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A rational layout of double-row stabilizing piles for large-scale landslide control

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Abstract Double rows of stabilizing piles can be applied to large-scale landslide control; however, the geometry of the layout can substantially affect the lateral bearing capacity of the structure. Based on slope slippage and deformation mechanisms, this paper proposes a specific pile layout configuration—an embedded rear-row pile (with the top of the pile embedded to a certain depth in the slope), and a full-length fore-row pile (with the top of the pile on the surface of the slope). This layout appears to be a rational arrangement for resisting a landslide with a polyline slip surface using double-row piles. As for landslides with a linear slip surface, a full-length pile layout of fore- and rear-row piles can be adopted. However, the area of sliding mass directly supported by the rear (upslope) and fore piles should be approximately equal (in plane) to ensure that the thrust force on the piles above the slip surface is close to the optimum condition. Based on a numerical simulation, this paper also discusses a method for determining a rational embedded depth for the top of the rear-row piles for landslides with polyline slip surfaces, as well as a more rational pile structural form in the case of relatively short distances between the two rows of piles. The results obtained in this paper provide theoretical support for a rational layout of double-row piles for large-scale landslide controls, and provide assistance for practical reinforced slope projects.

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Introduction

When controlling for landslides with a high thrust, using one row of single piles for stabilization typically requires a large sectional dimension and a significant amount of reinforcements (Ito et al. 1981; Poulos 1995, 1999; Wang et al. 2014), which increase project costs and entail complex construction and operation. These settings could be better served with the application of a double-row (or multiple rows) of piles for reinforcement (Ito et al. 1982). In this case, the primary criterion for the design of a multi-row pile system should be that the sum of the net landslide thrusts (i.e., the landslide thrust on the upslope side of a pile minus the slope resistance on downslope side of a pile) applied to each pile of the double- or multiple-row piles does not exceed that of the single-row piles. This ensures the mechanical rationality of adopting two or more rows of piles. Because the slope pressure on the sides of a stabilizing pile or the sliding thrust on a pile is closely related to the pattern of the slip surface and the pile arrangement, and has significant influence on the responses of the pile (Ito and Matsui 1975; Randolph 1981; Guo 2009; Cai and Ugai 2000; Chow 1996; Lee et al. 1995; Hassiotis et al. 1997), an acceptable pile arrangement should ensure the mechanical rationality of two or more rows of piles. Previous research on these problems has primarily discussed

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the load-carrying characteristics of regular full-length stabilizing piles, and variations in the distance between the fore (downslope) and rear (upslope) rows to optimize the distance between the piles and rows for a given pattern of slip surface (Shen et al. 2008; Lei et al. 2006; Xiong 2000; Zhao et al. 2009). Optimization of the pile top depth and pile layout geometry specific to an actual project has not been considered. This study presents a rational pile arrangement for double rows of stabilizing piles to reinforce high-thrust landslides.

Methods

Reinforcement mechanisms of landslides using double-row piles

Figure 1 shows a general layout of double-row piles for the reinforcement of a large-scale landslide control. For full-length double-row piles (see Fig. 1a) subjected to forward-
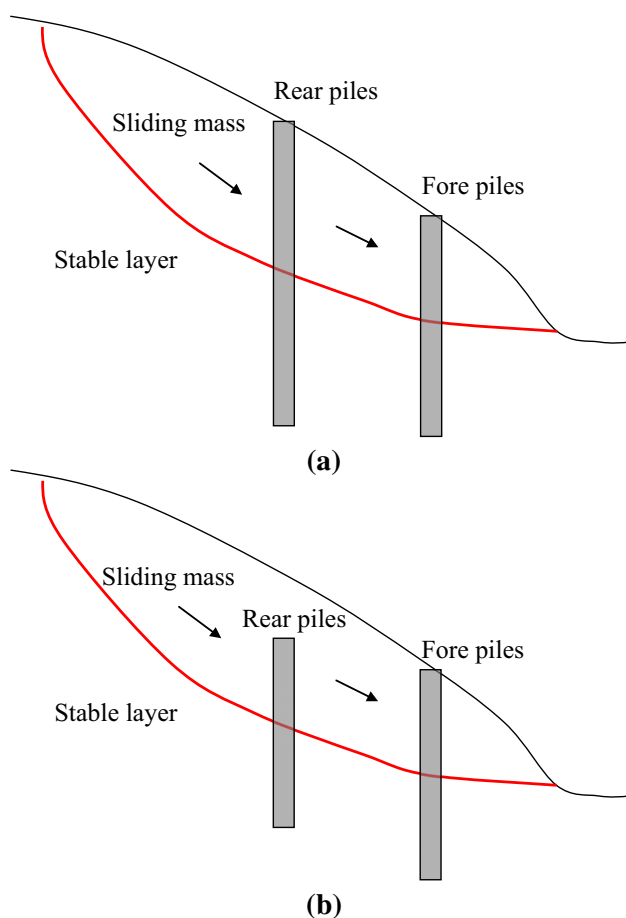

Fig. 1 Schematic diagram of double-row pile reinforcement for a large-scale landslide. **a** Two rows of full-length piles. **b** Rear-row embedded piles and fore-row full-length piles

transferred landslide thrust, the rear row of piles is subjected to a displacement because the landslide thrust on the uphill side of the rear piles compresses the medium between the two rows of piles. All of the sliding mass between the piles, and a portion of the sliding mass on the upslope of the rear piles must be carried by the fore piles. The fore-row piles are subjected to a displacement by this thrust that produces slope resistance at their fronts. Thus, during the transmission of landslide thrust, the upslope thrust on the rear-row piles is fully applied to the full-length rear-row piles. If the rear-row piles are located in the anti-sliding section of the slope, then the upslope thrust on the piles will be greater than that in the reinforcement of the landslide by a single row of full-length piles in the location of the fore-row piles. Thus, the sum of landslide thrusts for the double-row piles will be greater than that of the single-row piles, which means that the application of double-row piles is neither efficient nor economical. Therefore, effective measures should be taken to transfer a portion of the upslope thrust from the rear-row piles to the fore-row piles rather than have it totally borne by the rear-row piles. This will make it possible for the sum of the landslide thrusts of the double-row piles to be smaller than that of a single row of piles. To produce such a transfer mechanism in a landslide thrust, we have adopted rear-row piles that are not full length by embedding the tops of the piles at a certain depth, i.e., the rear-row piles are embedded (see Fig. 1b). In this manner, a portion of the landslide thrust incident of the upslope side of the rear-row piles bypasses over the top of the rear piles and is transferred to the fore-row piles, thereby reducing the landslide thrust on the rear-row piles. Thus, if the embedded depth of the top of the rear-row piles is correct, it is most likely that the sum of the landslide thrust on the double-row piles with "embedded rear piles and full-length fore piles" is consequently smaller than that on single-row piles located in the same place as the fore-row piles.

