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Physical test study on double-row long-short composite anti-sliding piles

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Abstract. The double-row long-short composite anti-sliding piles system is an effective way to control the landslides with high thrust. In this study, The double-row long-short composite anti-sliding piles with different load segment length (cantilever length) and different pile row spacing were studied by a series of physical tests, by which the influences of load segment length of rear-row piles as well as pile row spacing on the mechanical response of double-row long-short composite anti-sliding pile system were investigated. Based on the earth pressures in front of and behind the piles obtained during tests, then the maximum bending moments of the fore-row and the rear-row piles were calculated. By ensuring a equal maximum moments in the fore-row and the rear-row piles, the optimum lengths of the rear-row piles of double-row long-short composite system under different piles spacing were proposed. To investigate the validity of the reduced scale tests, the full-scale numerical models of the landside were finally conducted. By the comparisons between the numerical and the physical test results, it could be seen that the reduced scale tests conducted in this study are reliable. The results showed that the double-row long-short composite anti-sliding piles system is effective in the distribution of the landslide thrust to the rear-row and the fore-row piles.

Keywords: anti-sliding pile; double-row long-short composite system; load segment length; pile row spacing; earth pressures

1. Introduction

Landslide, as a geological disaster, is the 7th largest killer among natural disasters (Herath *et al.* 2009) and contributes to about 17% of mortalities (Kjekstad *et al.* 2009). In order to reduce the economic losses and casualties due to landsides, effective landslides prevention and mitigation methods are needed. In recent years, anti-sliding piles have been increasingly used in landslide stabilization and control (Yu *et al.* 2014, Ellis *et al.* 2010, Li *et al.* 2010), and it have been studied

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by a lot of physical tests home and abroad (Lirer 2012, Song *et al.*, Li *et al.* 2016). Compared with the single-row anti-sliding piles, the double-row anti-sliding piles are more common in large scale landslides control because of the larger lateral stiffness and the more powerful anti-sliding capability (Leung *et al.* 2003, Won *et al.* 2009, Kang *et al.* 2009, Yu *et al.* 2012). However, for the cantilever type of double-row anti-sliding piles, the distributed thrust force of the rear-row piles are usually significantly higher than fore-row piles, which may induce the progressive failure probability of the multi-row pile system under the uneven loadings (Kourkoulis *et al.* 2011, Xiao *et al.* 2011, Tang *et al.* 2010). To ensure a relatively equal thrust on the rear-row and the fore-row piles, based on the physical test results from both the pile systems with the full-length and the buried rear-row piles, a specific double-row long-short piles system was proposed by Xiao *et al.* (2016).

However, for such a new type of double-row long-short composite pile system, the mechanical behavior and the rationality arrangement of the piles are still needed further investigation because of the previous researches on anti-sliding piles are all focused on the common anti-sliding piles with full-length rear-row piles (Guo *et al.* 2009, Ashour *et al.* 2012, Kourkoulis *et al.* 2011). Based on the relationship between the safety factor and the buried depth of the rear-row piles derived from both physical tests and numerical modeling, the optimal buried depth for the rear-row piles under the circumstance of ‘‘buried rear-row combined with full-length fore-row’’ pile system has been discussed by Xiao *et al*. (2015, 2016). Based on numerical model of double-row long-short composite anti-sliding piles, the maximum bending moments and shear forces in the fore-row and the rear-row piles with different embedded depths of the rear-row piles were studied (Shen *et al*. 2015).

However, the influences of the load segment length (cantilever length) of the rear-row piles as well as pile row spacing on the mechanical response of the fore-row and the rear-row piles have not been fully considered. In addition, the optimal length of the rear-row piles for double-row long-short composite anti-sliding piles under different piles spacing is still needed to be further determined. In this study, the double-row long-short composite anti-sliding piles with different load segment length (cantilever length) and different pile row spacing were studied by a series of physical tests, by which the influences of load segment length of rear-row piles as well as pile row spacing on the mechanical response of double-row long-short composite anti-sliding pile system were investigated. Based on the maximum moments developed at the fore-row and the rear-row piles, the optimal length of rear-row piles under different piles spacing for double-row long-short composite system was discussed. To investigate the effect of reduced scale tests, the full scale numerical model of landside were conducted. By the comparisons between the numerical and the physical test results, the reduced scale tests conducted in this study were proved to be reliable.

2. Physical tests of double-row long-short composite anti-sliding piles

2.1 Test model

The physical tests conducted in this study were mainly focused on the investigation of the influences of landslide thrust, load segment length of rear-row piles and the pile row spacing on the earth pressures in front of (resistance forces)and behind (thrust forces) the fore-row and the rear-row piles. Based on the relationship between the internal forces and bending moment of the piles, the effect of the rear-row pile lengths on the bending moments of the piles is investigated.

By ensuring an equal maximum moment in the fore-row and the rear-row piles, the optimal length of the rear-row piles was suggested. To simulate the real work condition of cantilever anti-sliding piles, horizontal thrust forces are applied by jack to a flat thrust plate between the jack and the sliding body, then the thrust forces is uniformly applied to the sliding body. During tests, the earth pressures in front of and behind the fore-row and rear-row piles as well as the pile top displacements were measured.

