Model test of cantilevered double-row anti-sliding piles in steeply slipping landslides

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Abstract. The mechanism governing pile–soil and rock interaction in steeply slipping landslides is quite different from that observed in gently slipping landslides. In particular, the mechanism responsible for the double-row anti-sliding pile stress is notoriously complex. Using the K285 landslide along the Neijiang–Liupanshui railway route as an example in our study, we demonstrated that pile safety in steeply slipping landslides was based on the similarity principle. A physical model interaction test between the double-row anti-sliding piles and the landslide was performed to determine the impact of factors such as the failure mode as well as pile stress, bending moment, and head (top) displacement on the safety of a project site. Herein, we noted that the landslide thrust located behind the lower row was about \( \frac{1}{2} \) to 1 times that of the upper row when the distance between two rows of anti-sliding piles was about the same as the pile length, assuming that the same loading conditions were used. Also, the resistance of the sliding mass in front of the upper row piles had a maximum value, and the maximum bending moment of the lower row was about \( \frac{1}{3} \) to 1 times that of the upper row under the aforementioned assumptions. The results indicated that the anti-sliding pile heads should be 0.5–1.0 m higher than the ground surface around the piles and backfilled behind the piles. Additionally, the bedrock located before the piles adopted a “wedge” fracture with a depth corresponding to the position of the maximum bending moment. The associated fracture angle and depth were related to the friction angle of the bedrock and the inclination angle of the slipping surface. In conclusion, the study provided insight that will be useful for designing anti-sliding piles to mitigate the occurrence and impact of these types of landslides.

1. Introduction

The southwest mountainous region of China is prone to the formation of steep landslides that are characterized by large slopes, a slipping surface with an inclination angle between 30° and 45°, and a large slipping body thickness due to its unique evolution and mode of formation. Therefore, multiple rows of anti-sliding piles are usually used to retain landslides and mitigate their impact. The rock and soil surrounding the anchorage section of anti-sliding piles in steeply slipping landslides are asymmetric semi-infinite elastic bodies. Under the pressure of the pile, the slipping bed located before the pile becomes wedge-shaped[1–3]. Given this, researchers have determined that the project’s safety is typically ensured when each row of the anti-sliding piles independently bears the landslide thrust behind them. Consequently, the landslide thrust after each row of the anti-sliding piles is taken as the design thrust, and the resistance of the slide body in front of the pile and the pile group effects
are not considered. However, verification of this method’s economic benefits, safety, and effectiveness is still needed.

Recently, research has been focused on the core principles of retaining engineering using double-row anti-sliding piles. Xiao Shiguo et al.\cite{4,5} proposed a formula for calculating the landslide thrust for double-row anti-sliding piles based on the elastic foundation beam model; the proposed formula was rationalized using indoor model tests. Yang Bo et al.\cite{6} simulated the stress exerted on double-row anti-sliding piles using the finite element method. The results showed that the share ratio of the double-row anti-sliding piles was closely related to the row spacing; here, the rear row bore most of the thrust when the row spacing was small. Ye Jinbi et al.\cite{7} studied the reinforcement mechanism behind the variable rigidity of cantilever double-row anti-sliding piles using the horizontal push pile model test. The results showed that the double-row anti-sliding piles’ critical load was not significantly reduced by moderate increases in the spacing of the front row piles. In this study, it was shown that the front row piles were completely mobilized and that the observed difference between the maximum bending moment of the front and the rear piles was reduced. In addition to studying the ultimate bearing capacity of double-row circular anti-sliding piles, Wu Honggang et al.\cite{8} examined the observed deformation processes and failure modes using model tests. The results showed that the thrust distribution values of the front and rear piles were extremely disproportionate because the brunt of the thrust was borne by the rear piles. Here, the change in the soil pressure can be divided into three stages: an initial slow development stage, a rapid development stage, and an attenuation stage. Shen Yongjiang et al.\cite{9,10} and Fan Qiuyan et al.\cite{11} analyzed the stress exerted on double-row anti-sliding piles in light of numerical calculations and the principles governing elastic and structural mechanics.

