A Simulation Study of the Emergency Double-Row Micropile Reinforcement of the Xituo Landslide

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Abstract: This paper studies the suitability of a double-row anti-slide micropile solution for the emergency reinforcement project of the Xituo landslide. The FLAC3D program was used to simulate the stability of the landslide before and after micropile installation. Several key parameters were monitored in the simulation such as the landslide displacement, the shear strain rate at the slip surface, as well as the bending moments and the shear forces exerted on the piles. Both the displacement graph and the shear strain rate cloud map of the landslide before reinforcement indicate that the Xituo landslide is in an unstable state and tends toward accelerated collapse. After the double-row anti-slide micropiles were installed, the displacement of the slope toe gradually stabilized, and the displacement on the river side of the highway was significantly reduced. Moreover, the shear strain rate cloud diagram at the location of the micropiles developed upward, and the shear strain rate was small. These changes indicate that the double-row anti-slide micropiles could effectively restrain further deformation and damage because of the Xituo landslide. Furthermore, the simulated maximum shear forces exerted on the piles, 115.5 and 75.8 kN, are much lower than the maximum micropile design value of 260 kN. The simulated maximum pile body bending moments, 3173.8 and 1170.0 kN·m, also fall below the recommended maximum value of 4500 kN·m. Therefore, double-row anti-slide micropiles are an effective and practical solution for stabilizing the Xituo landslide.

Keywords: geology engineering; simulation; reinforcing effect; micropile; Xituo landslide

1 Introduction
A micropile is a sort of rapid-reinforcement structure commonly used in landslide treatment engineering[1-4]. It is quick to install, flexible in combination, and low in cost, which make it suitable for rapid reinforcement of geological landslide disasters induced by earthquakes, and rainfall. With the rapid development of micropile research, new structures, such as herringbone pile, steel-pipe pile[5], root pile[6], and composite micropile[7], have been gradually derived. Consequently, a lot of experience has been accumulated in the practice of micropile engineering; however, certain problems, such as the anti-slide mechanism of micropiles, the mechanical properties of a micropile, and the stability evaluation of a landslide strengthened by micropiles, are yet to be solved. These issues are holding back the theoretical development of landslide
control and damage prevention using micropile technology.

At present, numerical simulation is among the most commonly used methods to study the anti-sliding mechanism and evaluate the stability of micropiles. The primary goal of an anti-slide micropile simulation is to evaluate the relevant indexes. Scholars at home and abroad have done a lot of work in this area, as summarized in the rest of this paragraph. Sun et al. proposed that the shear force exerted on the piles is an important parameter when evaluating the reinforcement effect of composite anti-slide micropiles. Feng et al. used a finite-element simulation and found that the bending moment and the axial force are the key indexes for stability evaluation of a micropile system. Sun et al. found that when the anchoring depth of a micropile group is small the deformation of each pile is mainly a rigid rotation. They also showed that the deformation of the micropile group changes from a rigid inclination to a flexible bending deformation as the anchoring depth increases. In addition, for a slope with a weak interlayer the deformation is primarily a bending deformation. Chen et al. gave the reasonable values of pile length, pile diameter, and elastic modulus by analyzing the working performance of micropiles under horizontal loads using the finite-element method. Justo et al. established the elastoplastic model of micropiles and concluded that displacement is the key parameter in micropile design. Capatti et al. developed the response theory method of a micropile system under small strain. Xin et al. used the finite-element as well as the finite-difference methods to show that micropile failures in a mixed rock and soil slope occurred primarily at and above the sliding surface, where bending shear and simple bending failures occurred, respectively. For a rock slope, micropile failure was caused by the dislocation of the sliding zone, whereas for a soil slope, the micropiles mainly suffered bending failures on both sides of the sliding zone. In conclusion, many parameters are involved in the stability evaluation of micropiles, and their selection is complex. The abovementioned research results provide valuable information for in-depth research on the theory of micropiles.

This paper analyzes the emergency reinforcement project of the Xituo landslide. The FLAC3D program was used to simulate the stability of the landslide before and after the reinforcement. The forces exerted on the installed double-row anti-slide micropiles were also studied using the same method. The main goal of this study is to evaluate the suitability of double-row anti-slide micropiles for the stabilization of the Xituo landslide. Our results could support the practical application of micropiles in landslide treatment. Moreover, we provide a theoretical basis for the research on the applicability of micropile technology.