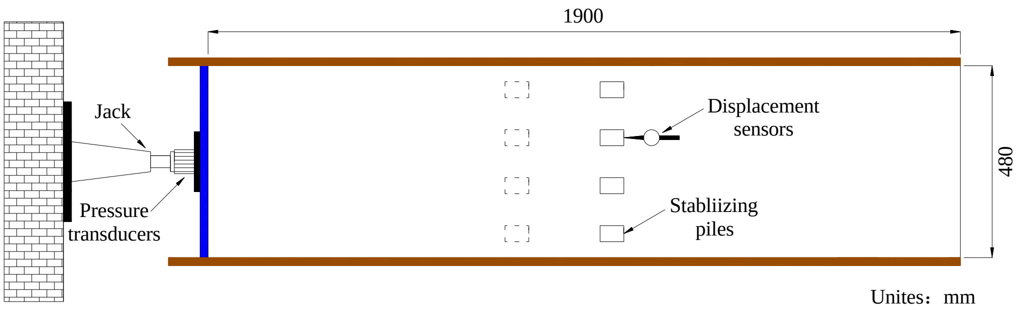


Fig. 1 Layout of the test model

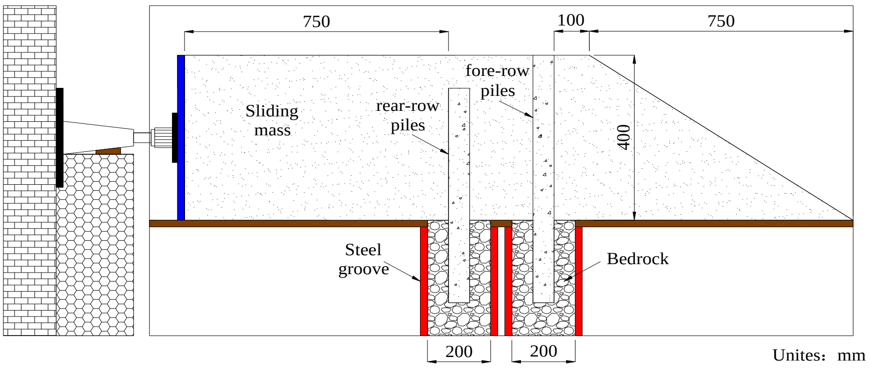


Fig. 2 Sectional drawing of the test model

(a) Actual model (b) Steel grooves

Fig. 3 Actual model and the steel grooves

As seen from Figs. 1 and 2, the model box mainly consists of the base panel, side panels and webs, which were all made of wood. In order to fix the model box, the four sides of the box were welding fixed by angle steel. The middle part of the box was reinforced by flat steel. In order to fixed the fore-row and the rear-row piles, two fixing grooves were fixed at the bottom of the box, as shown in Fig. 2. The length of the box was 1.90 m, and the clear distance of the side panels was 0.48 m. The depth of the fixing grooves was 0.40 m, and the clear distance between two groove webs was 0.20 m. In the tests, two rows of piles were inserted into the grooves, which were fully filled with compacted rock to simulate the fixed effect of the rock in site. The designed height of the landslide body was 0.40 m. The test box is shown in Fig. 3.

2.2 The fixation of the piles and the filling of the landslide body

Because the main aim of this study was to investigate the influences of the load segment length of the rear-row piles and the pile row spacing on the internal forces of the fore-row and the rear-row piles, the deformation of the piles during tests was kept in the elastic stage. The stainless steel pipes were used as the anti-sliding piles in the test, due to their rigidity can be easily controlled by adjusting the wall thickness of the pipes. In the tests, rectangular steel piles (40 mm×60 mm) with 1.2 mm wall thickness were adopted. The full length of the fore-row piles was 600 mm, including the 200 mm embedded segment and the 400 mm load segment. The length of the embedded segment of the rear-row piles was 200 mm, however, the length of the embedded segment of the rear-row piles was various, so that the length of the rear-row piles included 440 mm, 400 mm and 360 mm. Fig. 4 shows the pictures of the piles used in the tests. The material used to build the slide body consisted of clay and several crushed rock. The material used to fill the fixing grooves was crushed rock, and it was fully compacted to simulate the effect of bedrock in site. Fig. 5 shows the pictures of the mixture of the landslide soil and the crushed rock.

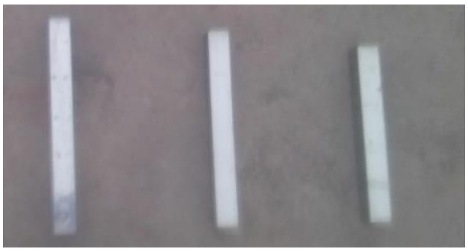


Fig. 4 Pictures of piles used in the tests

(a) Mixture of landslide mass

(b) Crushed rock

Fig. 5 Pictures of the mixture of landslide soil and the crushed rock

2.3 Arrangement of the pressure cells

The pressure cells were fixed behind and in front of the piles to measure the landslide thrust behind the piles and the resistant forces in front of the piles respectively. The detail arrangement of pressure cells along the piles are shown in Fig. 6.

2.4 Loading and monitoring systems

2.4.1 Loading system

Because the size of the test model was relatively small, the landslide thrust is also small. Therefore, a mechanical jack with 3 t maximum thrust was used as loading system. A mechanical sensor with maximum range 2 t was used to measure the thrust applied by the jack. The jack and the sensor used in the tests are shown in Fig. 7.

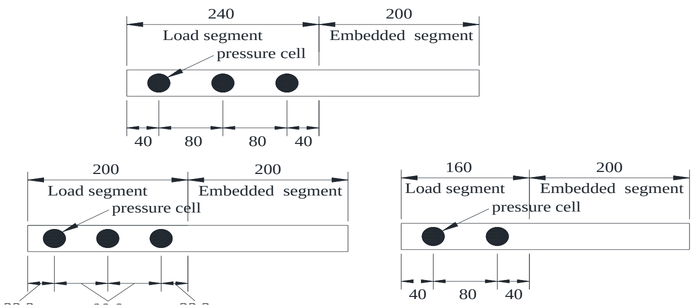
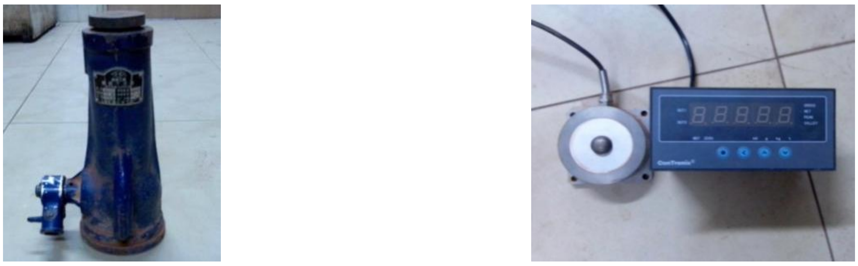


Fig. 6 Arrangement of pressure cells along the piles



(a) Jack (b) Pressure transducer and displayer

Fig. 7 Loading system used in the tests

(a) Data collector (b) Displacement sensor

Fig. 8 Monitoring system used in the tests

2.4.2 Monitoring system

In order to measure the internal forces of the piles, the pressure cells were connected to the DH3818 static resistance strain gauge were used in the tests, as shown in Fig. 8(a). The dial indicators were used to measure the displacements of the pile tops, as shown in Fig. 8(b).

Fig. 9 Schematic diagram of step 2

Fig. 10 Schematic diagram of step 4

Fig. 11 Schematic diagram of step 5

2.5 Test procedures

Changing the length of the rear-row piles, and the following procedures were repeated:

(1) First, fix the grooves at the bottom of the model box. Then fix the piles into the grooves. Fill the grooves with fully compacted crushed rock at last.

(2) Fix the pressure cells as shown in Fig. 9, and connected them to the DH3818 static resistance strain gauge.

(3) To reduce the friction between the slope and the box, plastic films were installed around the model box. Then fill the model box with the mixture. To obtain a dense slope with a height of 0.4 m, the landslide body was filled by layered compaction, and the hammer is used to compact the soil, which could provide the same pressure each time. The front part of the slope was naturally sloped as shown in Fig. 2.