In fact, the sliding mass on the upslope of the rear piles is initially resisted by the rear row piles. Thus, an arch effect occurs between two adjacent rear piles, and slope pressure is exerted on the piles. In addition, the rear piles will compress the media between the two rows due to the slope pressure. Because the sliding mass between the two rows is resisted by the fore-row piles, another arch effect similarly occurs between two adjacent fore-row piles and the corresponding slope pressure acts upon the fore-row piles. Due to the arch effect occurring between two adjacent piles in the same row, it is reasonable to assume in the slope pressure transmission process that one fore pile and one rear pile support the thrust between two adjacent piles out of plane. Therefore, a two-dimensional model can be used to simplify analysis.

Layout of double-row piles in idealized settings

The general mechanism of landslide protection reinforced with double-row piles as described above shows that the advantage of double-row piles over single-row piles is closely related to the pile positions selected and based on the slip surface pattern. In order to develop a detailed explanation of these problems, large-scale landslides characterized by two commonly observed slip surface patterns are used as examples: (1) landslides with a polyline slip surface, and (2) landslides with a linear slip surface.

Landslides with polyline slip surface

In order to provide a realistic picture of the resistance capacity of the anti-sliding section in a landslide with a polyline slip surface, the piles are set in the anti-slide section downslope from the sliding section during the set-up of full-length single-row piles for ease of construction. If a rear row of piles is added to form a double-row pile structure, then the rear-row piles should be subjected to a different pile top depth in order to ensure the mechanical superiority of the double-row piles, depending on their two specific locations, as follows:

Rear-row piles in the anti-sliding section   In this case, as discussed above, the double-row piles will be mechanically superior to the single-row piles with the embedded rear-row piles (see Fig. 2)

Rear-row piles in the sliding section   In this case, it is economically acceptable to use either full-length or embedded rear-row piles. In general, the full-length piles should not be set in front of the sliding section in order to avoid a negligible mechanical advantage—or even a mechanical disadvantage—of double-row piles over the single-row piles. As for the embedded piles, the mechanical advantage of double-row piles should be considered without causing a local sliding failure over the rear pile tops by the upslope sliding mass of the piles. This will then enable the determination of rational pile locations and the corresponding embedded depths of the pile top (see Fig. 3).

The upslope thrust is completely exerted upon the full-length stabilizing piles blocking the entire upslope sliding mass because they resist deformation of the entire sliding mass. However, the upslope thrust can act partially upon the embedded stabilizing piles because the piles only resist the sliding mass from the top of the piles to the slip surface of deformation. Because the deformation of the sliding mass above the top of the piles is not restricted by the rear piles, the upslope pressure from the sliding mass above the top of the piles directly transfers forward to the adjacent media and eventually influences the fore piles. Therefore, the landslide thrust on the portion of an embedded pile above the slip surface (called the loading section of the pile) is less than that on the portion of the full-length pile located in the same place.

Landslides with linear slip surface

In a landslide with a linear slip surface (see Fig. 4), a relatively small portion at the front edge of the sliding surface is the anti-sliding section; most of the surface is the sliding section. Therefore, rear-row piles placed at any position on the upslope of the single-row piles along the sliding surface will reduce the forward transmission of the landslide thrust. In other words, due to the obstruction of rear-row piles, fore-row piles almost entirely bear the upslope thrust of a sliding mass between the fore- and rear-row piles, whereas the upslope thrust due to the sliding mass on the upside of the rear piles is fully borne by the rear-row piles. The downslope displacement of the rear-row piles produces a compression stress in the sliding mass
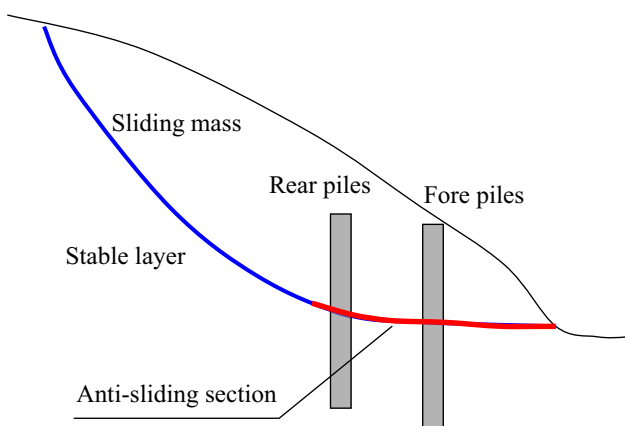

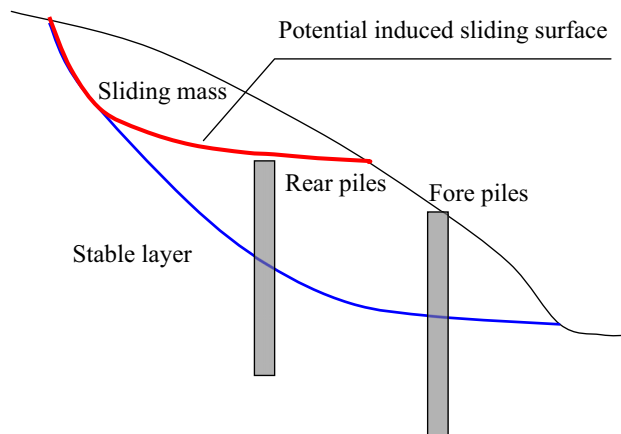Fig. 2 Rear-row piles in the anti-sliding section of the slope

