Contrastive Analysis of Indoor Model Test and Numerical Test on Pull-Out Failure of Fully-Embedded Anti-Slide Pile

Peng Qiu
Institute of Architectural Engineering, Nantong Open University, Jiangsu, P. R. China, 454736552@qq.com

Abstract. In this paper, the strain of steel bar, concrete of pile body, displacement of pile top and earth pressure around piles are monitored under pull-out failure mode of fully-embedded anti-slide piles, and the stress mechanism of fully-embedded anti-slide piles is studied by numerical simulation. The results show that when the anchorage depth of anti-slide piles is insufficient, the rigid rotation of piles is dominant, and the strain change of pile body is not obvious. Through the analysis of the working parameters of the anti-slide pile, it is concluded that both sides of the loading point of the anti-slide pile are subjected to an upward pulling force, which makes the anti-slide pile tend to pull out. Through the simulation analysis of the model test, it can be concluded that with the increase of load, the sliding up-welling zone behind the pile tends to expand, and the pile body is subjected to a "pull-out" effect of the surrounding sand.

Keywords: fully-embedded anti-slide pile, pulling-out failure mode, model test, numerical simulation

1. Introduction
Anti-slide pile is a transverse force pile which resists landslide or earth pressure by lateral foundation rock and soil resistance of anchorage section. Anti-slide piles were used to treat landslides abroad in the 1930s and at home in the 1950s [1]. Zhang Yongxing, Dong Jie and others [2] combined with the three-dimensional finite element calculation of cantilever anti-slide pile, compared and analyzed the sensitivity of pile spacing to the change of relevant parameters. Zheng Ying-ren, Lei Wenjie and others [3] calculated and compared the stability coefficients of anti-slide piles with different lengths by using finite element software. Hu Xiaojun and Wang Jianguo [4] Based on strength reduction and considering the related factors of anchorage depth of anti-slide piles, the calculation formula of anchorage depth of rigid anti-slide piles is derived by using cantilever pile method of internal force analysis of anti-slide piles.

Many scholars and researchers have studied cantilever piles, but the research on fully-embedded anti-slide piles is still relatively small, and the design theory has not been significantly improved for a long time. The main reason is that the understanding of the mechanism of interaction between piles and rock and soil is not systematic and comprehensive enough, so the design method is not mature and perfect. At present, the design of fully-embedded anti-slide piles mainly relies on engineering experience and industry standards. The calculation assumptions used in these experiences and standards are too simplified, the calculation formulas are complex and the parameters are arbitrary. Designers often increase the safety factor by experience due to unclear working mechanism of pile and soil. This method is either a great waste or a potential safety hazard [5]. Compared with cantilever anti-slide pile, fully-embedded anti-slide pile has less bending moment and less material consumption,
which greatly improves the mechanical performance of the pile and reduces the cost of the project. Therefore, the optimization design of fully-embedded anti-slide pile has been paid more and more attention by scientific researchers [6-12], and has been applied more and more widely.

In this paper, the pull-out failure modes of fully-embedded anti-slide piles are studied by laboratory model tests and dynamic monitoring of loading conditions. Then, the results of numerical simulation are compared and analyzed. It is reasonable for deepening the understanding of the stress mechanism of fully-embedded anti-slide piles and improving the design and calculation level of piles.

2. Indoor Model Test and Phenomenon Analysis

2.1. Test Overview
Because the anti-slide pile mainly bears horizontal load and the soil arching effect between piles is mainly horizontal direction, the actual working state of the anti-slide pile is simulated by applying horizontal thrust load to the sliding body in the indoor brick test pool. Finally, the anti-slide pile is analyzed based on the experimental results and theoretical analysis and numerical simulation. The interaction mechanism with rock and soil and the failure mechanism of anti-slide piles are analyzed. The layout of the test device is shown in Fig. 1.

![Figure 1. Sketches of model test](image)

2.2. Test Model
The design of the test model includes the selection of the model test pile and the filler of the test tank. In order to satisfy the similarity of the test, the rigid material, compacted gravel soil and sandy soil are selected for the anti-slide pile, sliding bed and sliding body. The detailed design is as follows: anti-slide pile is reinforced concrete structure, C30 concrete is selected, the section size is 100 mm x 100 mm, and the length is 1000mm. The tension surface of the pile is equipped with two 8mm steel bars, the compression surface is equipped with two 6mm steel bars, and each 50mm is equipped with a 4 mm stirrup. The reinforcement ratio of the cross section of the pile is 1.57%. The lithology of sliding bed is weathered rock. From the engineering experience, the commonly used anchorage depth is about 1/3-1/2 pile length for soil or soft rock stratum, and 1/4 pile length for complete and hard rock stratum [13]. Therefore, 300 mm anchorage depth is more appropriate. In order to achieve the purpose of overturning damage, the moderately weathered rock layer is simulated by compacted gravel soil, the gravel in gravel soil is made up of ordinary concrete limestone aggregate, and the clay soil is selected. The gravel soil is proportioned according to the mass ratio of gravel to clay soil of 2:1. The landslide body is simulated by sand, and the sand is selected by river sand. The friction coefficient between the landslide body and the sliding surface is 0.136.