They proposed a formula for the landslide thrust borne by the front and rear anti-sliding piles and suggested a distribution method for calculating the landslide thrust; this proposed distribution method was subsequently verified using various real-world applications. Even though the above-mentioned research was mainly conducted via model tests and the theoretical calculations were performed under specific assumptions, the interaction mechanism governing the relationship among the multi-row anti-sliding piles, the rock, and the soil mass remains unclear. Verification is needed to determine whether the results could be applied when designing anti-sliding piles for application in steeply slipping landslides. Further studies must be conducted to determine the load sharing ratio, row spacing, and other key design parameters of multi-row anti-sliding piles and how these parameters could be applied to other types of anti-sliding piles.

In the current study, the K285 landslide along the Neijiang–Liupanshui railway route was taken as a case example and used in combination with indoor model tests to understand the interactions governing double-row anti-sliding piles and their relationship with the surrounding rock and soil mass. The bearing, deformation characteristics, and failure modes of the anti-sliding piles were studied in detail. The difference in the working performance of the single-row and double-row anti-sliding piles was compared for improved design feasibility and rationality studies of multi-row anti-sliding piles. Finally, the real-world application of these types of multi-row anti-sliding piles was conducted to control steeply slipping landslides. The findings of this study have promising prospects and important practical value for numerous real-world scenarios.

2. Model test design

2.1. Test scheme design

The K285 landslide is about 430 m in longitudinal length and 100 m in transverse width. The landslide mass is mainly composed of colluvial debris and block-stone soil with an average thickness of 20 m; the slipping bed is composed of breccia-bearing silty clay with an average thickness of 0.4 m and an inclination angle of 26°–34°. The slipping bed is composed of argillaceous limestone and limestone\cite{1–2}. The main treatment measures are multi-row cantilever C30 concrete anti-sliding piles with a section
size of 2 m × 3 m and a pile length of 7–40 m. The distance from the middle to the middle of the pile is 6 m, and 108 HRB400 rebars of φ32 are arranged near the mountain[1–2].

The geometric similarity ratio of the model test is 50. Using the indoor mix ratio test, we determined that the slipping body material consists of a mix of gypsum, a machine-made sand (with particle size less than 2 mm), and water in a ratio of 1:58:5.45. The slide belt material consists of a mix of gypsum, silty clay, water, and fine sand in a ratio of 1:4:5:50. The slide bed material is a gypsum/stone/water/machine-made sand mix in a ratio of 1:0.37:1.11:6.481. The anti-sliding pile is a square steel pipe (40 mm wide × 60 mm high × 1 mm thick) that is filled with a concrete mixture containing water, cement, fine sand, and stone in the ratio of 1:2.667:2.333:8.111. The measured physical and mechanical parameters are close to the theoretical values[1–2].

The selected model parameters are as follows: the horizontal length of the slipping body and the slipping bed model is 120 cm, with a width of 60 cm and a slope–slipping surface inclination angle of 30°. In the model test of the double-row anti-sliding pile, the pile’s cross-section is 4 cm × 6 cm; there are four piles in the upper row that are 60 cm in length (including a 20-cm-long embedded section), and four piles in the lower row that are 67 cm in length (including a 27-cm-long embedded section). The distance from the middle to the middle of the anti-sliding pile is 12 cm. The embedded length of the anti-sliding pile is calculated from the slipping surface of the slope (Figure 1). The test model was placed in a natural state for 28 days after the filling process was complete (Figure 2).