2 Project overview[15]

The Xituo landslide is located in Xituo Town, 47 km north of Shizhu County, Chongqing, across the river from Shibaozhai, Zhongxian County, and in the 175 m water-storage-affected area of the Three Gorges Reservoir. Its geographical coordinates are 30° 24ʹ 15.7ʺ N, 108° 12ʹ 2.7ʺ E. The Xituo landslide is located on the right-hand side of the Yangtze River, and its geomorphic unit belongs to the denudation area of the lower mountains and hills along the river. The highest elevation within the landslide is 299.16 m, the lowest elevation is 108.26 m, and the relative elevation difference is 190.90 m. The overall terrain is high in the south and southeast parts of the landslide and low in the northwest. As shown in Figure 1, the east part of the landslide lies at the Fanjiapo gully and the west one at the Maluxi area. The front edge is located near the river erosion zone with an elevation of 112.0–116.0 m, and the back edge reaches the cliff with an elevation of 180.00–219.83 m. The height difference between the edges is 107.80 m. The main sliding angle of the landslide is 318°, the total length is 215.0 m, the width is 305.0 m, and the total area is 6.56 × 104 m². The average thickness is 6.0 m, and the volume is 39.3 × 104 m³. The overall thickness of the deformation mass is 2.40–12.00 m, and the largest thickness reaches 15.0 m. It has a thick rear edge and a thin front edge.
The landslide mass is mainly composed of quaternary alluvial rock-bearing silty clay and residual block stone soil. The latter is primarily composed of stone, silty clay, and crushed stone. The block stones themselves are generally feldspar and quartz sandstone, mudstone, etc., and have an angular, moderately weathered shape. The diameter of the block stones is roughly 0.5–2 m, with a maximum of about 5 m. The silty clay is plastic, and its composition is the same as that of the block stones but with particle size of 3–5 cm and their content of 30–50%. The rock-bearing silty clay is light yellow to brown yellow, plastic, denser and smoother, with some sandy sections. Its block diameter is generally 5–100 cm, and their content is 15–25%.

Generally, there are about 0.3 m of thick silty clay on the surface of the bedrock, and it is in a soft to a plastic state, constituting a potential slip zone of the overall landslide mass. The potential sliding surface is a strongly weathered bedrock surface at the middle and front edges and a moderately weathered bedrock surface at the rear edge. For the Xituo landslide specifically, the potential slip zone is a plastic-soft to plastic silty clay with a thickness of 0.3–0.6 m. Due to the influence of the sliding force on the trailing edge, the potential slip zone is mostly composed of silty clay soil. In exploratory wells, silty clay can be seen on the scratched surface and wrinkles during the sliding process. The potential sliding surface of the front edge of the landslide mass is relatively slow, with an inclination angle of about 3–8°, whereas the angle is 12–17° in the middle and 40–48° at the rear edge.

In recent years, many obvious deformation signs of the Xituo landslide have appeared due to rainstorms and fluctuations of the reservoir water level. For example, cracks with widths between 1 and 2 cm have appeared in residential houses in the area and cultivated land has been showing different degrees of slips and cracks. The height of the steps generated after sliding is about 30 cm. According to interviews, the steps still show signs of sliding every year, and the landslide mass presents an obviously stepped topography. Another example is the retaining wall built in 1995. After about two years, many five-centimeter-wide cracks occurred in its lower parts. Its stones were broken, some parts bulged and protruded, and some of its sections were pushed down. At present, due to the existence of the landslide, the construction of the new Riverside Avenue and the relocation of the wharf from Xituo Town to the county seat have been restricted. The landslide poses a serious threat to the lives, safety, and property of the 1015-immigrant population in the Fanjiapo Resettlement Reconstruction Area as well as the post offices, the Agricultural Banks of China, and other enterprises and institutions located around the Xituo landslide. The direct economic loss caused by the geological disaster is more than 100 million yuan. Therefore, the Xituo landslide reinforcement project is extremely urgent.

It is expected that when the deformation of the Xituo landslide intensifies the new Riverside Avenue and the Xituo wharf will be under construction. In order to avoid interfering with the timelines of these projects, after
a comprehensive evaluation by experts, it was proposed to adopt a double-row anti-slide micropile solution for the emergency reinforcement project (Figure 2). The cross-section of the selected micropile is circular, with a diameter of 60 cm. The holes are formed by rotary spray. The pile length is 25 m, with the embedded section being 8 m long, and the distance between the two rows of piles is 1 m. Anti-slide micropiles provide a large anti-slide force and take a short time to install. This means that the landslide can be reinforced very quickly, winning precious time for the Riverside Avenue and Xituo wharf construction projects.