2.3. Layout of Test Elements and Data Acquisition Equipment
In the case of pull-out failure of fully-embedded anti-slide piles, the displacement of pile top is monitored by percentile gauge in the whole process, the strain of concrete surface of anti-slide piles
and the strain of steel bars in piles are monitored by strain gauge, and the magnitude and variation law of landslide thrust are studied by laying earth pressure box.

There are 14 SYZ-3-B micro-resistance strain earth pressure gauges on both sides of a pile B in the middle of four piles, 7 on each side. Reinforcement strain gauges are arranged on two steel bars in the diagonal direction of tension and compression steel bars in pile B. The arrangement of earth pressure box and steel strain gauge is shown in Fig. 2. Concrete strain gauges are laid on both sides of C-pile concrete to test the curvature change of pile body under horizontal load. The specific layout position is shown in Fig. 3. The static signal test system TST3826 was used to collect the test data. The acquisition instrument is a resistive strain acquisition instrument. All the measuring points are sampled within 0.5 seconds with a resolution of $1 \times 10^{-6}$.

![Figure 2. Arrangement of earth pressure cells and steel strain gauge](image)

![Figure 3. Arrangement of concrete strain gauge](image)

2.4. Test Loading Scheme and Test Procedures

Indoor model tests were carried out with a 100 kN digital display pull-out tester with a load of 5 kN per stage. In order to make the landslide slide according to the force of the planned sliding surface, horizontal load should be applied. Therefore, as shown in Fig. 4, a cross beam is applied to the bulldozing board. Considering the small travel of the pull-out instrument, a hand-rocking jack is added
between the pull-out instrument and the reaction frame. Horizontal load is applied to the beam by the pull-out instrument to simulate the horizontal push of the landslide.

In the process of loading, the changes of earth pressure and percentile meter are obvious. At the same time, the changes of earth pressure and percentile meter are observed. When these two kinds of values tend to remain unchanged, they are regarded as stable states. Each stage of load keeps stable for about 5 minutes, and then continues to load to the next stage until the displacement of bulldozer exceeds the stroke of pull-out meter. The percentile meter reading, earth pressure box reading, steel bar strain gauge reading and concrete strain gauge reading are monitored during the whole process of the test.

![Figure 4. The loading device for model test](image)

2.5. Test Phenomenon Analysis

Throughout the whole test process, the pushing pile can be divided into three stages:

The first stage is the compaction stage of sand behind piles. When the anti-slide pile is preliminarily loaded (1kN~10kN), the sand filling behind the pile is gradually compacted, the displacement of the pile top has no significant change, and the change of internal force and earth pressure of the anti-slide pile body is relatively small.

The second stage: the anti-slide pile has the stage of pushing pile displacement. When the load grade is greater than 10 kN but not greater than 25 kN, with the continuous increase of load, the displacement and earth pressure at the top of piles increase obviously, the soil between piles has the phenomenon of compressive deformation, the top surface of sliding body behind piles appears the phenomenon of uplift, and the top surface of filling soil and slope before piles has no obvious deformation.

The third stage is the pull-out failure stage of anti-slide piles. When the load continues to increase, the anti-slide pile inclines obviously, as shown in Fig. 5; the sand on the top of the back of the pile appears obvious uplift and cracks, and the longitudinal cracks appear at the top corner of the front slope of the pile, which indicates that the sliding body in front of the pile has the tendency of collapse; and similar mud appears on the slope surface of the sliding body. The sand of the rock flow surges as shown in Fig. 6. In addition, the bulldozers also move up about 50 mm due to the upwelling of the filling due to loading.

![Figure 5. The inclination of the piles](image)  ![Figure 6. The slide of sand](image)
3. Numerical Model Test
FLAC3D is used for numerical simulation analysis. The simulation process is the same as that of indoor test, and the magnitude of loads at all levels is the same as that of indoor test. The Mohr-Coulomb model is adopted for the sliding body. Considering the rigid body rotation of the anti-sliding pile, the full elastic model is adopted.