(4) The mechanical jack and the pressure sensors were installed at the back of the bulldozing plate as shown in Fig. 10. The pressure sensors were connected with the pressure displayer. The dial indicator was installed at the top of the piles.

(5) Before testing, the initial data of the pressure cells, dial indicators and the pressure sensors are set to be zero. Apply the thrust gradually to the bulldozing plate in six steps by the mechanical jack. The time interval between two steps was 15 minutes. In each step, a 1.2 kN load was applied. During the tests, the earth pressures in front and behind of piles, the thrust of the jack, the displacement of pile tops and the extension length of the jack were recorded. The schematic diagram of step 5 is shown in Fig. 11.

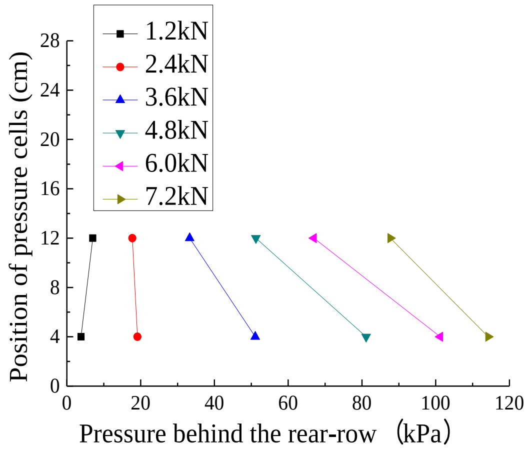
2.6 Test conditions

In this study, a total of six cases with different pile arrangement were conducted. In order to investigate the pile row spacing effect, two groups of tests with different pile row spacing 120 mm and 240 mm were conducted. In order to investigate the effect of the length of rear-row piles, three groups of tests with different load segment length of rear-row piles 240 mm, 200 mm and 160 mm were conducted.

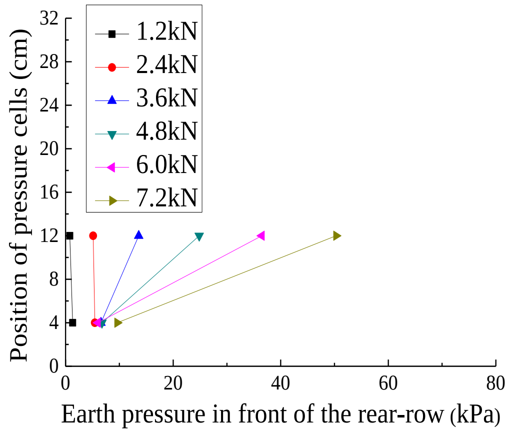
3. Test results

3.1 Effect of the landslide thrust force on the earth pressures of the piles

During tests, the landslide thrust force was applied gradually in steps. The variations of earth pressures in front and behind of the fore-row and the rear-row piles were measured. Fig. 12 and Fig. 13 show the variation of earth pressures in front and behind of the fore-row and rear-row piles with the applied thrust and the load segment length of 160 mm of the rear-row piles. As illustrated in Figs. 14 (a) and 14(b), the earth pressures behind the rear-row piles were high at the upper part and low at lower part, and the earth pressures in front of the rear-row piles are low at upper part and high at lower part. As observed from Figs. 13(a) and 13(b), the distribution of earth pressures behind the fore-row piles was anti-“S” shape, and the earth pressures in front of fore-row piles were high at the middle and low at the two ends of the piles. It can also be observed from Figs. 12 and 13 that all of the earth pressures increased with the increase of the applied thrust. However, because there was little soil in front of the tops of the fore-row plies, and these soils might move

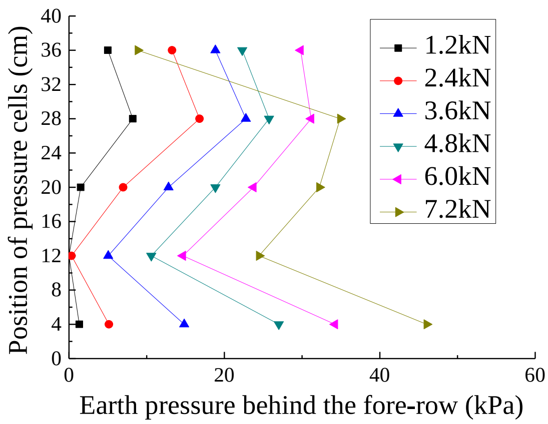


(a) Earth pressures behind the rear-row piles

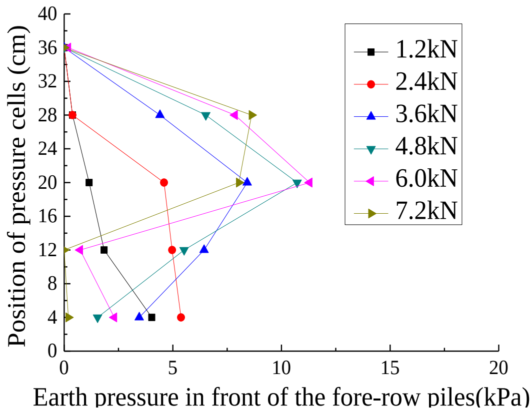


(b) Earth pressures in front of the rear-row piles

Fig. 12 Variation of earth pressures of piles with the applied thrust



(a) Earth pressures behind the fore-row piles



(b) Earth pressures in front of the fore-row piles

Fig. 13 Variation of earth pressures of piles with the applied thrust

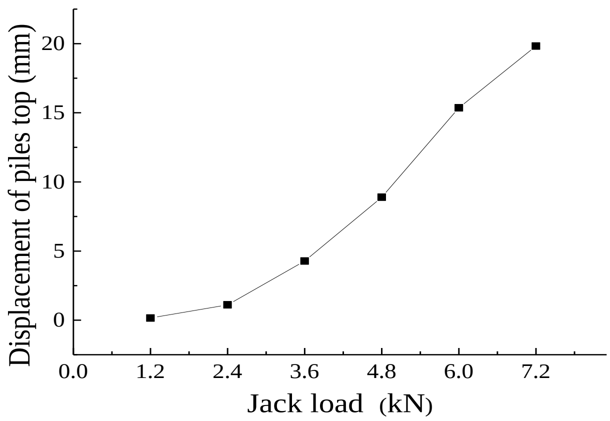
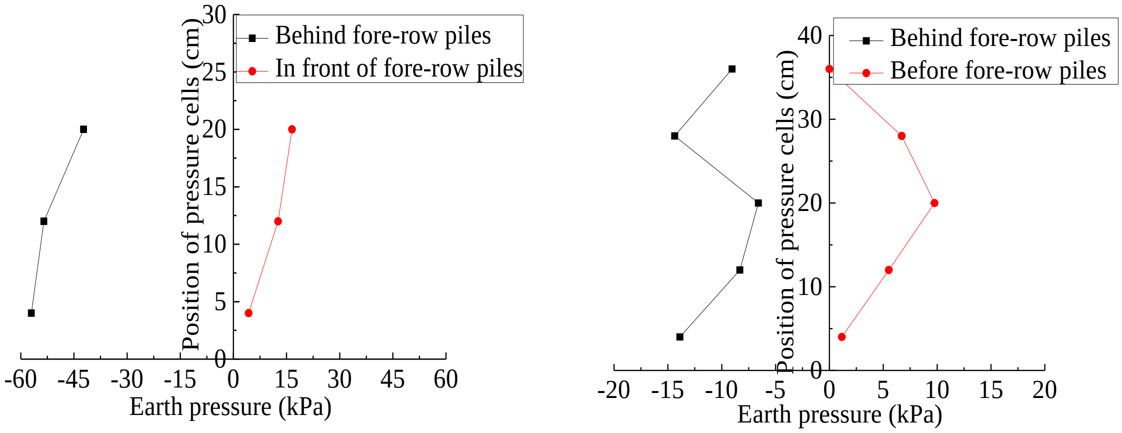


