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Research Paper

Numerical Analysis of the Factors Affecting the Anti-Slide Pile Design

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The use of anti-slide piles is one of the most important landslide remediation methods, and it is widely used in practical engineering. Anti-slide pile design elements include pile plane position and spacing, the anchorage depth, and pile cross-sectional shape and size. With the displacement of an anti-slide pile head as the evaluation index of the anti-sliding effect of anti-slide pile, ANSYS was used to establish models for numerical simulation to provide analysis of the pile spacing and to determine the anchoring depth and cross- sectional dimensions of the impact of pile top displacement. Using the control variable method, the influence trends and the degree of influence of three factors on the displacement of pile top were studied. Through this analysis, we found that the influence of the pile cross-section size change on the maximum displacement of the pile head is relatively weak, whereas the anchoring depth and pile spacing have a greater impact on the changes in the maximum displacement of the pile; there is a limit of the design parameters, beyond which improvement in the design value is not obvious regarding the limiting of the displacement of the pile top. Further study could investigate the choice of design parameters to optimize the design of anti-slide pile.

Key words: anti-slide pile, displacement, design elements, numerical analysis.

1. Introduction

Within China's vast mountainous area, a wide variety of geologic hazards occur, and landslide is one of the main geologic hazards [1]. At present, an anti-slide pile has become one of the most widely used treatments in landslide mitigation [2–4]. The anti-slide pile has many advantages, including flexible pile point arrangement, good effect and anti-slide ability, and wide scope of application [5]. In the optimal design of an anti-slide pile, to make the pile the premise of meeting the security and stability at the lowest engineering cost, one must understand the selection principle of the anti-slide pile design elements and their influence factors.

Anti-slide pile design elements include the plane position of piles, the pile section size and shape, and the depth of the pile anchorage [6]. Considerable research was conducted on landslides and anti-slide measures at home and abroad. Kellogg [7] studied the soil arching effect of soil in 1987. Poulos [8] proposed an approach for the design of piles to reinforce slopes. Muraro *et al.* [9] carried out three-dimensional finite element analyses to investigate the response of a single pile when subjected to lateral soil movements. Kahyaoglu *et al.* [10] adopted three-dimensional finite element analyses to evaluate the load transfer mechanism of free head passive pile groups in purely cohesionless soils, and it was observed that the load transfer decreases parallel to a decrease in pile spacing for piles adjacent to embankments contrary to piles used for slope stabilization. Miao *et al.* [11] brought three-dimensional finite element analyses to investigate the response of a single pile when subjected to lateral soil movements. Kanagasabai *et al.* [12] investigated the behavior of a single pile used to stabilize a slipping mass of soil by using embedment into a stable stratum. Kourkoulis *et al.* [13] developed a hybrid method for designing slope-stabilizing piles, combining the accuracy of rigorous three-dimensional (3D) finite-element (FE) simulation with the simplicity of widely accepted analytical techniques. Kourkoulis *et al.* [14] used a hybrid method for analysis and design of slope stabilizing piles to gain insights about the factors influencing the response of piles and pile-groups. In this paper, the FE established by ANSYS was used to analyze the pile spacing and to determine the anchoring depth and sectional dimensions of the impact of pile top displacement.

2. Design elements of the anti-slide pile

Anti-slide pile design elements include the plane arrangement of the anti-slide pile, the pile spacing, the pile anchorage depth and the pile cross-sectional size.

2.1. The plane position and spacing of piles

To confirm the plane position and anti-slide pile spacing, we must consider such factors as the landside formation properties, the size of the thrust, the landslide sliding surface slope, the sliding body thickness, and the construction conditions. In the upper part of the landslide, where the sliding surface is steep, there are many slippery tension cracks, and anti-slide piles should not be placed there; in the middle part of the landslide, where a sliding surface is deep and downward force is large, anti-slide piles also should not be placed; in the lower sliding surface, where the slope is more gentle, and the sliding force is reduced, a certain amount of pile resistance can be provided, making it a good location for anti-slide piles.

The pile spacing should meet the requirement that the soil between piles has sufficient stability. Determination of the pile spacing depends on the size of the landslide thrust, the density and strength of the slippery soil, the pile-sectional size, the pile length, the anchoring depth, and the construction conditions.

2.2. The anchorage depth of the piles

The depth of the pile buried in the sliding soil is the anchoring depth of the pile. If the anchoring depth is too shallow, the stability of the pile is poor and the anti-sliding ability is weak; if the anchoring depth is too deep, construction difficulties and material waste arise. Having determined the position and depth of the pile, the pile length is also confirmed.