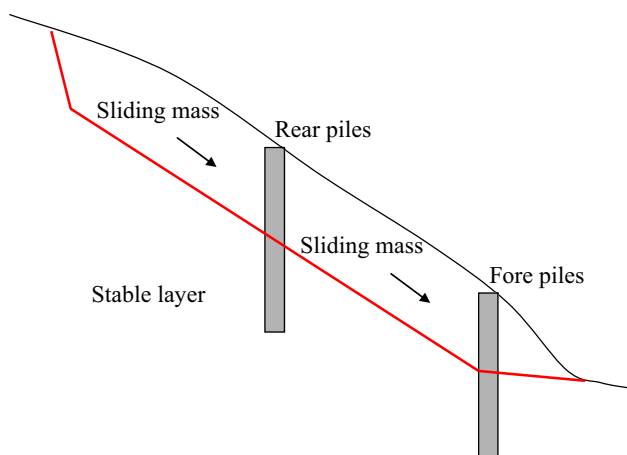Fig. 3 Rear-row piles in the sliding section

Fig. 4 Schematic diagram of landslide with a linear sliding surface reinforced by double-row piles

Fig. 5 Schematic diagram of slope test models

between the fore- and rear-row piles, which then transfers to the fore-row piles. However, in this case, the sliding mass between the pile rows is within the slip range; therefore, the compression stress transferred to the fore-row piles is quite low compared to the landslide thrust between the fore- and rear-row piles. When the distance between the fore- and rear-row piles is relatively great, this stress can even be neglected. Therefore, from the perspective of an actual field setting, with overall considerations of construction convenience and mechanical rationality, a landslide area with a linear slip surface could be reinforced with two rows of full-length stabilizing piles set a certain distance apart. In this case, the selection of the distance between the rows should account for the minimum difference of the maximum internal forces of the two rows of piles to ensure the mechanical rationality of the pile arrangement. Based on the characteristics of a landslide with a linear slip surface, it is ideal that the sliding mass directly supported by each row maintain an equal area in the plane.

Results

Tests and verifications

To further investigate and verify the rationality of the aforementioned double-row pile arrangement, two large-scale geotechnical laboratory models were developed. As shown in Fig. 5, each slope model was built layer by layer with prepared soils in a model test box. Meanwhile, three kinds of compound soil represented the stable layer, slip surface and sliding mass, respectively. Stabilizing pile models with soil pressure cells laid out on both sides of
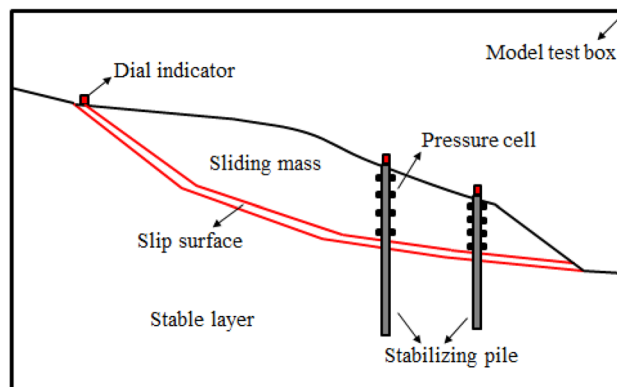
them, and dial indicators on the pile tops, were simultaneously installed in the course of building the slope model. After the whole slope model was built, dial indicators were immediately installed on the upslope surface of the sliding mass.

The main features of the tests are presented as follows:

1. The two types of actual landslides involved in this study have a basic sliding mechanism. Cracks occur on the local ground surface in the rear area of the slope as a result of slope weight action, and these cracks tend to widen and deepen further. The resistance gradually decreases in the potential sliding surface from the potential sliding mass in the rear area of the slope, particularly during rainy seasons. The related slope pressure that transfers forward via the sliding mass progressively increases. When the slope pressure transferred from the rear area to the fore area of the slope reaches a point where the shear strength of the potential sliding surface in the fore area of the slope cannot accommodate the corresponding shear stress, the entire potential slip surface of the slope will be in a limited state, i.e., the sliding crack from the fore area propagates to the rear area in the slope and forms a continuous sliding surface. The movement along the sliding surface of the rear sliding mass generates pressure to the fore sliding mass; the sliding mass moves forward and down along the sliding surface.

2. In the model tests, displacement of the piles was partially restricted so that no pile would develop excessive displacement such that relevant data could not be measured. Based on practical experience from many projects in China, the control criterion of the displacement of any pile set the horizontal displacement at the pile top not to exceed 0.5 % of the pile length.

3. In the model tests, the pressure sensors were specifically manufactured by a military factory to measure the slope pressure on the piles. These pressure sensors are characterized by a small measurement range, a high level of accuracy, and excellent moisture-proof performance. The related results of slope pressure measured by these pressure sensors in the model tests were also available.

4. A stable layer, sliding surface, and sliding mass were simulated by using different materials in the model tests. The sliding mass in the rear area of the slope was indeed observed to slide along the corresponding designed sliding surface. However, it was also observed in the tests that the upslope designed sliding mass near the rear piles did not slide along the corresponding designed sliding surface due to pile resistance; this mass tended to develop a new potential sliding surface within the designed sliding mass.

5. The sliding surfaces in the model tests were determined by the survey results of related actual landslides. The pre-determined sliding surfaces were regarded as the reference sliding surfaces for the design of the related landslide control in the model tests.

6. Based on physical and mechanical parameters of the slope models, the self-weight of each slope model was the trigger for the movement of it, and relevant calculation results of a stability analysis showed that a model slope without stabilizing piles would be unstable. With this in mind, stability tests for slopes without stabilizing piles were not conducted in this study.

7. We determined the soil properties in model tests in such a manner that the model would be in a failure state without piles, and that the landslide thrust on the rear piles in the model tests and all other soil parameters would be reasonably similar to an actual landslide of the type relevant to this study.

8. The materials of the slope models were prepared according to the related physical and mechanical parameters determined by the aforementioned requirements. Because the models in this study were used primarily for landslide control in a mountainous area, the slope models were not entirely saturated. However, the sliding surfaces were simulated to have a fair water content to simulate the saturation degree of practical sliding surfaces that were likely penetrated by rain under some extreme conditions.

9. Because of the small cross-section of the pile models, and the limited measuring conditions of the pile strains in the model tests, it was too difficult to measure the pile strains with precision. Thus, the bending moments of the piles could not to be determined based on the strains, and there was no ability to compare the measured pressure distributions and the bending moment distributions. However, the measured pressure distributions were very consistent in several tests, suggesting that the measured pressure distributions in the model tests were plausible and realistic.