3.1. Establishment of FLAC3D Numerical Calculation Model
The landslide model is divided into two parts: landslide body and sliding bed. The landslide body is sandy soil and the sliding bed is gravel soil. The main calculation parameters of sand and gravel are as follows, as shown in Table 1. The model of landslide anti-slide pile is established and meshed as shown in Fig. 7.

| Model material | Density (kg/m³) | Bulk modulus (MPa) | shear modulus (MPa) | Cohesive force (kPa) | internal friction angle (°) |
|----------------|-----------------|-------------------|---------------------|----------------------|-----------------------------|
| gravel         | 2200            | 13.3              | 8                   | 10                   | 39                          |
| sand           | 1600            | 0.56              | 0.42                | 0                    | 15                          |

Figure 7. Model of FLAC3D numerical analysis

3.2. Establishment of Pile Structure Unit
The anti-slide pile in this numerical test is simulated by establishing pile element. In order to study the state of the cross-section of the pile body under load, each pile element is divided into 10 structural elements, so there are 40 structural elements and 44 structural nodes in the four pile elements. The elastic modulus of pile element is 32.5 Gpa and Poisson's ratio is 0.2.

4. Comparative Analysis of Indoor Model Test and Numerical Test
4.1. Pile Top Displacement
Through the numerical analysis of pile top displacement, the numerical simulation results are compared with the previous measured results, and the following conclusions can be drawn:

(1) The failure load of push-pile test calculated by finite difference method is located at 30 kN, which is slightly larger than that near 25 kN of the measured results.

(2) Under the action of the same load grade, the displacement of pile top calculated by numerical simulation is larger than that measured at first, and the results are similar near 10 kN. The displacement of pile top measured by subsequent tests is larger than that of numerical simulation. The reason may be that in the initial stage of the test, the thrust load is mainly to make the sand behind the pile compact. The influence of top displacement is relatively small.
(3) The numerical simulation shows that the displacements of the top of the four piles are basically the same. The main reason is that the cohesion between the retaining plates on both sides and the sand is not taken into account in the numerical calculation. In the actual test, the retaining plates on both sides can prevent the sliding of the sand, which makes the displacement of the top of the piles on both sides smaller than the displacement of the top of the middle two piles.

(4) The numerical simulation shows that when the failure load is reached, the calculation can not converge and the displacement of the top of the pile increases. The measured results show that when the failure load is reached, the pile has been pulled out and destroyed. The pile can not bear the thrust by its own anchorage, and the displacement of the top of the pile will not increase with the increase of the load. It is basically stable near a fixed value.

4.2. Pile Earth Pressure

The earth pressures in front of and behind piles in the laboratory model test and numerical simulation test are compared and analyzed, as shown in figs. 8 and 9.

**Figure 8.** Comparisons of earth pressures in front of piles between numerical simulation test and indoor model test

**Figure 9.** Comparisons of earth pressures behind piles between numerical simulation test and indoor model test
The analysis shows that:

1. In the initial stage of loading, the lateral earth pressure of pile body is mainly caused by the self-weight stress of soil, which shows that it increases gradually from top to bottom, which is consistent with the theory.

2. With the increase of loading grade, the change of earth pressure in front of piles above sliding surface is smooth from top to bottom. When loading to 15 kN, the earth pressure in front of piles gradually decreases from top to bottom, and the minimum value appears near the sliding surface.

3. The earth pressure distribution curve of pile body is approximately parabolic distribution with small upper and lower and large middle, which is basically consistent with the experimental soil pressure distribution law.

4. Compared with the measured earth pressure figure of pile body, above the sliding surface, the maximum earth pressure value of the test appears in the middle of the sliding body, and the numerical simulation result is different from the experimental value. The main reasons are as follows: the earth pressure and the resistance are taken into account in the numerical simulation; while in the model test, the earth pressure caused by self-weight was reduced to zero before loading.

4.3. Internal Forces of Piles

By extracting the bending moment of the section around the y-axis at each node of the middle pile under various loads, the distribution curve of the bending moment in the whole length of the pile can be obtained, as shown in fig. 10 (a).

The distribution of earth pressure is integrated twice by using the software of MATLAB, and the cross-section moment values of each measuring point of pile body under various loads are obtained. The results are shown in fig. 10 (b).

![Comparison diagram of pile internal force between numerical simulation test and indoor model test](image)

As can be seen from Fig. 10:

1. During the loading process, the bending moment of pile body increases significantly near the sliding surface, and the maximum bending moment of pile body appears at the sliding surface under various loads, while the bending moment of pile top and pile bottom is smaller.