Fig.2 The engineering geology profile of the Xituo landslide and the locations of the micropiles

3 Numerical simulation method

In current research, the FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions, Itasca Consulting Group, Inc.) program is commonly used to determine the stability and the development trends of landslides[15,16]. In addition, the structural units of the FLAC3D program can be used to simulate the common governance structures such as piles and anchor rods. The numerical simulation model of the Xituo landslide consisted of three parts: the sliding mass, the bedrock, and the sliding surface (Figure 3). Both the sliding mass as well as the sliding surface were simulated as solid elements. In this study, the constitutive model was based on the Mohr-Coulomb criterion, and the sliding surface was simulated by a contact element. The physical and mechanical parameters required for the numerical simulation of the Xituo landslide are given in Table 1. They were determined through field investigations as well as in-lab studies. In order to observe the changes in landslide stability, two surveillance sites were set up: one at the foot of the landslide and one next to the highway, on the side closer to the river. The coordinates of surveillance site 1 were (11.1, 13.2, 1) and those of site 2 were (109.7, 63.5, 1). The former site monitored the displacement change of the front slope, whereas the latter site monitored the displacement change in the middle of the slope. Taking the data from the two sites together, the displacement of the whole slope can be determined.

Tab.1 The physical and mechanical parameters of the sliding mass, the sliding surface, and the bedrock for the Xituo landslide

| Model unit     | Bulk modulus (kPa) | Shear modulus (kPa) | Tensile strength (kPa) | Internal friction angle (°) | Cohesive forces (kPa) | Normal stiffness (MPa·m) | Shear stiffness (MPa·m) |
|----------------|--------------------|---------------------|------------------------|----------------------------|-----------------------|--------------------------|------------------------|
| Sliding mass   | 1×10⁴              | 3×10³               | 34.1                   | 25.0                       | 21.8                  | -                        | -                      |
| Sliding surface| -                  | -                   | 15.6                   | 15.0                       | 15.6                  | 2×10³                   | 2×10³                 |
| Bedrock        | 1×10⁵              | 3×10⁴               | 1.3×10³                | 36.5                       | 1.3×10³               | -                        | -                      |
In order to evaluate the effect of double-row anti-slide micropiles on the Xituo landslide, the pile unit that comes with the FLAC3D program was used to simulate 2 anti-slide micropiles. Figure 4 shows the mesh diagram model of the #1 as well as the #2 piles. Note that both piles are of the exact same type. Table 2 gives the physical and mechanical parameters of the anti-slide piles required for the numerical simulation.

| Model pile | Elastic modulus (MPa) | Poisson ratio | Cross-sectional area (m²) | Circumference of outer ring (m) | Shear stiffness (MPa·m) | Normal stiffness (MPa·m) | Tangential cohesion (kPa) | Normal cohesion (kPa) | Tangential internal friction angle (°) | Normal internal friction angle (°) |
|------------|-----------------------|---------------|----------------------------|---------------------------------|------------------------|-------------------------|-------------------------|------------------|-------------------------------------|------------------------|
| Anti-slide pile #1 | 3×10⁴ | 0.2 | 0.2826 | 1.844 | 1.3×10⁵ | 1.3×10⁵ | 1×10⁴ | 10 | 10 | 10 |
| Anti-slide pile #2 | 3×10⁴ | 0.2 | 0.2826 | 1.844 | 1.3×10⁵ | 1.3×10⁵ | 1×10⁴ | 10 | 10 | 10 |

Fig.3 The mesh model and the monitoring points of the Xituo landslide

Fig.4 The mesh model of the micropiles in the Xituo landslide
4 Result analysis and discussion

To evaluate the stability state of the Xituo landslide, FLAC3D was used to simulate a total of 2000 steps before adding the anti-slide piles. As shown in Figure 5, the displacements of both surveillance sites rose sharply between 1000 and 2000 steps. After 2000 steps, the displacement of surveillance site 1 was 2.25 mm, and that of site 2 reached 1.06 mm. These results show that the Xituo landslide is in an unstable state and tends towards increasing damage. After setting up the anti-slide piles in the model of the Xituo landslide, additional 2000 simulation steps were calculated. It can be seen from Figure 5 that the displacement curves of monitoring points 1 and 2 have both changed from an accelerating increase to a slow increase. At 2500 simulation steps the displacement of the monitoring point 1 approaches a stable value of 2.62 mm, whereas the monitoring point 2 reaches its maximum displacement of 1.24 mm and its displacement decreases thereafter. After 4000 steps the displacement of the monitoring point 2 was only 0.99 mm. Therefore, the toe displacement of the landslide was successfully controlled, and the displacement on the side of the highway was significantly reduced. These results show that double-row anti-slide micropiles can effectively restrain further deformation of the Xituo landslide.