Fig. 14 Displacement of piles top of fore-row piles

along with the piles, so that the earth pressure in front of the pile tops of the fore-row piles kept relatively small. The variation of the pile tops displacement of the fore-row piles under the applied thrust is given in Fig. 14. As illustrated in the figure, the pile top displacement of the ore-row piles increased with the increase of the applied thrust. Generally speaking, the displacement developed at the top of the fore-row piles increase more quickly than the others, which indicates that the landslide becomes weaker with the increase of the applied thrust.

3.2 Effect of the load segment length of rear-row piles on the internal forces of the piles

Based on the earth pressures in front of and behind the fore-row and rear-row piles obtained in section 3.1 and assuming that the piles are cantilever beams, the bending moments of the piles were calculated.



(a) Earth pressures of the fore-row piles (b) Earth pressures of the rear-row piles

Fig. 15 Earth pressures of piles under the thrust of 7.2 kN when the load segment length of rear-row piles was 240 mm and the pile row spacing was 120 mm

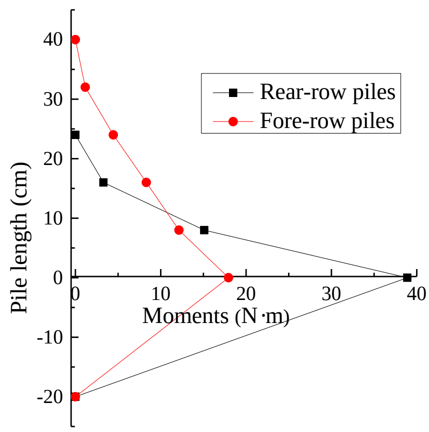
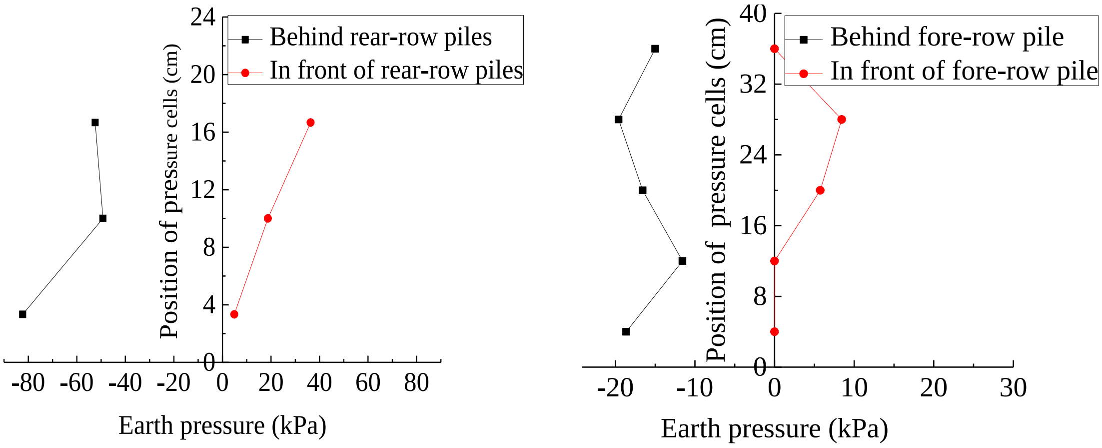


Fig. 16 Comparison of the bending moments of the fore-row and rear-row piles when the load segment length of rear-row piles was 240 mm and the pile row spacing was 120 mm



(a) Earth pressures at fore-row piles (b) Earth pressures at rear-row piles

Fig. 17 Earth pressures of the piles under thrust force of 7.2 kN when the load segment length of rear-row piles was 200 mm and the pile row spacing was 120 mm

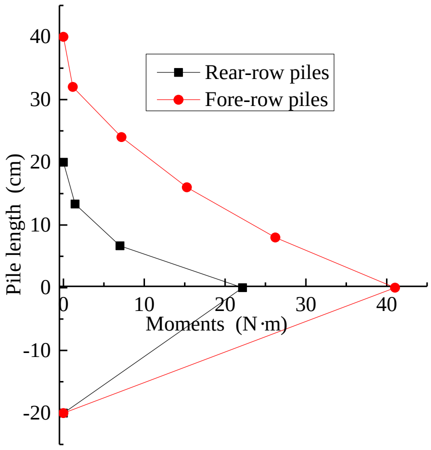
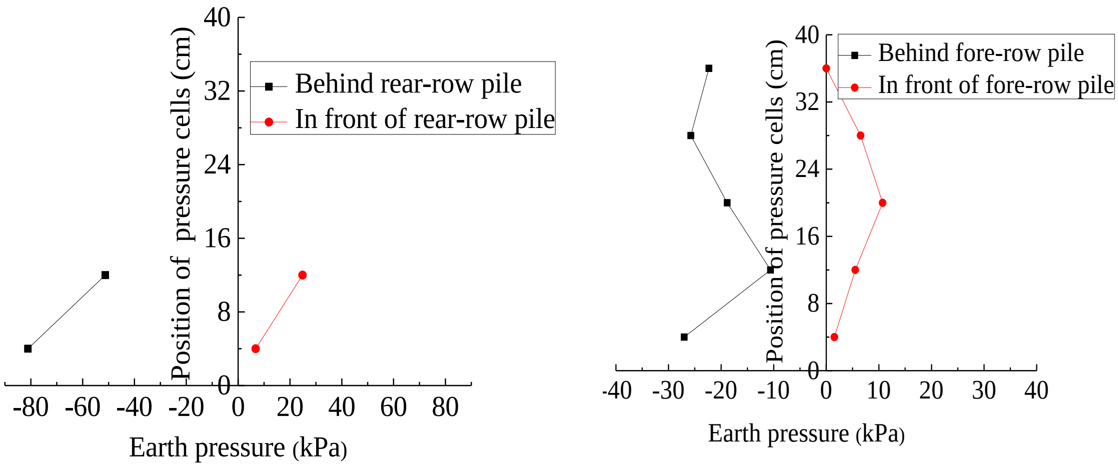


Fig. 18 Comparison of bending moments of the fore-row and the rear-row piles when the load segment length of rear-row piles was 200 mm and the pile row spacing was 120 mm

The earth pressures of the piles with different load segment length of rear-row piles under the thrust of 7.2 kN are presented in Figs. 15, 17 and 19. The calculated bending moments of are presented in Figs. 16, 18 and 20. In this section, all of the discussed results were obtained from the cases with the pile row spacing of 120 mm.