2.3. Cross-sectional shape of the pile

The cross-sectional shape of the pile has an important influence on the anti-sliding ability. Rectangular and circular shapes are the primary cross-sections of anti-slide piles. The cross-sectional shape of the pile should enable its upper bearing cross-section to produce larger positive friction, and the lower cross-section should produce larger resistance; also, the cross-section should have a good flexural and shear strength. Currently, the rectangular cross-section is generally used in the design of anti-sliding piles, and the force is acting on the short edge.

3. Finite element model and parameter selection

In this paper, the finite element software ANSYS was used.

A generalized model of an anti-slide pile is established using ANSYS to simulate an anti-slide pile force under different working conditions, taking the displacement of the pile top as the observation point to determine the reasonable value ranges of the design elements. In this model, both SOLID65 and SOLID95 units are primarily used. The sliding bed (gravel) and sliding body (sand) are simulated using SOLID95 and the reinforced concrete anti-slide pile is simulated using SOLID95.

3.1. Establishment of the model

In the numerical simulation presented in this paper, three factors are considered, *the anchoring depth*, *the pile spacing and the cross-sectional size*. By examining the effect of each of these factors on the displacement of the pile, the analysis of the reasonable values of the three elements is performed.

First, the geometric size of the finite element model is shown in Figs. 1 and 2, respectively. The sides along both long edges are constrained and other sides along short edges are free. According to the geometric size, the analysis model established by ANSYS is shown in Fig. 3.

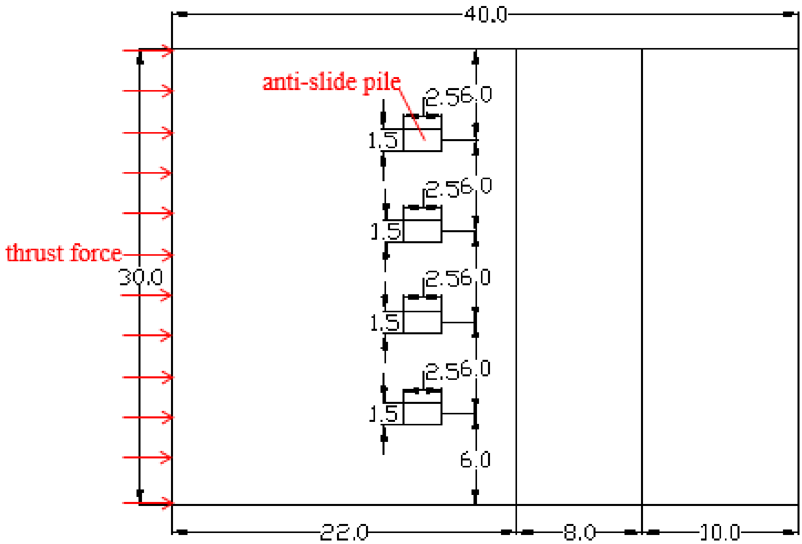

FIG. 1. The generalized model of a landslide [m].

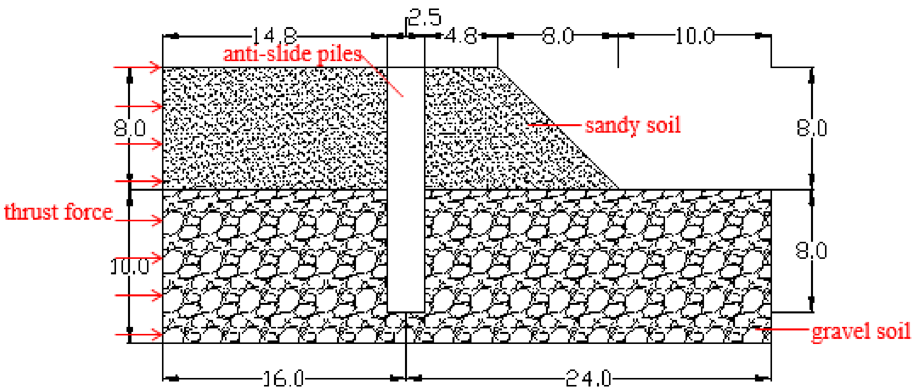

FIG. 2. The elevation of the generalized model of a landslide [m].

