were constrained in the Z direction to limit the compression deformation of the sliding mass in the pile length direction. In addition, the constraint conditions of the micropiles were restrained in all three dimensions: X, Y, and Z.
Figure 8. Numerical calculation model of the arching effect of the arched micropile groups. Different representative Y profiles were selected to calculate the normal stress. Crown-fronts of 2S, 4S, and 8.5S were selected to represent the sliding mass in front of the micropile group’s crown. Crown-backs of 2S, 4S, and 8.5S were used to represent the sliding mass to the rear of the pile crown.

4.2. Load sharing pattern
To determine the different stress distribution in the Y direction under the condition of a free front boundary, seven representative profiles were chosen to show the stress distribution (Fig. 9). The stress value in each Y section can be obtained and monitored easily using HIST command in FLAC3D. As shown in Fig. 9, the normal stress on the crown-back 8.5S–2S profile in the Y direction is approximately equal to 50 kPa. This value indicates that it is far enough from the top of the piles’ crown. Therefore, the soil arching effect is very weak beyond point 4b, i.e., the scale of the soil arching effect is within the 2S scale.

Figure 9. Stress distributions of the different Y direction profiles along the X direction.
Furthermore, the load sharing changes from crown-back 2S to the pile–group crown, as shown in Fig. 9, thereby indicating that the load is transferred from the sliding mass to the arched micropile groups. The load that is transferred from the soil mass to the pile groups in the profile pile groups’ crown is 41 kPa. The transferred load in the profile of crown-front 2S is 9 kPa. Thus, the latter is much smaller than the former. The profile of crown-front 4S is close to that of the crown-front 8.5S, whose value is nearly zero.

The pie graph in Fig. 10 shows the load sharing percentage of the soil arching. Therefore, we conclude that the load transferred by the micropile–soil interaction process exhibits a two-part load sharing pattern, and the soil arching behind the micropile groups takes most of the total load.

![Pie chart showing load sharing percentage]

**Figure 10.** Comparison pie chart of the load sharing ratio of the different soil arching effects along the Y direction.

5. **Factors influencing the soil arching**

To study the soil arching effect of the different arching directions of the micropile groups, the arch protruding upward and the one dipping downward were chosen to analyze the relationship between the arc direction and the soil arching effect. In this study, the width of the micropile spacing and the rise–span ratio remained unchanged.

On the basis of the results presented in Figs. 11–12, the following conclusions were drawn: (1) From the maximum stress contour plot, the maximum stress of the soil arching can be seen clearly in Fig. 11(a), and the stress concentration is located near the top of the pile–group arc’s crown, with a maximum stress greater than 16 kPa (a positive value indicates tension). In Fig. 12(a), the soil arching occurs only inside the pile–group arc and the stress concentration is located at the foot of the pile–group arc, with a maximum stress greater than 86 kPa. (2) According to the minimum stress contour plot, the minimum stress of the soil arching is also located at the top of the pile–group arc’s crown in Fig. 11(b) and outside of the pile–group arc in Fig. 12(b), with minimum stresses of about 20 and 5kPa, respectively (a negative value indicates compression). This finding indicates that the pressure was transmitted to the area in front of the pile groups in Fig. 12. (3) In the Y direction on the displacement contour plot, the displacement of the piles is almost equal to zero because of its large stiffness value. Compared with the displacement of the sliding mass in Fig. 11(c), the displacement in Fig. 12(c) is larger and has narrower contours.
Figure 11. Soil arching effect contour plot under the arch protruding upward: (a) maximum stress contour, (b) minimum stress contour, (c) Y direction displacement contour.

Figure 12. Soil arching effect contour plot for the arch dipping downward: (a) maximum stress contour, (b) minimum stress contour, (c) Y direction displacement contour.

6. Conclusions and discussion
In this study, landslide stability improvements achieved by the implementation of embedded micropile groups alone and micropile groups combined with long prestressed anchor cables were carefully investigated using the FD-SRM and FOS contour analysis methods, respectively, on the basis of the geological characteristics of the Tizicao high-position landslide. The soil arch effect and the load sharing law of the arched micropile group due to arc-shaped arrangements of the micropile groups were analyzed using the numerical simulation method. The main conclusions of this study are as follows:

(1) The landslide is a high-position giant landslide with a thickness of more than 60 m. This landslide is currently in a state of reactivation and exhibits severe deformation at the front area. Certain parts have completely disintegrated, indicating that the landslide is in an unstable state of continuous collapse. Controlling this landslide is more difficult than controlling other landslides.

(2) The design scheme of the embedded micropile groups improves the stability of this type of thickly layered, high-position landslide, and the construction of these embedded micropile groups is convenient and the mechanism is clear. These results provide a good engineering reference for the treatment of similar landslides. The improvement in the landslide’s stability due to the installation of micropiles is even better than that of micropiles combined with prestressed anchor cables.

(3) The arching effect of multirow micropile groups is significant, which indicates that they can effectively block the movement of the sliding body. The load that is transferred in the micropile–soil interaction process exhibits a new two-part load sharing pattern. The soil arching behind the micropile groups takes more than 80% of the total load. A notable detail is that a tangential tension zone appeared along the top of the pile–group arc’s crown when the arch protruded upward. Thus, a related structural performance design should be considered in the future.

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