2.2. Measuring the pile contents and components

2.2.1. Pile pressure. The pressure exerted on the pile, which is caused by the slipping body behind the pile, the slipping body in front of the pile, and the slipping bed before the pile are measured using resistance soil pressure cells that can only be used after being calibrated. For the double-row anti-sliding pile model test, piles S2, S4, S6, and S8 are selected for the soil pressure cells, which are numbered as YLS2-1, YLS2-2, ……, YLS2-11 according to the corresponding sequence from the top to the bottom of the pile as well as the back and front of the pile (Table 1).
2.2.2. Pile strain. The strain exerted on the pile was measured using a resistance strain gauge with a grid length of 5 mm and a width of 3 mm that had been glued to the outer surface of the model pile. The microstrain values of each strain gauge were read using the TST3826 static strain testing system. The influence of the soil pressure cell’s superposition and the strain gauge on the test results was avoided by selecting piles S1, S3, S5, and S7 for the double-row anti-sliding pile model test (Table 2).

2.2.3. Displacement of the pile. Pile displacement under the influence of the load was measured using a displacement meter with a range of 100 mm and an accuracy of 0.01 mm placed on the top of each anti-sliding pile.

2.3. Loading mode

The displacement of the top of the S2 pile was preset before the start of the model test, followed by the continuous application of the load to the model’s sliding body. After the S2 pile top displacement reached the predetermined value, the load application was kept constant for 5 minutes while simultaneously conducting instrument readings. Once this stage was complete, the application of the next higher load was undertaken. This test was repeated until the displacement of the top of the pile continued to increase and no changes in the load were observed (Table 3).
Table 3. The horizontal displacement and loading force of the model.

| Load times | Applied loads/t | Horizontal displacement of the respective piles/mm |
|------------|-----------------|---------------------------------------------------|
|            | S1      | S2      | S3      | S4      | S5      | S6      | S7      | S8      |
| 1st load   | 0.188   | 0.25    | 0.25    | 0.18    | 0.19    | 0.09    | 0.12    | 0.11    | 0.10    |
| 2nd load   | 0.273   | 0.52    | 0.50    | 0.38    | 0.40    | 0.19    | 0.22    | 0.22    | 0.24    |
| 3rd load   | 0.340   | 0.72    | 0.75    | 0.59    | 0.64    | 0.28    | 0.33    | 0.33    | 0.36    |
| 4th load   | 0.421   | 0.95    | 1.00    | 0.95    | 0.91    | 0.40    | 0.46    | 0.53    | 0.52    |
| 5th load   | 0.473   | 1.22    | 1.25    | 1.10    | 1.18    | 0.50    | 0.57    | 0.58    | 0.64    |
| 6th load   | 0.545   | 1.49    | 1.50    | 1.35    | 1.43    | 0.63    | 0.71    | 0.73    | 0.80    |
| 7th load   | 0.589   | 1.72    | 1.75    | 1.58    | 1.67    | 0.72    | 0.82    | 0.84    | 0.92    |
| 8th load   | 0.630   | 1.99    | 2.00    | 1.86    | 1.93    | 0.82    | 0.92    | 0.95    | 1.04    |
| 9th load   | 0.813   | 3.04    | 3.00    | 2.88    | 2.92    | 1.25    | 1.35    | 1.44    | 1.55    |
| 10th load  | 0.953   | 4.03    | 4.00    | 3.97    | 3.99    | 1.69    | 1.78    | 1.90    | 2.02    |
| 11th load  | 1.113   | 5.06    | 5.00    | 4.90    | 4.92    | 2.12    | 2.23    | 2.39    | 2.54    |
| 12th load  | 1.273   | 6.18    | 6.00    | 6.00    | 6.00    | 2.58    | 2.70    | 2.88    | 3.05    |
| 13th load  | 1.417   | 7.11    | 7.00    | 6.93    | 6.89    | 3.04    | 3.15    | 3.35    | 3.53    |
| 14th load  | 1.496   | 8.13    | 8.00    | 7.95    | 7.89    | 3.51    | 3.60    | 3.82    | 4.01    |
| 15th load  | 1.556   | 9.15    | 9.00    | 8.96    | 8.88    | 4.03    | 4.05    | 4.29    | 4.50    |
| 16th load  | 1.698   | 10.11   | 10.00   | 10.05   | 9.95    | 4.57    | 4.35    | 4.55    | 4.85    |
| 17th load  | 1.869   | 12.32   | 12.00   | 12.04   | 11.87   | 5.66    | 5.43    | 5.68    | 5.96    |
| 18th load  | 2.035   | 14.49   | 14.00   | 14.11   | 13.90   | 6.70    | 6.47    | 6.75    | 7.03    |
| 19th load  | 2.183   | 16.53   | 16.00   | 16.12   | 15.78   | 7.78    | 7.45    | 7.75    | 8.08    |
| 20th load  | 2.289   | 18.69   | 18.00   | 18.28   | 17.70   | 8.88    | 8.51    | 8.79    | 9.19    |
| 21st load  | 2.378   | 20.91   | 20.00   | 20.46   | 19.77   | 9.70    | 9.51    | 9.75    | 10.25   |
| 22nd load  | 2.530   | 26.39   | 25.00   | 24.82   | 24.68   | 12.54   | 12.51   | 12.80   | 13.06   |
| 23rd load  | 2.530   | 32.07   | 30.00   | 30.19   | 29.81   | 15.69   | 15.66   | 15.80   | 15.54   |
| 24th load  | 2.612   | 41.47   | 39.89   | 39.51   | 40.05   | 21.70   | 21.49   | 21.86   | 21.91   |