10. In many practical large-scale landslide control projects that use stabilizing piles, the cross-sections of the piles are rather large; for instance, 2 m × 3 m is typical in China. The flexural rigidity of the cross-section of the piles is also significant. In addition, landslides with polyline and linear sliding surfaces have hard and stable rock strata under their sliding surfaces; the pile lengths underneath the slip surfaces are approximately equal to those above the slip surfaces. Therefore, the stable layers have strong restriction effects on the piles. Although the entire pile can develop deflection due to the slope pressure on the section above the sliding surface, this deflection would be so small that the pile can still respond elastically, particularly if the deflection under the sliding surface is even smaller than that above the sliding surface because of the strong constraint from the surrounding rock mass. Thus, the pile models are relatively rigid and fairly deflectable in the model tests in order to ensure that the deformation behaviors of practical piles could be simulated as reasonably as possible.

Landslide with polyline slip surface

As shown in Fig. 6, there are two ways to arrange the piles: as double-row full-length stabilizing piles (see Fig. 6a), and as a fore-row full-length and rear-row embedded array (where the embedded pile top depth is one-third of the sliding mass thickness at the location of the pile) (see Fig. 6b). Note that the two models differ only in the depth configuration of the rear-row piles. The test parameters used for the model slope are shown in Table 1. As indicated in Fig. 6, the elastic modulus of the modeled stabilizing piles is 0.86 GPa; their cross-sections are 5 × 7.5 cm, their lengths are as shown and the pile spacing out of plane is 20 cm (the corresponding spacing in the actual project is 8 m), in which three piles are symmetrically co-located in the longitudinal direction of the model test box, with the intermediate pile being tested. The flexural rigidity, EI, and yield moment of the pile models are shown in Table 2, where the corresponding yield moment of the actual piles is also given. The slope pressure on the portion of the piles above the slip surface is

Fig. 6 Test models of landslide with a polyline slip surface reinforced by double-row piles. **a** Rear-row full-length type. **b** Rear-row embedded type
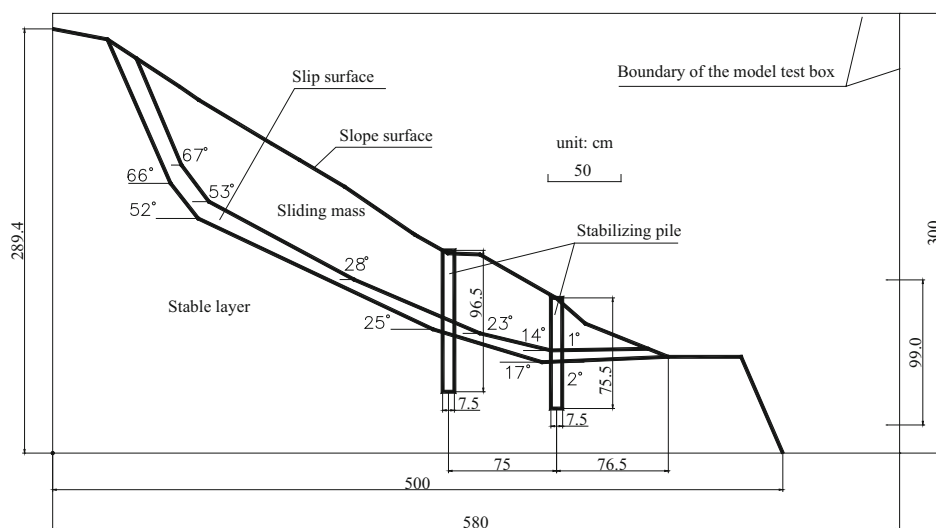
(a)
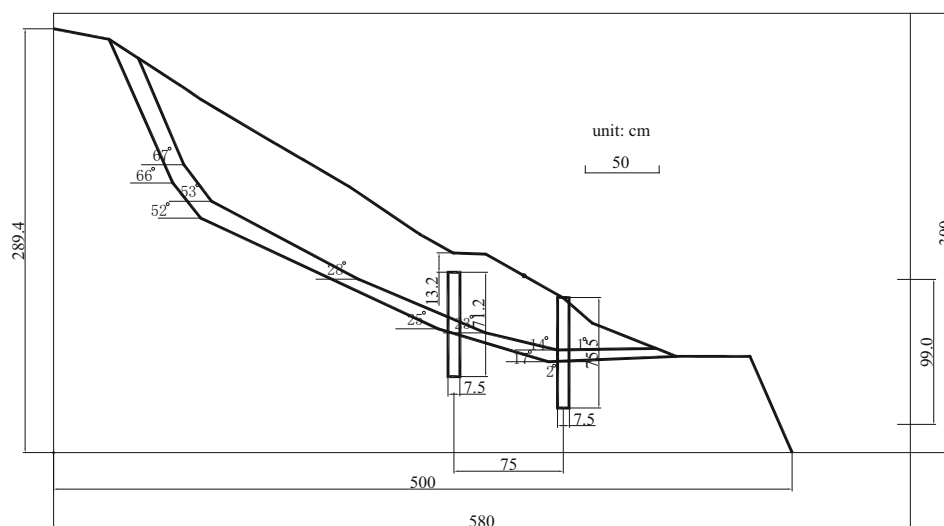
(b)

Table 1 Physical and mechanical parameters of sliding surface, sliding mass and stable layer in each test

Type of layout	Location of materials	Internal friction angle (deg)	Cohesion (kPa)	Unit weight (kN/m³)	Water content (%)
Rear-row full-length type	Sliding surface	20.6	0.5	19.3	6.21
	Sliding mass	24.5	1.6	20.5	6.09
	Stable layer	27.7	19.5	21.6	5.12
Rear-row immersion type	Sliding surface	20.3	1	20.1	7.21
	Sliding mass	24.5	1.6	20.5	6.09
	Stable layer	28.2	20.3	21.8	5.23

measured by pressure sensors deployed on the two sides of the fore and rear piles during the tests.