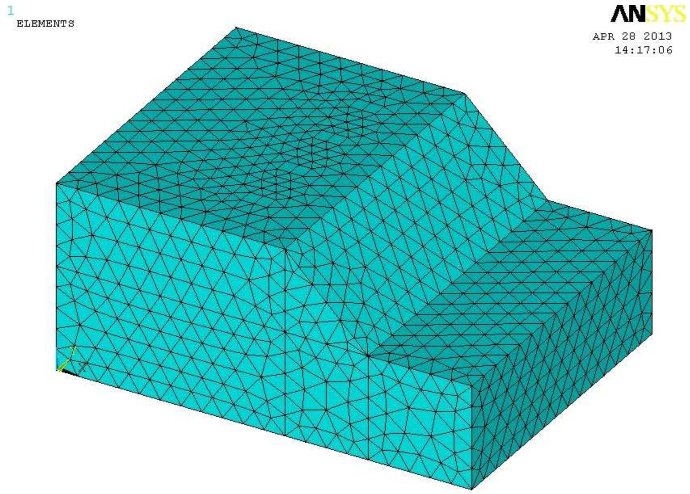

Fig. 3. Models for the finite element analysis.

3.2. Parameter selection

Based on the studies and the related data, the simulation parameters were selected as presented in Table 1.

Table 1. Parameters of the model materials.

Material	Modulus of elasticity [MPa]	Poisson's ratio	Density [kg/m^3]	Cohesion force [kPa]	Friction angle [°]
Sandy soil	1.0	0.2	1600	8	15
Gravel soil	1.95	0.25	2200	0.01	39
Concrete	$2.55 \cdot 10^4$	0.2	2500	–	–

4. Numerical simulation

4.1. Anchorage depth changes

According to engineering practice, the commonly used anchoring depth for soil or soft rock strata is approximately 1/3 to 1/2 of the pile length; for high integrity soil and hard rock, an anchoring depth of 7 1/4 of the pile length can be chosen. The landslide is assumed 30 m in width, the pile cross-section is assumed 1.5×2.5 m, the pile spacing is assumed 6 m, and the thrust force of 500 kN/m is exerted onto the sliding body. For different pile anchorage depths ranging from 3 m to 9 m, the sliding body's displacement images under different conditions are shown in Figs. 4–10.

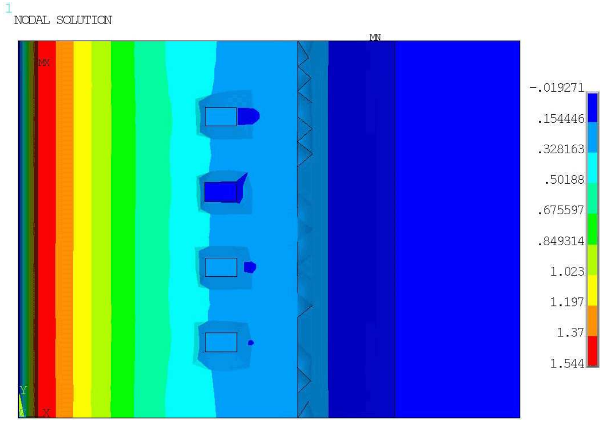

FIG. 4. The displacement image of an anchoring depth of 3 m.

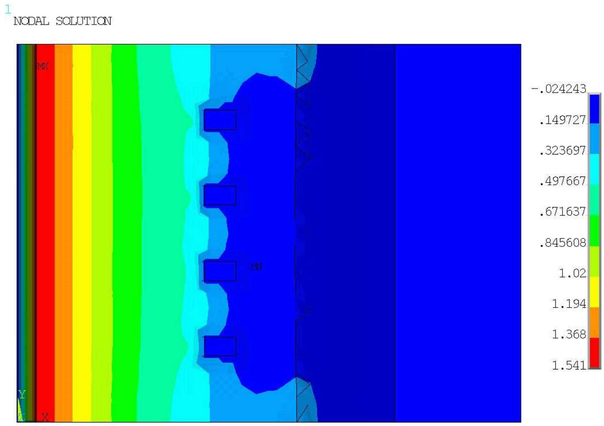

FIG. 5. The displacement image of an anchoring depth of 4 m.