3. Model test analysis

3.1. Analysis of the pile pressure test

The measured results were converted using the stress–strain calibration curves obtained for each soil pressure cell. A negative soil pressure value meant that the soil pressure cell was located before the pile, whereas a positive value meant that the soil pressure cell was located behind the pile (Figure 3).
Figure 3. The stress distribution curves obtained along the pile’s shaft.
From Figures 3(a)–(d), it can be seen that the soil pressure of the double-row anti-sliding pile has the following characteristics:

1. Even though the landslide thrust located behind the piles presents a trapezoidal distribution under different loading orders, the thrust behind the lower row is less than the thrust behind the upper row, with a ratio between 0.5 and 1.0. Assuming the application of appropriate row spacing, the distribution form of the landslide thrust must be considered when designing double-row anti-sliding pile treatment projects by focusing in the trapezoid distribution factors. The results should be checked using the appropriate guidelines governing rectangular distribution.

2. When considering the distribution form adopted by the resistance of the slide body located before the pile under different loading orders, the resistance of the slide body located before the upper row piles exhibits trapezoidal distribution. The resistance near the lower row’s slide belt is large, whereas its counterpart near the slope’s surface located in the upper region is small. The resistance of the slide body located before the lower row pile adopts a triangular distribution, and it is at its maximum near the slide belt. The resistance of the front slide of the upper row is much greater than that observed for the lower row. The resistance of the front slipping body of the upper row has a maximum value. With increasing loading order, the resistance value decreases, i.e., it changes from a higher to a lower value than that observed for the landslide thrust located behind the lower row. When designing double-row anti-sliding pile treatment engineering projects, the resistance of the slide body located before the pile should be considered for the piles in the upper row and not for those in the lower row, given that the appropriate row spacing guidelines are applied.

3. The resistance of the slipping bed located before the pile adopts a triangular distribution form. We note that an increase in the loading order leads to a rapid increase in the resistance of the front slipping bed. Beyond a certain depth, this resistance value is very small and does not increase when the loading order increases.

4. The failure mode of the slipping bed dictates that the wedge failures occur in front of the upper and lower row piles, resulting in a change in the rule governing the resistance of the front slipping bed of both the upper and lower row piles. During the ninth loading cycle, in which the displacement of the top of the S2 pile is 3 mm, the pressure exerted on the YLS2-9 pressure cell (located below the pile top at -47.3 mm) suddenly increases. Additionally, the pressure exerted on the YLS4-7 pressure cell (located below the pile top at -50.3 mm) and the YLS2-10 pressure cell (located below the pile top at -53.3 mm) also increases abruptly across a small range, indicating that the wedge-shaped failure of the front slipping bed of the upper row piles occurs during the ninth loading process. Here, the S2 pile top displacement is 3 mm, and the pile and the slipping body also enter the plastic deformation stage. During the 12th loading cycle, the pressure exerted on the YLS6-9 pressure cell (located below the pile top at -47.3 mm) suddenly increases. Additionally, the pressure exerted on the YLS8-7 pressure cell (located below the pile top at -50.3 mm) and the YLS6-10 pressure cell (located below the pile top at -54.3 mm) also increases abruptly across a small range, indicating that the wedge-shaped failure of the slide bed located in front of the lower row pile occurs in the twelfth loading process when the displacement of the S6 pile top is 2.7 mm.