Test pictures are shown in Fig. 7, and net slope pressure test results of the fore and rear piles under the two conditions are shown in Table 3 and Fig. 8. The maximum horizontal displacement on the rear slope surface was 1.45 mm in the model tests with the full-length rear piles, and 1.72 mm in the model tests with the embedded rear

Table 2 Flexural rigidity (EI) and yield moment of the two types of pile models used in the tests

Type of landslide	EI of a pile (N m^2)		Yield moment of a pile (N m)	
	Model	Real project	Model	Real project
Polyline slip surface	1512	155×10^9	33	84×10^6
Linear slip surface	4780	116×10^9	78	63×10^6
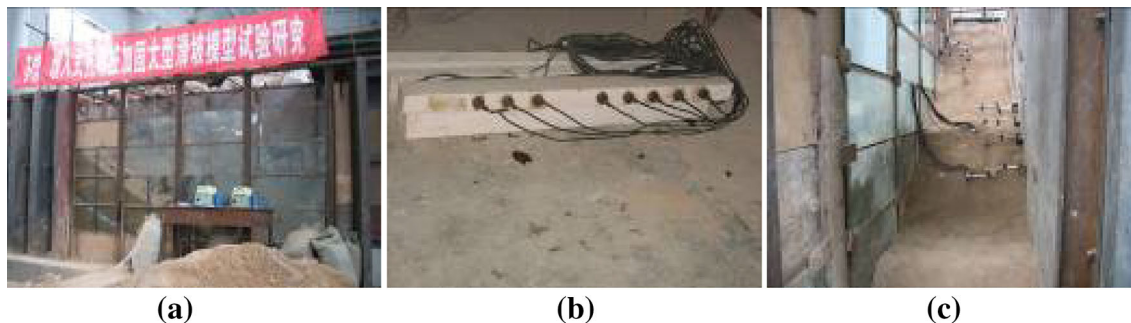
Fig. 7 Model test photos. **a** Front view. **b** Arrangement of soil pressure cells on the sides of the piles. **c** Photos of the slope surface

Table 3 Comparison of resultant of the net slope pressure on the portion of piles above slip surface under two different pile arrangements (kN/m)

	Rear-row full-length type	Rear-row embedment type
Rear-row pile	1.857	1.514
Fore-row pile	0.298	0.316

piles. Based on these results, it is clear that the net landslide thrust on the embedded rear-row pile is lower than that of the rear-row full-length type, but the thrust on the fore pile is greater than that on the rear-row full-length type. A plausible explanation for these observations is that the sliding mass over the rear-row pile top pushes forward in a deformable manner and further presses the fore pile on the embedded rear-row type, resulting in a greater net slope

pressure on the fore pile. These test results suggest that the foregoing relevant analyses are reasonable.

Landslide with linear slip surface

In the test model of the linear slip surface landslide (Fig. 9), the double-row full-length stabilizing piles were arranged with row spacings of 100 cm and 200 cm; all other parameters were the same. Test parameters for the model slope are shown in Table 4. As seen in Fig. 9, the elastic modulus of the model stabilizing piles is also 0.86 GPa; their cross sections are 6.67×10 cm, their lengths are as shown and the pile spacing out of plane is 20 cm (the spacing for the corresponding actual project is 6 m). The EI and yield moment of the pile models are presented in Table 2 along with the corresponding yield moment of the actual piles. Three of the piles are symmetrically co-located in the longitudinal direction of the model test box,

Fig. 8 Comparison of distribution pattern of the net slope pressure on loading section of piles above slip surface under two different pile arrangements. **a** Rear-row pile. **b** Fore-row pile
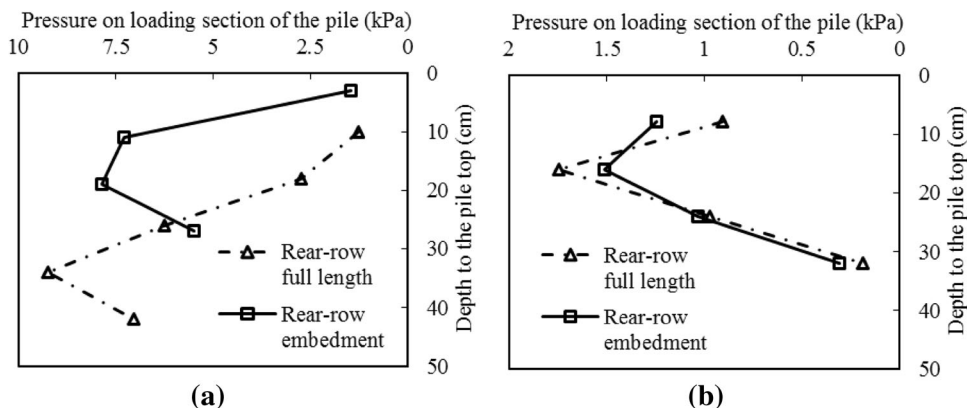
Fig. 9 Test models of a landslide with linear slip surface. **a** Small row spacing. **b** Large row spacing
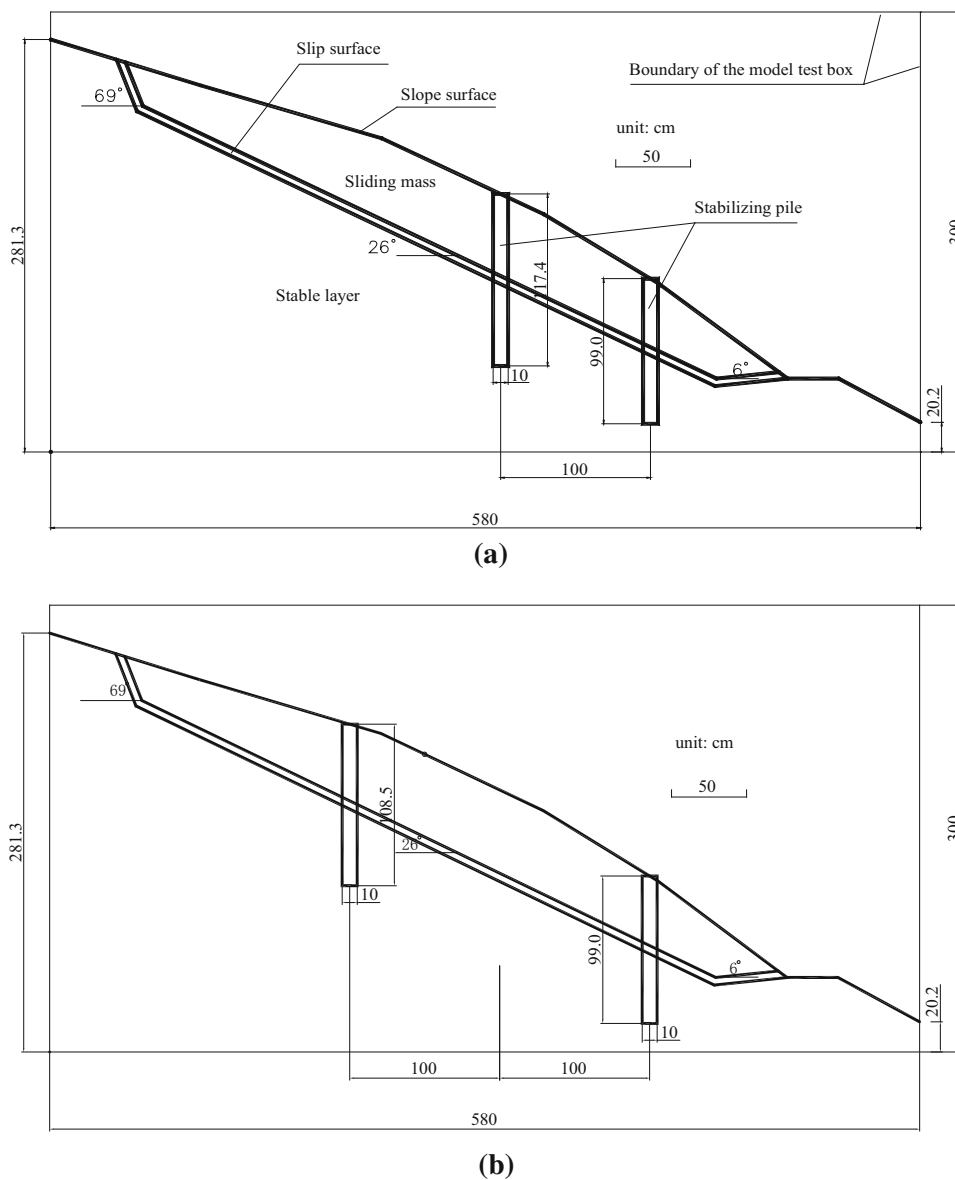