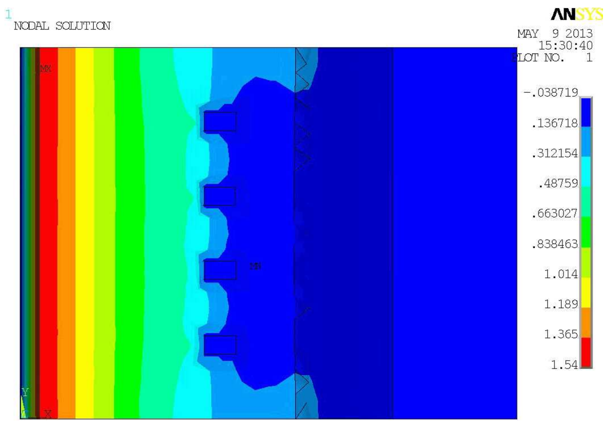

FIG. 6. The displacement image of an anchoring depth of 5 m.

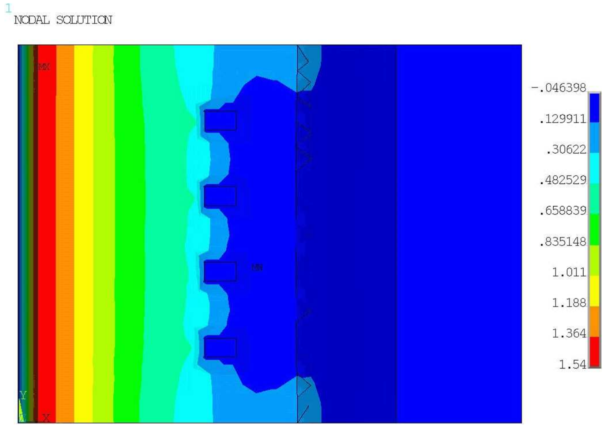

FIG. 7. The displacement image of an anchoring depth of 6 m.

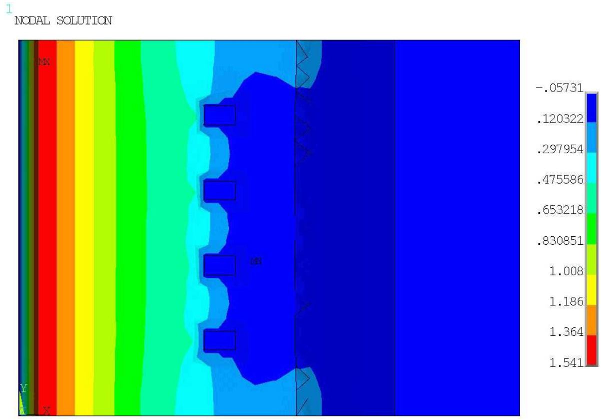

FIG. 8. The displacement image of an anchoring depth of 7 m.

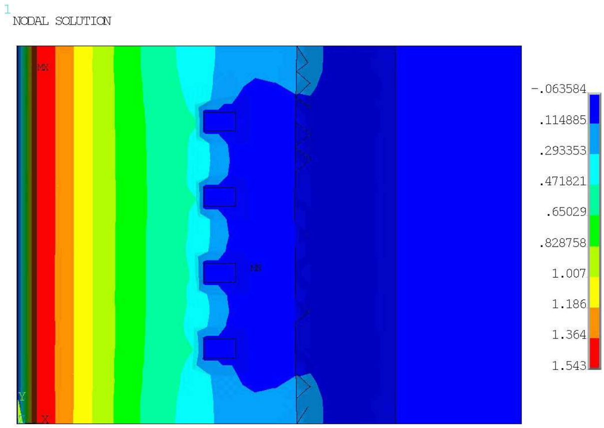

FIG. 9. The displacement image of an anchoring depth of 8 m.

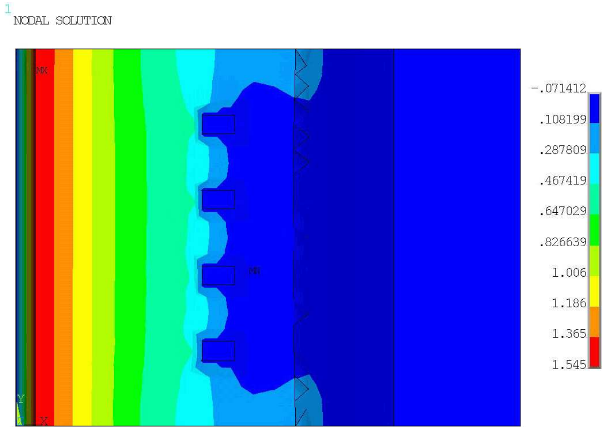

FIG. 10. The displacement image of an anchoring depth of 9 m.