5. The physical model tests reveal that the distribution pattern of the landslide thrust located behind the upper row and the slipping mass resistance found in front of the lower row are similar for both the double-row and single-row piles, with a few obvious differences between the upper and the lower rows. Here, we note that the slipping resistance is in front of the upper row piles, whereas the landslide thrust is behind the lower row. The resistance of the aforementioned slide mass is larger and the distribution is relatively homogenous, whereas the landslide thrust located behind the lower row is slightly smaller with a different distribution form. Generally, the distribution form and the failure mode of the slide bed located before both rows are similar to the observations made in the single-row system. Additionally, the failure time is noticeably delayed, especially for the slide bed located before the lower row. The above-mentioned phenomena are the embodiment of the interaction between the
upper and lower row piles, assuming that the appropriate row spacing guidelines are followed. This is commonly called the “pile group effect.”

3.2. Analysis of the pile bending moment

The relationship between the exerted stress and the noted strain in material mechanics dictates that there is a converted relationship between the strain and the bending moment (Figure 4).
As seen in Figures 4(a)–(d), the bending moment observed along the piles has the following characteristics:

1. The maximum bending moment of the pile decreases when the loading order increases. Here, the maximum bending moment of the S1 anti-sliding pile is -45 cm below the top of the pile. The maximum bending moment of the S3 anti-sliding pile is reduced from -35 cm to -45 cm below the pile top. At -35 cm, the loading order is less than 5-fold when the displacement of the pile top is less than 1.1 mm. At -45 cm, the loading order is more than 5-fold when the displacement is more than 1.1 mm. Similarly, the maximum bending moment of the S5 anti-sliding pile is reduced from -35 cm to -45 cm below the pile top. At -35 cm, the loading order is less than 8-fold when the displacement is less than 0.82 mm. At -45 cm, the loading order is more than 8-fold when the displacement is more than 0.82 mm. The maximum bending moment of the S7 anti-sliding pile is reduced from -35 cm to -45 cm below the pile top. At -35 cm, the loading order is less than 8-fold when the displacement is less than 0.95 mm. At -45 cm, the loading order is more than 8-fold when the displacement is more than 0.95 mm.

Based on the above analysis, the force exerted on the lower row is more homogenous than that exerted on the upper row for double-row anti-sliding piles.

2. When the loading order increases, the distribution form of the pile bending moment gradually transitions from a parabola or an inverted trapezoid to a triangle. The distribution form of the bending moment of the S1 anti-sliding pile is triangular, with the center of gravity close to the slide zone. Additionally, the distribution of the bending moment of the S3 anti-sliding pile gradually transitions from a parabola to a triangle, with its center of gravity close to the slide zone. When the loading order is less than 5-fold (i.e., the pile top displacement is less than 1.1 mm), there is homogenous distribution of the pile bending moment. Conversely, the pile bending moment distribution is more concentrated and triangular with the center of gravity close to the slip zone when the loading order is more than 5-fold (i.e., the pile top displacement is greater than 1.1 mm).