(a)

(b)

Table 4 Physical and mechanical parameters of sliding surface, mass and stable layer in each test

| Type of layout	Location of materials	Internal friction angle (°)	Cohesion (kPa)	Unit weight (kN/m^3)	Water content (%)
Smaller row spacing	Sliding surface	15.5	0.0	20.2	6.52
	Sliding mass	16.3	6.5	21.0	7.40
	Stable layer	28.2	20.3	21.8	5.23
Larger row spacing	Sliding surface	14.5	1.5	19.6	7.21
	Sliding mass	17.6	7.5	21.3	7.83
	Stable layer	28.0	18.6	21.5	5.02

with the intermediate pile being tested. The net slope pressures on the upslope sides of the fore and rear piles under two conditions are shown in Table 5 and Fig. 10.

The maximum horizontal displacement on the rear slope surface was 2.78 mm in the model tests with the smaller row spacing and 2.12 mm in the model tests with the larger

Table 5 Test results of the net slope pressure on loading section of piles under two different pile arrangements

	Smaller row spacing		Larger row spacing	
	Resultant of the pressure (kN/m)	Area of sliding mass (m²)	Resultant of the pressure (kN/m)	Area of sliding mass (m²)
Rear-row pile	2.626	1.101	1.716	0.549
Fore-row pile	1.448	0.528	2.985	1.080

Fig. 10 Test results of distribution pattern of the net slope pressure on loading section of piles under two different pile arrangements. **a** Rear-row pile. **b** Fore-row pile
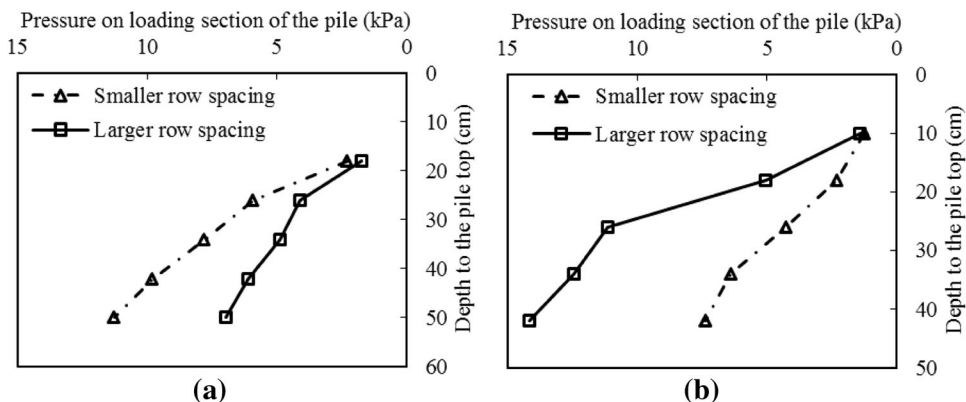
row spacing. Based on these results, we can observe that the area ratio of sliding mass blocked by the fore and rear pile is 1:0.48 with a smaller row spacing, and their net slope pressure ratio is 1:0.55. Under the larger row spacing, the two ratios are 1:1.97 and 1:1.74, respectively. These results show that the ratio of net slope pressure on the two rows of piles is very consistent in the model, with the area ratio of sliding mass blocked by each of the row piles. The above test results support the reasonableness of the foregoing relevant analysis.

Discussion

We first address the determination of an appropriate embedded depth for the rear-row pile tops under the circumstance of "embedded rear-row combined with full-length fore-row" double-row piles with a large row spacing targeting the control of a landslide with a polyline slip surface.

A finite element method using the commercial program PLAXIS (Brinkgreeve 2002) was performed to investigate this problem by analyzing the stability of a landslide with a polyline slip surface reinforced with double-row piles (Fig. 11). The stability analysis was determined for five embedded depths of 0, 4, 8, 12, and 16 m for the embedded

pile top depth of the rear-row piles. The slope and pile properties are shown in Table 6. The pile cross section size was 2 × 3 m as well as pile spacing out of plane at 6 m, and the most dangerous sliding surface locations of slope calculated under these different conditions are shown in Fig. 12. The corresponding safety factors of the slope that change with the embedded depth of the rear-row pile tops are presented in Fig. 13. These figures show that the potential failure model for a landslide reinforced with double-row piles is the sliding mass in the upslope of the rear-row piles as it passes over the top of the piles. This model is linked closely with the embedded depth of the rear-row pile top. In other words, the embedded depth of the rear-row pile top influences the slip failure model of the slope. Figure 13 shows that the safety factor of the slope is inversely proportional to the rear-row pile top depth. If the design safety factor of the slope is 1.25, then the maximum embedded depth should be less than 5.4 m. We can thus calculate the safety factor curve of the slope changing with the pile top embedded depth of the rear-row piles, and then determine an appropriate embedded pile top depth according to a design safety factor.