From the above displacement images, we know that for different anchorage depths, the maximum displacement of the pile head changes greatly. Figure 11 shows that the maximum displacement decreases with an increase of the pile anchorage depth. When the anchorage depth reaches 7 m, which is approximately 1/2 of the pile length, the trend of the displacement becomes weaker. After achieving the stability of the pile, an additional increase in the anchoring depth has little effect on the limit of the pile displacement. There is a critical value beyond which improvement of the anchorage depth does not have a significant effect in limiting the displacement.

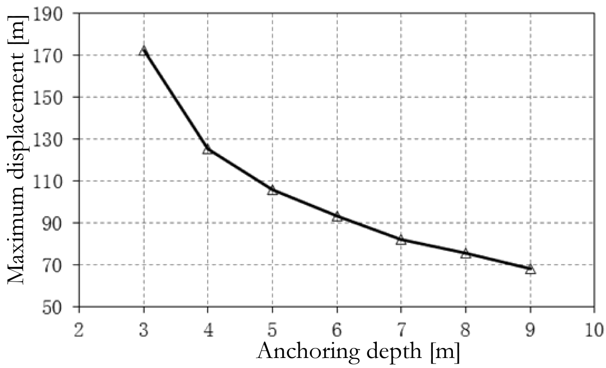

FIG. 11. The relation curve between the maximum displacements of the pile head and the anchoring depth.

4.2. Pile spacing changes

In the design of an anti-slide pile, the pile spacing is also a very important factor. If the pile spacing is too large, then the sliding body may slip from the piles, and the anti-slide pile does not work, if the pile spacing is too small, then we cannot make a full use of the soil arch effect. The landslide is assumed 30 m in width, pile cross-section is assumed 1.5×2.5 m, the anchorage depth is assumed 6 m, and 500 kN/m of thrust force is exerted on the sliding body. For different pile spacing ranging from 4 to 10 m, the sliding body's displacement images under different conditions are shown in Figs. 12–18.

The above displacement images show that with an increase of the pile spacing, the displacement of the pile head increases gradually, but the displacement does not change significantly. Therefore, to achieve the stability of the structure, the pile spacing can be appropriately increased. From the relation curve, we know that an excessive decrease of the pile spacing did not significantly reduce the displacement of the pile head. As with the anchorage depth, the pile spacing value also has a critical value, below which the reduction of the pile spacing does not have a significant effect on limiting the displacement.

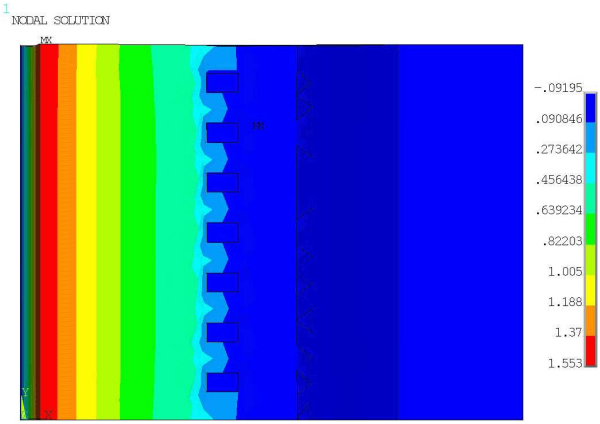

FIG. 12. The displacement image of the pile spacing for 4 m.

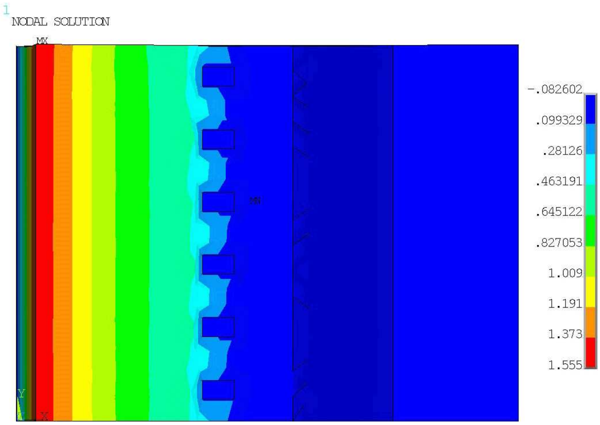

FIG. 13. The displacement image of the pile spacing for 5 m.