When the loading order increases, the distribution form of the bending moment of the S5 anti-sliding pile gradually transitions from an inverted trapezoid to a triangle with its center of gravity close to the slide belt. The pile top displacement is less than 0.82 mm when the loading order is less than 8-fold, resulting in the homogenous distribution of the pile bending moment that adopts an inverted trapezoid shape. A loading order of more than 8-fold (i.e., the pile top displacement is greater than 0.82 mm) results in a more concentrated pile bending moment distribution that adopts a triangular shape with its center of gravity close to the slip zone.
When the loading order increases, the distribution form of the bending moment of the S7 anti-sliding pile gradually transitions from an inverted trapezoid to a triangle whose center of gravity is close to the slide belt. The pile top displacement is less than 0.95 mm when the loading order is less than 8-fold, resulting in a homogenous pile bending moment distribution that adopts an inverted trapezoid shape. When the loading order is greater than 8-fold (i.e., the pile top displacement is greater than 0.95 mm), the pile bending moment distribution is more concentrated and adopts a triangular shape with its center of gravity close to the slipping zone. Thus, for double-row anti-sliding piles, the distribution form of the bending moment of the upper row gradually transitions from a parabolic shape to a triangular one with its center of gravity close to the slide belt when the loading order increases. Under similar conditions, the distribution form of the bending moment of the lower row transitions from an inverted trapezoid to a triangle with its center of gravity close to the slide belt. Additionally, there is more homogeneity in the force exerted on the lower row than that exerted on the upper row. When these findings are viewed in light of the position of the maximum bending moment of the pile, it can be seen that the distribution form of the bending moment has a corresponding relationship with the position of the maximum bending moment. Thus, when the location of the maximum bending moment changes, the distribution of the bending moment changes accordingly.

3.3. Analysis of the pile top displacement

The horizontal displacement of the anti-sliding pile heads as a function of the applied loads is shown in Figure 5.

![Figure 5. The horizontal displacement of the anti-sliding pile heads vs. the applied loads.](image)

Several conclusions can be drawn from Figure 5:

(1) The top displacement of the upper row is about twice that of the lower row under the same loading conditions.

(2) When the loading order is less than 13-fold, the average top displacement of the upper row is less than 7 mm, the average displacement of the lower row is less than 3.5 mm, and the displacement curve shows slight and stable growth. However, when the loading order is greater than 13-fold, the average displacement of the upper row is greater than 7 mm. Additionally, the average displacement of the lower row of piles is greater than 3.5 mm.
(3) When the displacement curve of the pile top enters the accelerated growth stage, the pile body and slipping mass are also close to achieving the progressive failure state. Therefore, the allowable maximum displacement of the top of the lower row should not exceed 3.5 mm for double-row half-slope piles. When the geometric similarity ratio (C1) is 50, the allowable maximum displacement of the actual half-slope at the top of the pile should not exceed 175 mm.

3.4. Failure mode analysis

At the end of the model test, the model is excavated in the section to define the deformation and failure mode of the slipping body, as well as the slipping bed and the pile body.

3.4.1. Analysis of slipping mass failure mode.

The failure mode of the slipping mass in the double-row anti-sliding pile model test is as follows:

(1) The observed failure phenomenon of the slipping body’s surface can be defined as a longitudinal crack with a width of 0.2–0.5 cm and a 30-cm extension length developed behind the S2 pile of the upper row. Also, a longitudinal crack with a width of 0.1–0.2 cm and a 15-cm extension length developed behind the S3 pile parallel to the sliding direction. A transverse crack perpendicular to the sliding direction developed at the upper row, which extended to a depth of 12 cm. A longitudinal crack with a width of 0.1–0.3 cm and a 30-cm extension length developed behind the S5 pile of the lower row. A longitudinal crack with a width of 0.1–0.3 cm and a 20-cm extension length developed behind the S8 pile. A transverse crack perpendicular to the sliding direction developed at the lower row (Figure 6).

(2) The internal failure of the slipping mass is defined as the microcracks located behind the upper row and 10 cm above the slipping surface that are nearly parallel to the direction of the slipping surface. On average, each microcrack is 0.1–0.2 mm wide with an extension length of 5–10 cm. Between the upper and lower rows, a crack nearly parallel to the slipping surface developed 5 cm below the slope’s surface and moved forward to the top of the lower row of piles, resulting in a transverse crack perpendicular to the sliding direction of the slope’s surface. Thus, soil arching was subsequently noted in the lower row (Figure 6).