We then drew a rational comparison of the integrated loading of the double-row and door-type piles with a small row spacing for the control of a landslide with a polyline slip surface.

Fig. 11 Schematic diagram of numerical model for a landslide with polyline slip surface reinforced by double-row piles
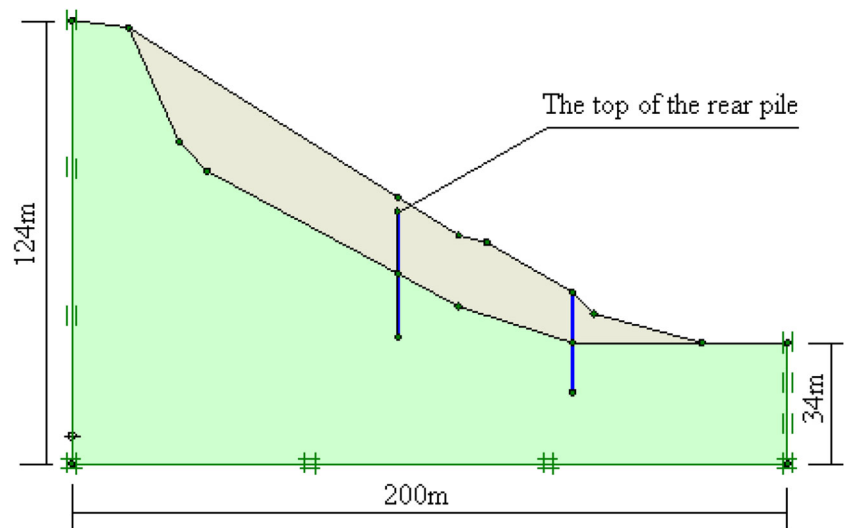

Table 6 Main properties of slope materials and stabilizing piles

Material	Unit weight γ (kN/m^3)	Cohesion c (kPa)	Internal friction angle φ (°)	Elastic modulus E (MPa)	Poisson's ratio μ	Strength weakening coefficient of pile-soil interface
Sliding mass (including slip surface)	20	30	28	30	0.33	0.6
Stable layer	22	500	35	600	0.25	0.9
Piles	25	Elastic body		30,000	0.15	–

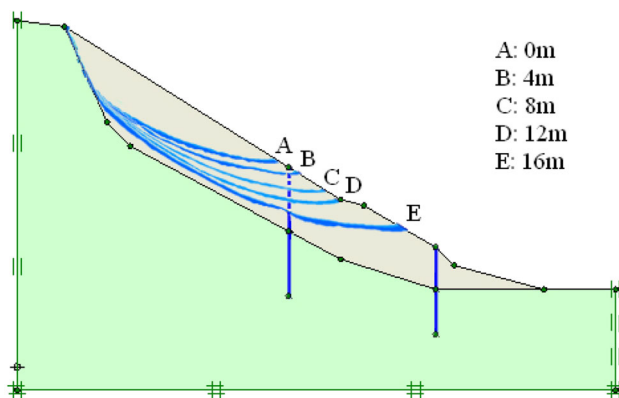**Fig. 12** Positions of the most likely sliding surface for a range of different embedded depths of the rear-row pile tops

Fig. 13 Safety factor curve of slope as a function of embedded depth of pile top of the rear-row piles

Once again, Fig. 11 is used as an example for this comparison. The finite element analysis models (see Fig. 14) indicate that the landslide is reinforced by a double-row pile with a smaller row spacing (see Fig. 14a; row spacing is 6a, where a is the width of the larger horizontal dimension of the pile cross section) and a door-t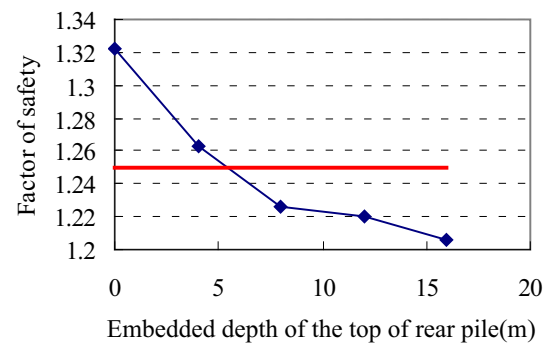ype pile configuration (see Fig. 14b; a connecting beam is located between two piles forming a door-type stabilizing structure) located at the same position. The internal forces of the two structures were then obtained through the finite element analysis method. The maximum bending moment and shear force values of the piles are given in Table 7. Distributions of bending moment and shear force on the piles by the numerical simulation method are shown in Fig. 15.
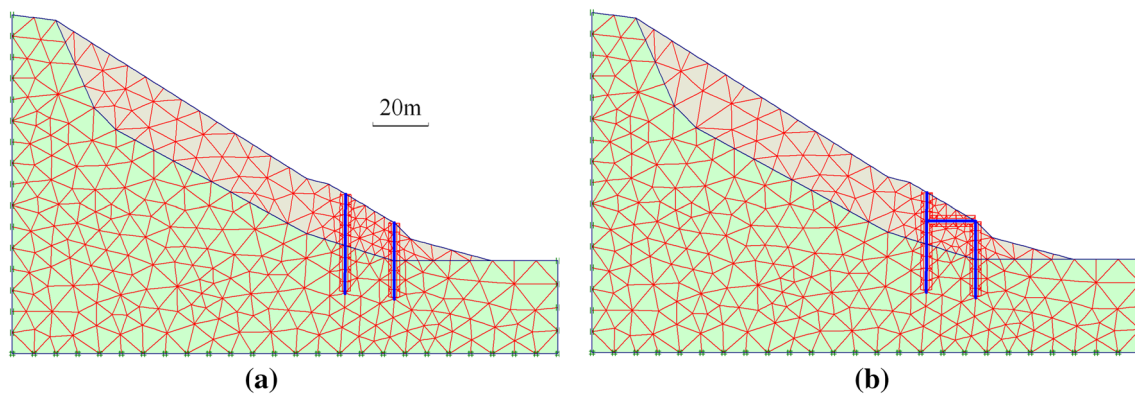
Fig. 14 Finite element model of a slope reinforced with two different types of structures. **a** Double-row piles. **b** Door-type piles