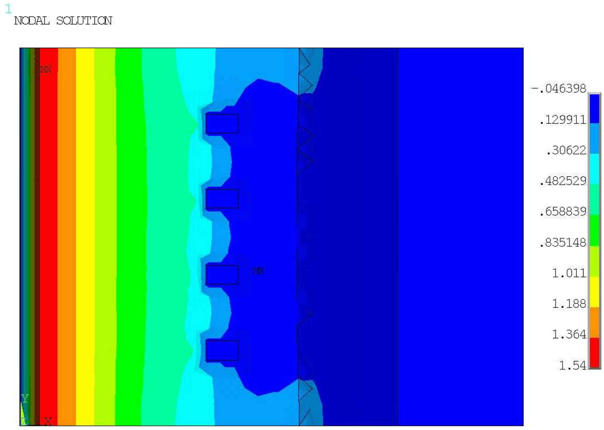

FIG. 14. The displacement image of the pile spacing for 6 m.

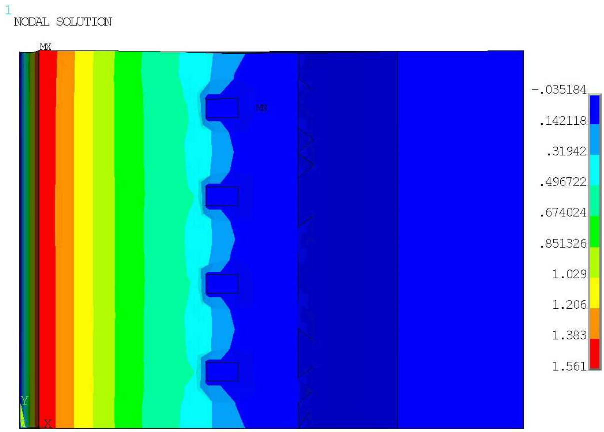

FIG. 15. The displacement image of the pile spacing for 7 m.

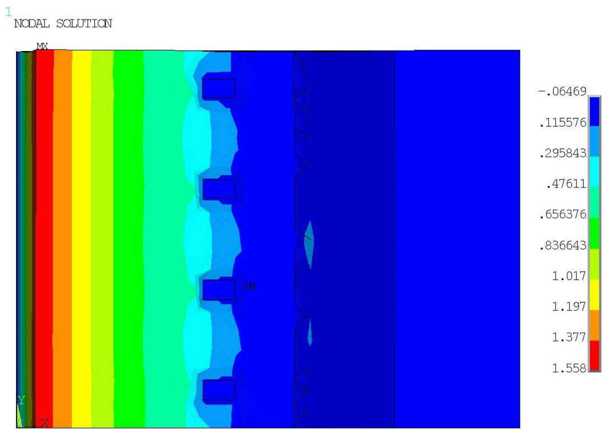

FIG. 16. The displacement image of the pile spacing for 8 m.

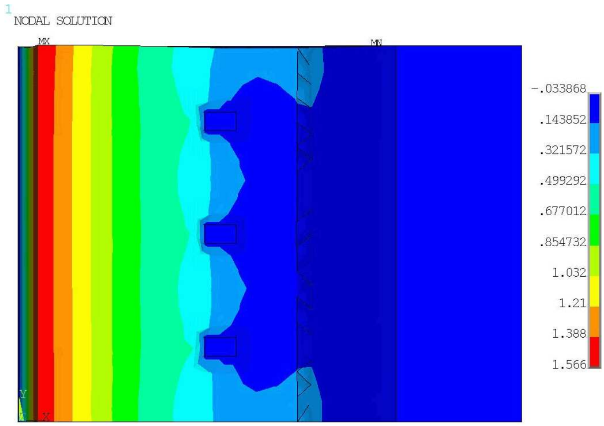

FIG. 17. The displacement image of the pile spacing for 9 m.

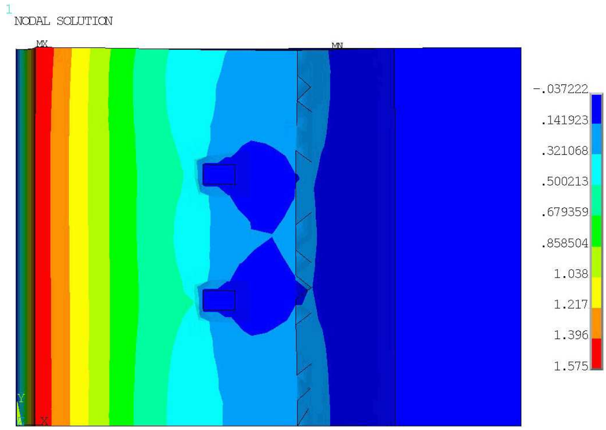

FIG. 18. The displacement image of the pile spacing for 10 m.