As illustrated in Figs. 15 to 20, with the decrease of the load segment length of the rear-row piles, the difference between the earth pressure in front of and behind the rear-row piles decreases, however, the difference between the earth pressure in front of and behind the fore-row piles increases. Similarly, with the decrease of the length of the load segment of rear-row piles, the difference between the bending moments of the rear-row piles decreases, however, the difference between the bending moments of the fore-row piles increases. In order to compare the effect of the load segment length of rear-row piles on the maximum moments of the fore-row and the rear-row piles, the maximum bending moments of the fore-row piles and the rear-row piles with the different load segment length of the fore-row piles are shown in Fig. 21. When the load segment of the rear-row piles was long, the maximum bending moments of the fore-row piles were much smaller than those in the rear-row piles. When the load segment is short, the bending moment of the fore-row piles were bigger than those in the rear-row piles. When the pile row spacing was 120 mm, the optimal load segment length of the rear-row piles could be obtained to be around 220 mm by ensuring that the maximum bending moments of the fore-row and the rear-row plies were equal. The above method of determining the optimal load segment length of the rear-row piles is applicable for the bending anti-slide piles, which are subjected to bending failure. When the anti-sliding piles are subjected to shear failure, the similar method can be used to determine the optimal buried depth of rear-row piles by ensuring the same shear force in the fore-row and the rear-row piles.



(a) Earth pressures at fore-row piles (b) Earth pressures at rear-row piles

Fig. 19 Earth pressures of the piles under the thrust of 7.2 kN when the load segment length of rear-row piles was 160 mm and the pile row spacing was 120 mm

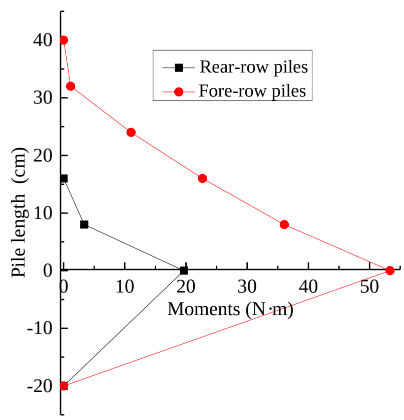


Fig. 20 Comparison of moments in fore-row and rear-row piles when the load segment length of rear-row piles was 160 mm and the pile row spacing was 120 mm

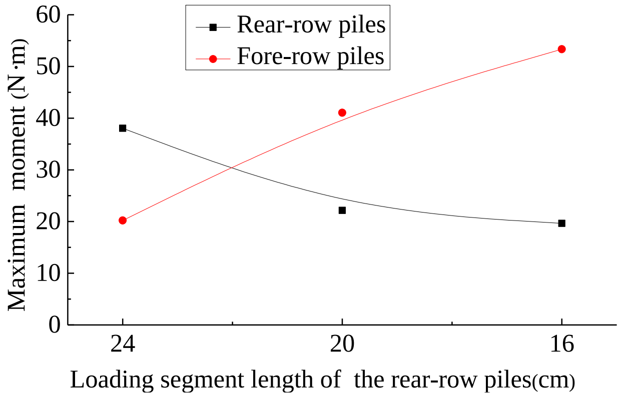
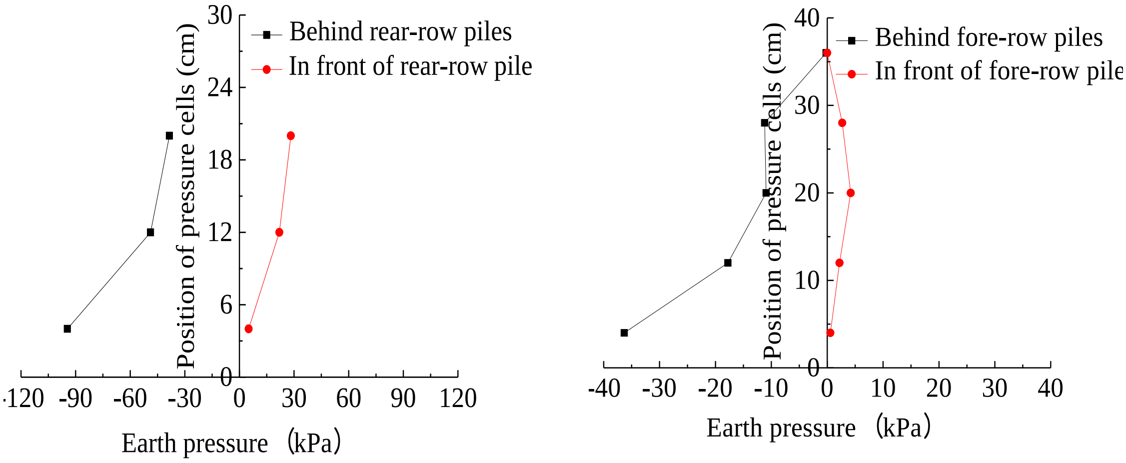


Fig. 21 Comparison of the maximum bending moments of the fore-row and the rear-row piles when the pile row spacing was 120 mm



(a) Earth pressures at fore-row piles (b) Earth pressures at rear-row piles

Fig. 22 Earth pressures of the piles under the thrust of 7.2 kN when the load segment length of rear-row piles was 240 mm and the pile row spacing was 240 mm