2. When the thrust load increases from 5 kN to 15 kN, the bending moment of each section increases obviously, reaching the maximum value at 15 kN, while the bending moment decreases slightly when the thrust load continues to increase. The analysis may be that when the bending moment of the pile reaches the maximum value, the crushed stone soil in the anchorage section of the pile appears local failure. The stress redistribution caused by stress release changes the pile bending moment.
(3) When the thrust load is greater than 20 kN, the negative bending moment in the middle of the pile above the sliding surface is the same as that measured.

(4) Comparing the curves of bending moment distribution and numerical simulation results, it can be seen that the changing trend of the two is basically the same, but the numerical simulation results are slightly smaller than the measured values. The analysis may be that the physical parameters of the numerical simulation are different from the actual values of the test materials, and the number of measuring points in the test is limited.

5. Conclusion

(1) The pull-out failure of fully-embedded anti-slide piles is mainly due to the insufficient anchoring depth of piles, the loss of restraint on piles in the stratum of anchoring section, the rigid rotation of piles as a whole, and the upward friction of piles under the combined action of landslide thrust and soil around piles.

(2) The displacement-load curve of the pile top is approximately three segment line. In the first stage, the displacement of pile top increases slowly, the slope is relatively small, the filling behind the pile keeps compacting, and the force of the pile body is not large; in the second stage, the displacement of pile top increases linearly, and the slope increases obviously compared with the first stage, and the pile body rotates rigidly in this stage. In the third stage, the increase of pile top displacement is slowed down. In this stage, the pile body is overturned and pulled out. At the same time, the phenomenon of overtopping occurs in sandy soil.

(3) Comparing the experimental results with the numerical simulation results, it can be found that the distribution rules of all kinds of data obtained by the two methods are basically the same. However, the maximum value of measured earth pressure above the sliding surface appears in the middle of the sliding body. The main reason for the difference between the numerical simulation results and the measured values is that the earth pressure under self-weight is reduced to zero before loading after the instrument is installed, while the earth pressure under self-weight is taken into account in the numerical simulation.

(4) The measured data (soil pressure, displacement of pile top and internal force of pile body) are basically consistent with the distribution law of numerical calculation, but the measured value is slightly larger than the simulated value. The simulation method based on FLAC3D can be used as a supplementary means of model test.

References

[1] Li Haiguang. Design and Engineering Example of New Type Support Structures [M]. Beijing: People's Transportation Press, 2004
[2] Zhang Yongxing, Dong Jie, Wen Haijia, et al. Study on the three-dimensional soil arch effect and reasonable spacing of cantilever anti-slide piles considering self-weight stress [J]. China Journal of Highway, 2009, 22 (2): 18-24
[3] Zheng Yingren, Lei Wenjie, Zhao Shangyi and others. Two problems in the design of anti-slide piles [J]. Highway Transportation Science and Technology, 2005, 22 (6): 45-51
[4] Hu Xiaojun, Wang Jianguo. Determination of anchorage depth of rigid anti-slide pile based on strength reduction [J]. Journal of Civil Engineering, 2007, 40 (1): 65-68
[5] Liao Zhongyuan. Study on the Practical Design Method of Embedded Anti-Slide Piles [D]. Chongqing: Chongqing University, 2006
[6] Chen Liang. Determining the embedded depth of embedded anti-slide piles by optimization method of foundation coefficient [J]. Shanxi Architecture, 2010, 36 (23): 149-150
[7] Guo Yansheng, Lu Guosheng. Preliminary Study on Working Mechanism of Embedded Anti-Slide Piles [J]. Subgrade Engineering, 2009, 146: 159-160
[8] Xu Hongbo, Zheng Ying-ren, Ye Haiin et al. Research on seismic slope supported by embedded anti-slide piles [J]. Journal of Underground Space and Engineering, 2011, 7(4): 781-787
[9] Tang Xiaosong, Zheng Ying-ren, Duan Yongsheng et al. Application of artificial intelligence in
design of embedded anti-slide piles [J]. Journal of Underground Space and Engineering, 2010, 6(2): 375-381
[10] Xiao Shiguo, Zhou Depei, Song Congjun. Application of Embedded Anti-Slide Piles in High Rock Slope Engineering [J]. Journal of Geotechnical Engineering, 2003, 25 (5): 638-641
[11] Wang Yuping. Discussion on the Maximum Pile Spacing of Fully Embedded Anti-Slide Piles [J]. Sichuan Architectural Science Research, 2008, 34 (5): 120-123
[12] Xiong Zhiwen, Ma Hui, Zhu Haidong. Stress Distribution of Fully Embedded Double Row Anti-Slide Piles [J]. Subgrade Engineering, 2002, 102:5-11
[13] Liu Jiaqi. Design and calculation of anti-slide piles [M]. Institute of Science and Technology, Second Survey and Design Institute, Ministry of Railways, 1981:33-34