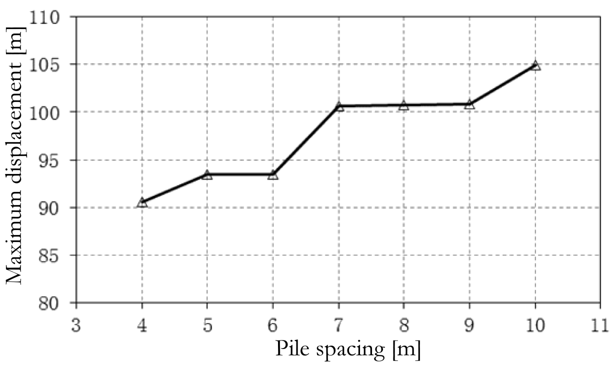

FIG. 19. The relation curve between the maximum displacement of the pile head and the pile spacing.

4.3. *Cross-sectional size changes*

The landslide width is assumed to be 30 m and the pile spacing and the anchoring depth are assumed to be 6 m each. In the case of changing the pile cross-section, we analyze the change of the maximum displacement of the pile head. The sliding body's displacement under different conditions is presented in Figs. 20–25.

As shown in the images above, along with an increase of the cross-sectional size of the pile, the displacement of the pile head is decreased. In Fig. 26, when the cross-section increases to a certain limit, the change of the displacement is not obvious with an increase in the cross-section. Therefore, to meet the structural strength and stability, blindly increasing the cross-sectional size is not reasonable. This will increase the difficulty of construction and the project

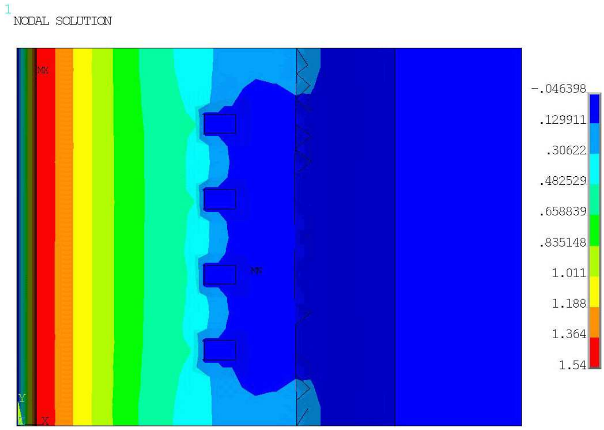

FIG. 20. The displacement image of pile cross-section of 1.5×2.5 m.

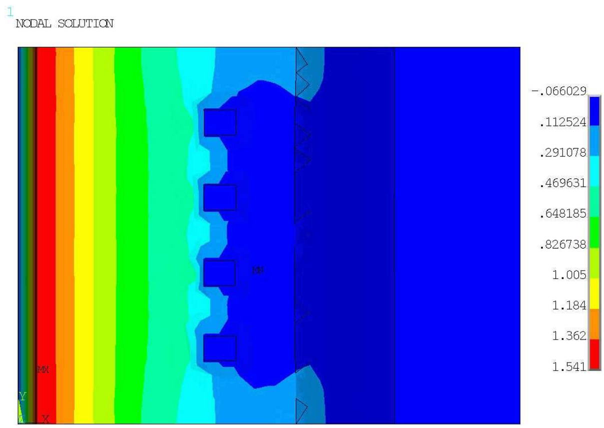

FIG. 21. The displacement image of pile cross-section of 2.0×2.5 m.

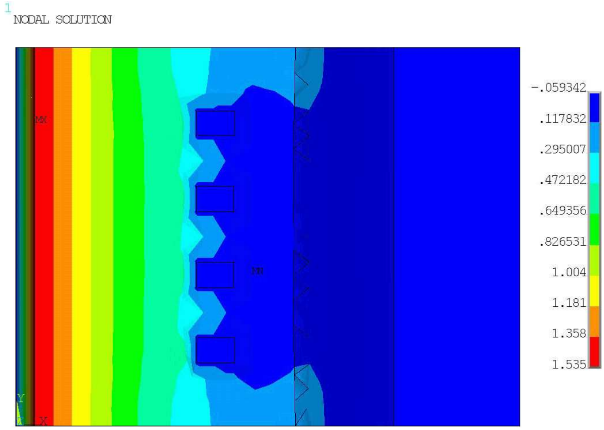

FIG. 22. The displacement image of pile cross-section of 2.0 × 3.0 m.