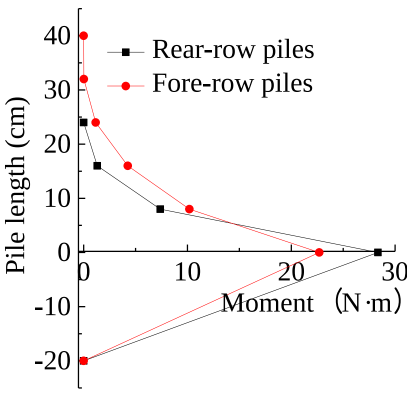
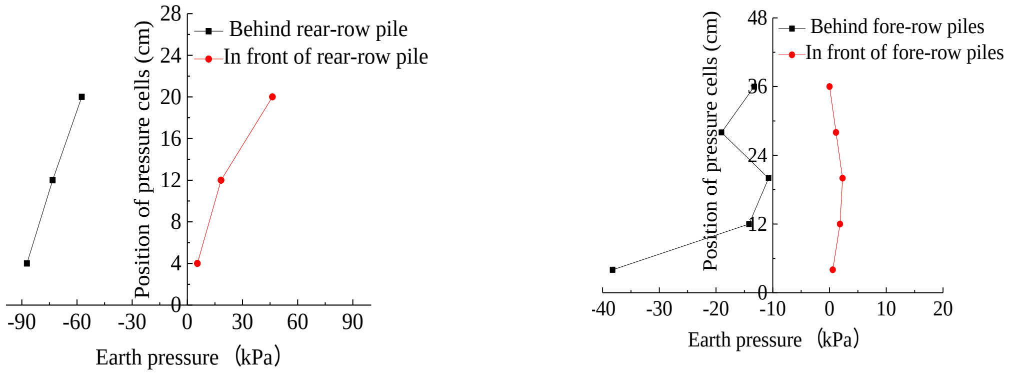


Fig. 23 Comparison of moments of the fore-row and the rear-row piles when the load segment length of rear-row piles was 240 mm and the pile row spacing was 240 mm



(a) Earth pressures at fore-row piles (b) Earth pressures at rear-row piles

Fig. 24 Earth pressures of the piles under the thrust of 7.2 kN when the load segment length of rear-row piles was 200 mm and the pile row spacing was 240 mm

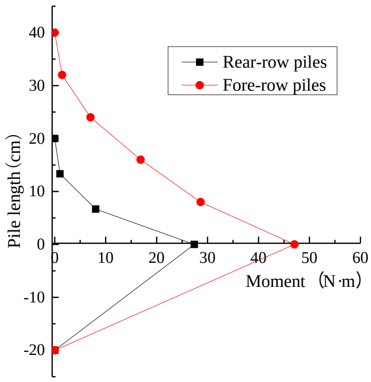
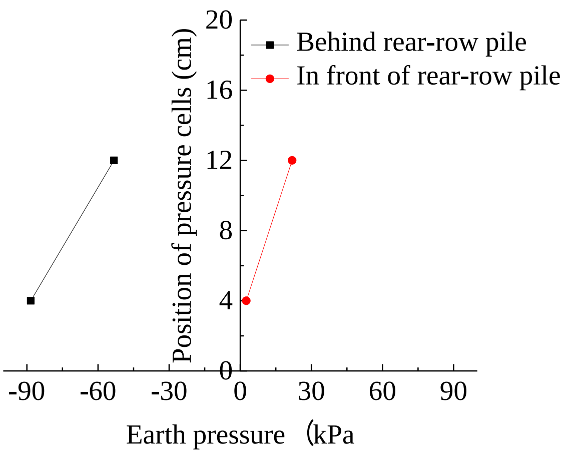
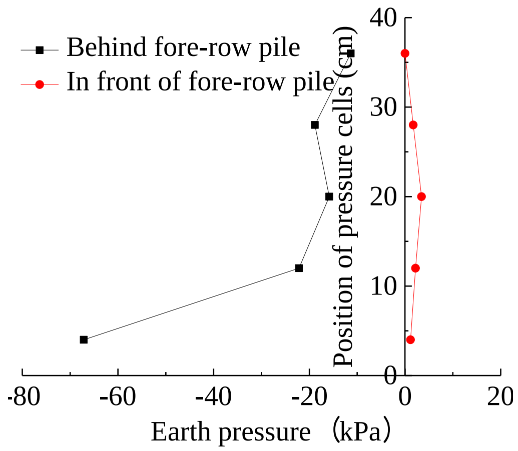


Fig. 25 Comparison of the bending moments of the fore-row and the rear-row piles when the load segment length of rear-row piles was 200 mm and the pile row spacing was 240 mm





(a) Earth pressures at fore-row piles (b) Earth pressures at rear-row piles

Fig. 26 Earth pressures of the piles under the thrust of 7.2 kN when the load segment length of rear-row piles was 160 mm and the pile row spacing was 240 mm

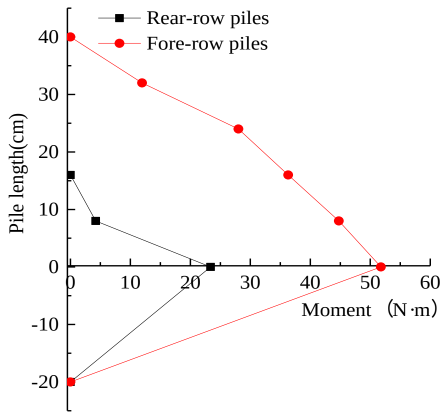


Fig. 27 Comparison of the bending moments of the fore-row and the rear-row piles when the load segment length of rear-row piles was 160 mm and the pile row spacing was 240 mm

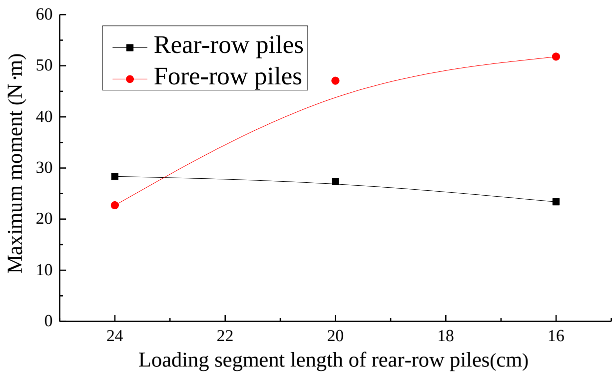


Fig. 28 Comparison of the maximum bending moments of the fore-row and the rear-row piles with the 240 mm pile row spacing

3.3 Effect of pile row spacing on the internal forces of the piles

In order to investigate the effect of the pile row spacing on the internal force of the double-row long-short anti-sliding piles, three additional tests were conducted. In the additional tests, all of the pile row spacing was 240 mm, and the load segment length of rear-row piles included 240 mm, 200 mm and 160 mm. The earth pressures and the bending moments of the fore-row and the rear-row piles under the thrust force of 7.2 kN are shown in Figs. 22 to 27. Comparing the results of the 240 mm pile row spacing with the results of the 120 mm pile row spacing, it can be seen that the earth pressures in front of and behind the rear-row piles increased obviously with the increase of the pile row spacing. However, with the increase of the pile row spacing, the earth pressures in front of the fore-row piles decreased obviously, and the earth pressures behind the fore-row piles only increased a little. Therefore, it can be concluded that with the increase of the pile row spacing, the rear-row piles undertook more landslide thrust than the fore-row piles. The maximum bending moments of the fore-row and the rear-row piles of the 240 mm pile row spacing are shown in Fig. 28. Comparing the results of the 240 mm pile row spacing with the results of the 120 mm pile row spacing, it can be concluded that with the increase of the pile spacing, the general distribution of the bending moments of the fore-row and the rear-row piles are similar. With the increase of the pile row spacing, the bending moments of the fore-row piles decreased, on the contrary, the bending moments of the rear-row piles increased. As a result, the optimal load segment length of the rear-row piles increased with the pile row spacing. It can be seen from Fig. 28, the optimal load segment length of the rear-row piles of the 240 mm pile row spacing was about 232 mm, which was bigger than the result of the 120 mm pile row spacing.