Shear strain rate is the rate of change of the shear strain with time. Figure 6 shows the shear strain rate cloud diagram of the Xituo landslide before (Figure 6a) and after (Figure 6b) the piles were installed. Figure 6a demonstrates that the shear strain rate is concentrated near the slip surface, forming a significant slip zone. It also shows that plastic deformation has occurred at this location, which means that the Xituo landslide is unstable and slipping. After installing the double-row anti-slide micropiles, as shown in Figure 6b, the overall shear strain rate of the landslide increases and the slip zone area expands. However, at the pile position the shear strain rate cloud diagram develops upwards and the shear strain rate becomes smaller. Therefore, the simulation confirms that the double-row anti-slide micropiles can play an important role in stabilizing the slope and effectively curb further development of the landslide.
were installed

A micropile is a reinforced concrete structure with high stiffness and strength. These two properties allow a micropile to prevent further deformation of a landslide, since its sliding force is borne by the pile body through its deformation. To ensure the stability of a pile, its bottom end is embedded in the stable bedrock beneath the sliding mass; thus, any residual sliding force can be transferred to the stable stratum to achieve the purpose of landslide prevention and control.

The key parameters for the design of anti-slide micropiles are the pile body bending moment and the shear force. The pile structure unit that comes with the FLAC3D program was used to simulate these parameters for the piles in the Xituo landslide. Figure 7 shows the shear force graph of the two anti-slide piles and Figure 8 shows their bending moment graph. It can be seen from the shear graph that the shear force is negative for pile #1. It is free of shear force at 0–5 m, and between 6 m and 14 m the force is approximately constant. At 16 m, close to the sliding surface, the shear force suddenly increases; however, below the sliding surface the shear force becomes small again. For pile #2, the shear force diagram is more complex with the force increasing to a positive value and decreasing to a negative value a few times. The maximum positive shear force occurs at the 17 m position of the pile, corresponding to the sliding surface, and the maximum negative shear force occurs right after at 18 m. Going further along the length of the pile, the shear force gradually decreases until it is nearly zero at the bottom. Comparing the maximum shear forces of the two piles, it can be found that the maximum shear force of pile #1 is twice of that of pile #2. In addition, while the shear force with the largest magnitude is negative for pile #1, it is positive for pile #2. These results mean that part of the landslide thrust on pile #2 is transmitted to pile #1. In other words, the two piles work together to transfer most of the landslide thrust to the back row of the anti-slide piles.

The pile body bending moment diagram (Figure 8) shows that all moments for pile #1 are negative, whereas those for pile #2 are mostly positive. Above the sliding surface, the magnitudes of the bending moments for both of the piles increase until they reach their largest values at the sliding surface positions; however, the maximum value for pile #1 is nearly 3 times larger than that for pile #2. Finally, going below the sliding surface positions, the bending moment magnitudes decrease for both piles.

According to the design of a typical anti-slide micropile, the maximum allowed shear force and bending moment are 260 kN and 4500 kN·m, respectively. In the simulation, the maximum shear force exerted on pile #1 was 115.5 kN, and that on pile #2 was 75.8 kN. In addition, the simulated maximum bending moment was 3173.8 kN·m for pile #1 and 1170.0 kN·m for pile #2. All of these values are well below the abovementioned pile specifications; therefore, the double-row anti-slide micropile is a viable solution for the control of the Xituo landslide disaster.

5 Conclusion

In this study, the FLAC3D program was used to evaluate the suitability of a double-row anti-slide micropile solution for the emergency reinforcement project of the Xituo landslide. The main findings from the results
are as follows:

1. Without the anti-slide micropiles, the displacement of the Xituo landslide increases continuously with a sharp upward trend. This means that the landslide is in an unstable state and tends towards further damage. With the double-row anti-slide piles installed, the displacement at the foot of the slope gradually approaches stability, and the displacement at the river side of the highway decreases significantly. Therefore, the double-row anti-slide micropiles can effectively restrain further deformation of the Xituo landslide.

2. The shear strain rate is concentrated near the sliding surface of the Xituo landslide, forming a significant sliding zone. After installing the double-row anti-slide micropiles, the shear strain rate cloud diagram at the location of the piles develops upward, and the shear strain rate is small. These results confirm the role the piles play in stabilizing the slope and preventing further damage.

3. The bending moment and shear force exerted on the pile are the key parameters in the design of the anti-slide micropile. Our simulation shows that for the Xituo landslide the maximum shear force exerted on pile #1 is twice that of pile #2. The maximum bending moment for pile #1 is negative, while that for pile #2 is positive. Part of the landslide thrust borne by pile #2 is transmitted to pile #1. In other words, the two work together to transfer most of the landslide thrust to the rear row of the anti-slide piles. The maximum bending moments of the piles occur at the sliding surface, and the maximum of pile #1 is nearly three times larger than that of pile #2. Above the sliding surface, the pile bending moments increase with pile length; however, below the sliding surface they decrease with the pile length. In addition, the maximum simulated shear force as well as the maximum simulated bending moment of both piles fall well below the maximum recommended values for a typical micropile. Thus, the double-row anti-slide micropile is a practical solution for the reinforcement project of the Xituo landslide.

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