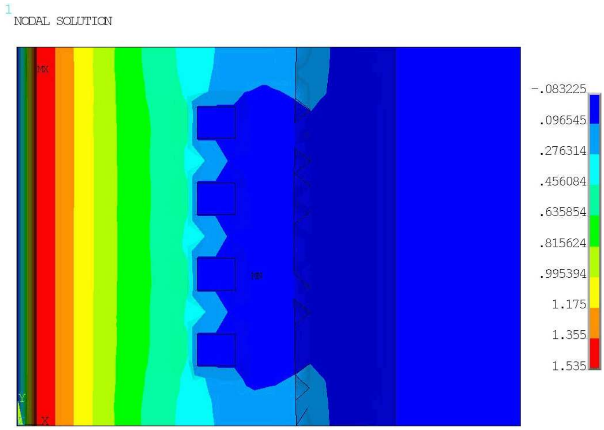

FIG. 23. The displacement image of pile cross-section of 2.5 × 3.0 m.

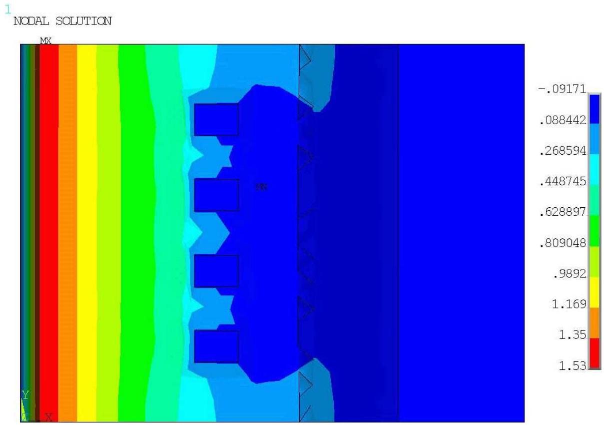

FIG. 24. The displacement image of pile cross-section of 2.5 × 3.5 m.

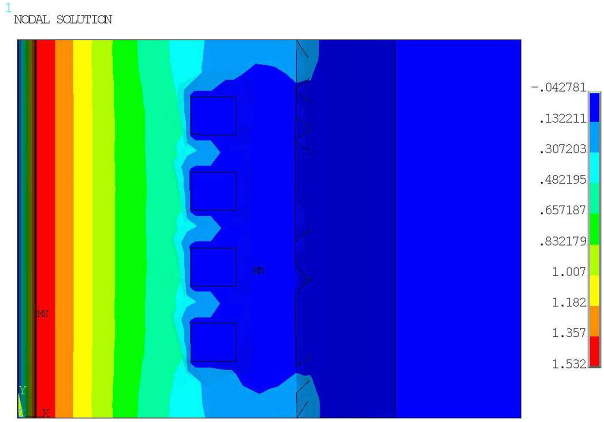

FIG. 25. The displacement image of pile cross-section of 3.0 × 3.5 m.

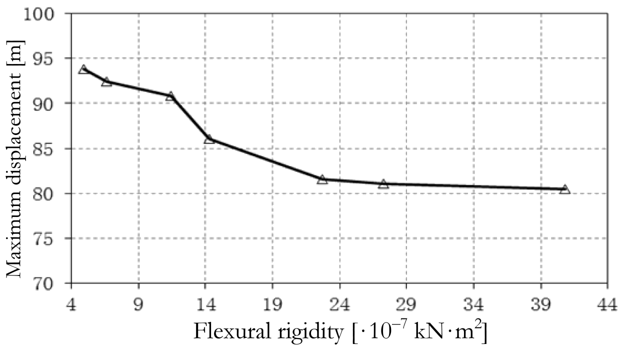

FIG. 26. The relation curve between the maximum displacement of the pile head and the pile cross-section.

cost. Accordingly, once the structural strength and stability are satisfied, we should design the cross-section to be as small as possible.

5. Conclusions

1. The anchorage depth, pile spacing and cross-sectional size greatly influence the displacement of the anti-slide pile head, and the degrees of influence of each factor are not identical.
2. The displacement of the pile head decreases with an increase of the anchorage, and the cross-sectional size and the displacement also decrease with the reduction of the pile spacing, which indicates that a critical value exists for these three factors.

3. In these three factors, the influence of the cross-sectional size on the maximum displacement of the pile head is relatively weak, and the influence of the anchorage and the pile spacing are relatively greater.
4. In the design of an anti-slide pile, these three parameters can be optimized to make the anti-slide pile design and construction more convenient and economical on the premise of meeting the security and stability requirements.

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