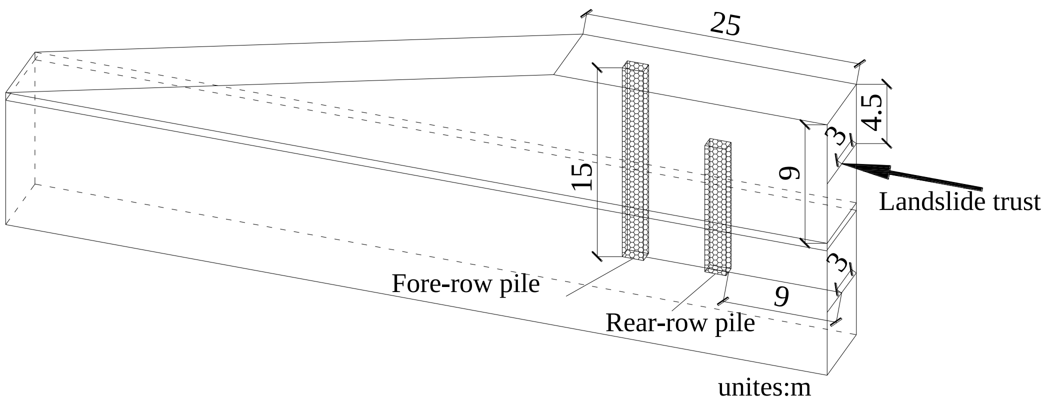


Fig. 29 Sketch of the numerical model

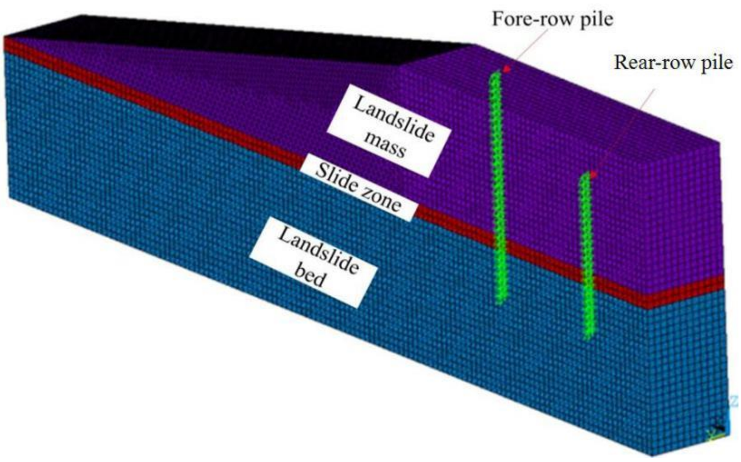


Fig. 30 Model of finite element analysis

Table 1 Material properties of the anti-sliding piles and landslide

Material	Elasticity Modulus/(MPa)	Poisson's Ration	Cohesive Force /(kPa)	Internal Friction Angle /(°)	Density/ (kg·m-3)
Piles	30000	0.2	-	-	2500
Landslide Mass	30	0.3	30	22	2150
Sliding Zone	10	0.35	5	12	1900
Landslide Bed	3000	0.25	250	45	2300

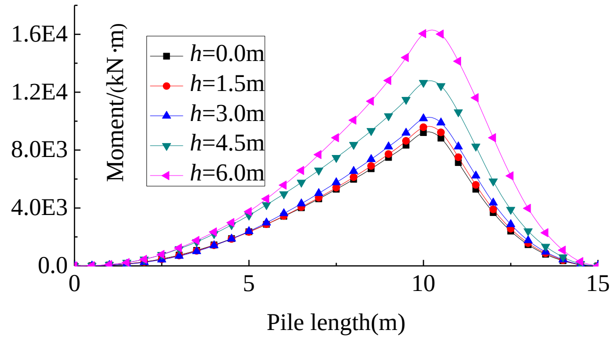


Fig. 31 Bending moments of the fore-row piles with different buried length of the rear-row piles

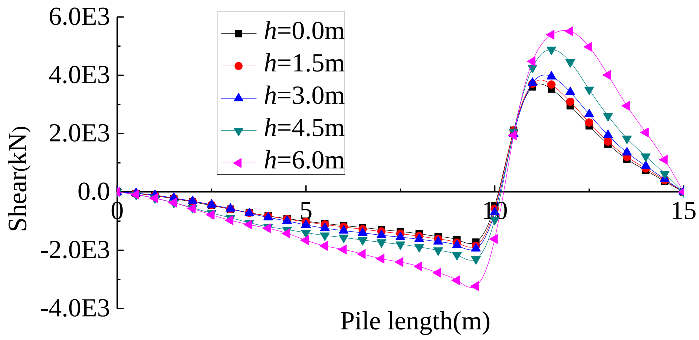


Fig. 32 Shear of the fore-row piles with different buried length of the rear-row piles

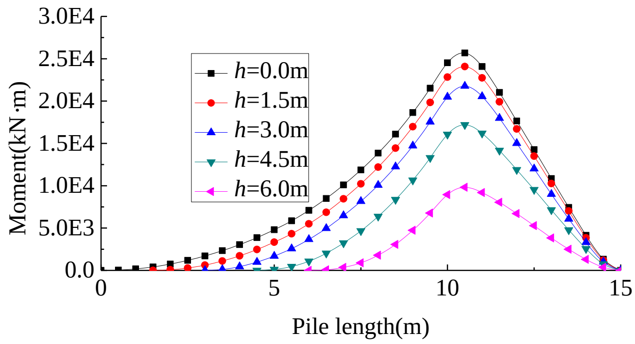


Fig. 33 Bending moments of the rear-row piles with different buried length of the rear-row piles

4. Numerical investigation

Due to the limit of the test condition, the above tests are based on the reduced scale models. In order to investigate the influence of the reduced scale on the test results, the full scale numerical were carried out in this section, as shown in Fig. 31. The dimensions of the model were 60 m in length, 6 m in width and 20 m in height. The piles had a cross section of 2 m×3 m and a pile row spacing of 6 m. The fore-row piles were 15 m long with 5 m embedded segments. The embedded segments of the rear-row piles were 5 m, and their buried length h is varied to simulate the load segment of different length, as shown in Fig. 31.