Based on the above failure phenomena, it can be concluded that the failure mode of the slipping mass in the physical model test of the double-row piles is mainly due to the downward slide of the slipping body. Here, the anti-sliding pile prevents this from occurring. The longitudinal shear cracks parallel to the sliding direction appear at the back of the anti-sliding piles, which leads to the slipping body between the upper and lower rows and exists from the top of the lower row.

3.4.2. Analysis of the bedding rock failure mode.

The failure mode shown in Figure 7 highlights several key points:
(1) The slide bed’s surface is located in front of the upper and lower rows and is slightly arched.

(2) The front slipping bed of the upper row produces cracks about 3.0 cm below the interface of the foundation cover (about 47.3 cm below the pile top and in the middle of the SYL2-9 earth-embedded pressure box). The angle between the crack and the vertical plane is about 45° and extends to the interface of the foundation cover. The angle between the horizontal plane and the side of the pile is about 30° along the horizontal plane.

(3) The front slide bed of the lower row has cracks about 4.5 cm below the foundation cover interface, which is about 48.8 cm below the pile top and the bottom of SYL6-9 soil-embedded pressure box. The angle between the cracks and the vertical plane is about 60° and extends to the foundation cover interface. The angle between the horizontal plane and the side of the pile is about 45°. It can be seen from the above discussion that wedge failure occurs in the front of the slipping bed of both the upper and lower rows when double-row anti-sliding piles are used to treat steeply slipping landslides. The angle between the wedge-shaped failure surface and the vertical plane is about 45°–60°, and the angle between the horizontal plane and the side of the pile is about 30°–45°. For the location of the wedge-shaped failure surface of the upper row is shallower than that of the base cover interface, the angle between the wedge-shaped failure surface of the upper row and the vertical plane is smaller than the angle between the horizontal plane and the side of the pile. The location of the wedge-shaped failure surface of the lower row is deeper than that of the base cover interface. The angle between the wedge-shaped failure surface and the vertical plane is larger than the angle between the horizontal plane and the side of the pile.

Figure 7. The bedrock failure mode in the double-row pile model tests.

Through a comprehensive analysis of the failure mode of the slide bed in the physical model test of double-row piles, it can be seen that the wedge-shaped failure of the slipping bed located in front of the pile occurs when the double-row anti-sliding pile is used to treat steeply slipping landslides. The position of the wedge-shaped failure surface is consonant with the lower limit of the bending range of the pile and corresponds to the position of the maximum bending moment. Although the failure mode of the slipping mass and slipping bed of the double-row piles is similar to that of the single-row piles in the physical model tests, the wedge-shaped failure area of the slipping bed of the upper and lower rows is slightly smaller in the double-row system than that observed in the single-row system. The bending deformation of the double-row piles is noticeably less than that of the single-row system. This phenomenon is the embodiment of the interaction between the upper and lower rows under the appropriate row spacing conditions and is typically known as the “pile group effect.”
4. Conclusion

The results of this study have shown that multi-row anti-sliding piles are better for treating steeply slipping landslides than using single-row anti-sliding piles. Under the same loading conditions, the landslide thrust located behind the lower row of piles is about $\frac{3}{4}$–1 times higher than that of the upper row when the distance between the two rows of anti-sliding piles is the same as the pile’s length. The resistance of the sliding mass located in front of the upper row has a maximum value. The maximum bending moment of the lower row is about $\frac{2}{3}$–1 times that of the upper row. We note that the anti-sliding pile heads should be placed 0.5–1.0 m higher than the ground’s surface around the piles and backfilled behind the piles. The bedrock in front of the piles underwent a wedge fracture, with a depth corresponding to the maximum bending moment position. Here, the fracture angle and depth were related to the friction angle of the bedrock and the inclination angle of the slipping surface. Due to the vast differences between the landslide thrust and the bending moment of the upper and lower rows in steeply slipping landslides, the upper and lower rows should be connected as a whole with coupling beams to take advantage of pile group effects.

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