Table 7 Comparison of maximum internal forces of the piles in the two different configurations

|		Double-row piles	Door-type piles
Maximum bending moment (kN m)	Rear pile	12,352	6055
	Fore pile	6969	5138
	Sum of rear pile and fore pile	19,321	11,193
	Difference between rear pile and fore pile	5383	917
Maximum shear force (kN)	Rear pile	1521	1169
	Fore pile	923	1300
	Sum of rear pile and fore pile	2444	2469
	Difference between rear pile and fore pile	598	131

We can see that the maximum bending moment of the rear-row pile in the double-row piles is twice that of the door-type piles. In this example, the maximum bending moments of the fore-row piles under the two conditions are similar, and both are smaller than that of the rear-row piles in the double-row piles. In addition, the maximum shear force of the rear-row pile in the door-type piles is lower than that of the rear pile in the double row piles, whereas the maximum shear force of the fore pile in the door-type configuration is greater than that of the fore pile in the double-row pile configuration. However, the maximum shear force and bending moment of the fore and rear piles are close in the door-type configuration. The sum of maximum bending moments in the door-type configuration is much smaller than that of the double row pile configuration, whereas the sum of maximum shear forces in the door-type configuration is slightly greater than that of the double-row piles. These results suggest that the door-type pile configuration may be generally more economical and therefore rational than double-row piles with the same small row spacing.

Conclusions

The reinforcement of large-scale landslide controls with double-row piles is a plausible geotechnical method. However, the layout of such a scheme significantly influences pile loading. The following conclusions have been drawn:

1. For a landslide with a polyline sliding surface, a layout with embedded rear-row and full-length fore-row piles is appropriate. This design allows the reasonable loading of double-row piles and optimizes the positioning of double-row piles from both technological and economic points of view. During the design of this particular type of double-row system, an initial analysis should be performed to derive the safety factor of the slope as a function of the embedded depth of the pile top of the rear-row piles; the appropriate pile top depths according to a given design safety factor must then be determined. If the row spacing between the fore and rear full-length pile is small, they can be linked using a connecting beam to form a "door-type pile" structure; this structure

Fig. 15 Bending moment and shear force on the piles by the numerical simulation method (a) and (b), the rear-row pile (c) and (d) the fore-row pile
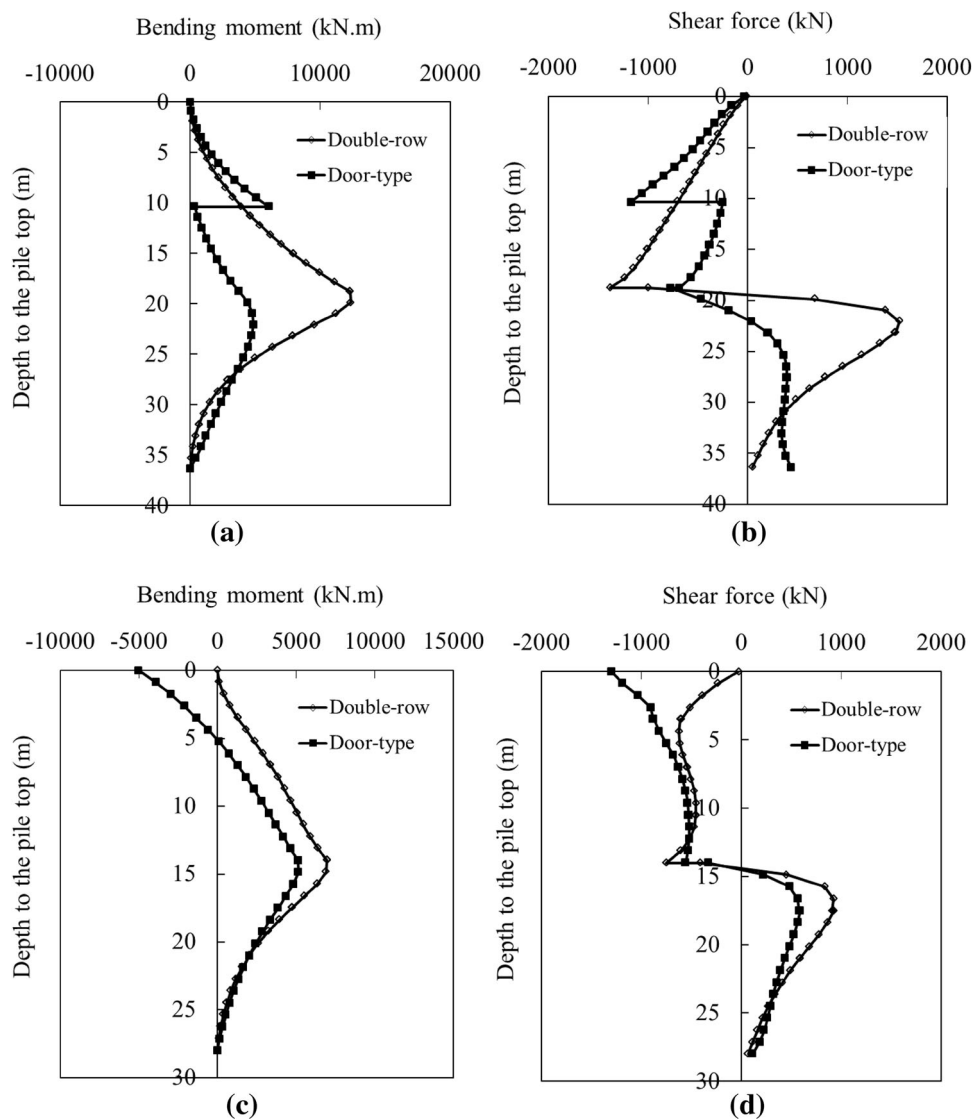
can create an almost even distribution of bending moment and shear forces on the two piles and result in an economic design.

2. Full-length double row piles can be used for a landslide control with a linear sliding surface strengthened by double-row piles. However, the row spacing should be rationally set to make the directly blocked area (in plane) of the sliding mass in the upslope of each pile nearly equal, thereby optimizing the integrated loading effect of the two piles.

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