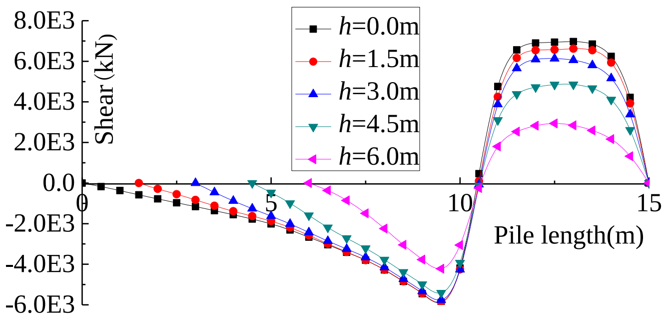


Fig. 34 Shear of the rear-row piles with different buried length of the rear-row piles

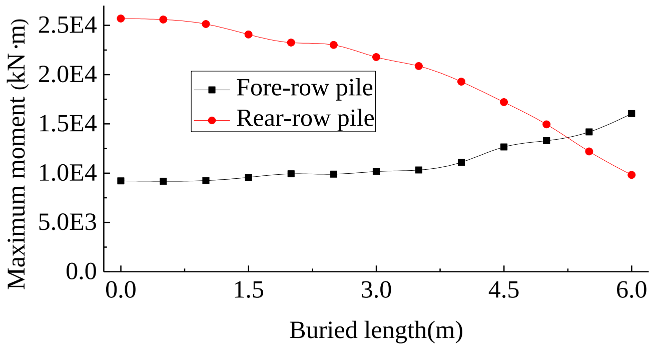


Fig. 35 Maximum bending moments of the fore-row and rear-row piles with different the buried length

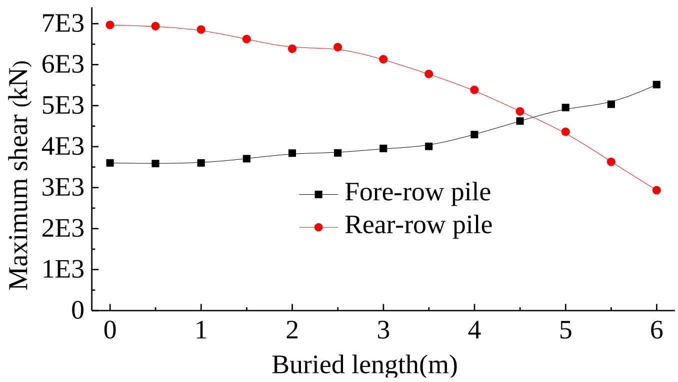


Fig. 36 Maximum shear of the fore-row and rear-row piles with different the buried length

As shown in Fig. 29, in order to simulate the landslide thrust, a horizontal displacement load was applied on the upper part of the back of the landslide body, which increased from the top to the bottom of the landslide body. Three layers were used to simulate the landslide body, as shown in Fig. 30. The mechanical behavior of the landslide bed, landslide zone and landslide mass were defined as elastic-plastic material, and the piles were defined as elastic material. The detail material properties of the simulations are listed in Table 1. In order to investigate the effect of the length of the load segment on the internal forces of the fore-row and the rear- row piles, the buried length of the rear-row piles h is varied from 0 m to 6 m with a 0.5 m interval.

The numerical results of the shear and bending moment of the fore-row and rear-row piles of different buried length of rear-row piles are shown in Figs. 31 to 34. By comparing these results, it can be seen that the numerical results of the full scale models were similar to the corresponding results of the physical tests, so that the reduced scale tests conducted in this study were reliable. When the buried length was small, the internal forces (the bending moment and the shear) of the rear-row piles were much larger than those of the fore-row piles (about 3 times larger when $h \approx 0$). With the increase of the buried length, the internal forces of the fore-row piles also increased, however, the forces at the rear-row piles decreased. As shown in these Figures, the effect of the buried length on internal forces of the piles was nonlinear. When the buried length was small (<=3 m), the internal forces of the fore-row piles and the rear-row piles gradually increased and decreased respectively with the increase of the buried length. When the buried length was large (>3 m), the effect of the buried length on the internal forces of the piles became obvious, and the internal forces of the fore-row piles and the rear-row piles increased and decreased more quickly. The maximum bending moments and the maximum shear of the fore-row and the rear-row piles varied with the buried length of the rear-row pile, as shown in Figs. 35 and 36. When the buried length reached about 5.0 m, the bending moments of the fore-row piles turned to be bigger than the bending moments of the rear-row piles. When the buried length reached about 4.5 m, the shear of the fore-row piles turned to be bigger than the shear of the rear-row piles.

5. Conclusions

The double-row long-short composite anti-sliding piles system is an effective way to control the landslides with high thrust. In this study, The double-row long-short composite anti-sliding piles with different load segment length (cantilever length) and different pile row spacing were studied by a series of physical tests, by which the influences of load segment length of rear-row piles as well as pile row spacing on the mechanical response of double-row long-short composite anti-sliding pile system were investigated. Based on the physical test and the numerical modelling results, the following conclusions can be drawn:

• The double-row long-short composite anti-sliding piles system is effective in distributing the landslide thrust to the rear-row and the fore-row piles, so that it can avoid the progressive failure of multi-row piles system.

• The earth pressures behind the rear-row piles are high at the upper part and low at lower part, while the earth pressures in front of the rear-row piles are low at upper part and high at lower part. The distribution of earth pressures behind the fore-row piles is anti-“S” shape, and the earth pressures in front of fore-row piles are high at the middle and low at the two ends of the piles.

• With the decrease of the length of the load segment of rear-row piles, the difference between the earth pressure in front of and behind the rear-row piles decreases. However, the difference between the earth pressure in front of and behind the fore-row piles increases.

• With the decrease of the length of the load segment of rear-row piles, the difference between the bending moments of the rear-row piles decreases. However, the difference between the bending moments of the fore-row piles increases. By ensuring the bending moments at the fore-row and the rear-row piles to be equal, the optimal load segment length of the rear-row piles can be obtained.

• The earth pressures in front of and behind the rear-row piles increase obviously with the increase of the pile row spacing. However, with the increase of the pile row spacing, the earth pressures in front of the fore-row piles decrease obviously while the earth pressures behind the fore-row piles only increase a little.

• With the increase of the pile row spacing, the bending moments of the fore-row piles decrease. On the contrary, the bending moments of the rear-row piles increase. As a result, the optimal load segment length of the rear-row piles increases with the pile row spacing.

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