Research Status and Prospect of Anti-slide Piles for Slope Stabilization

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Abstract. The research status of anti-slide piles for slope stabilization is summarized in this paper. The calculation method in pile design is comprehensively reviewed, and special attention is paid to the selection of design parameters according to the actual engineering conditions. The key points in the design and application of anti-slide piles are presented in detail, especially the interaction and deformation coordination between anti-slide piles and soil. Finally, some important issues, such as the soil arching effect and internal force calculation, are discussed.

Keywords: Anti-slide pile · Landslide · Slope stability · Soil arching · Pile-Soil interaction · Pile-Soil interface

1 Introduction

Landslides are one of the most widespread and serious geohazards in the Belt and Road countries, which usually lead to a great loss of human life and property [1, 2]. Consequently, the enormous challenges to maintaining the stability of landslides inspired researchers to develop various stabilizing structures [3, 4]. The anti-slide pile, as known as the stabilizing pile, is designed to be installed through the unstable soil layer and embedded below the potential sliding surface in the stable soil/rock strata (Fig. 1). The slope can be effectively stabilized by these piles, which can transfer part of the thrust force from the sliding soil to the stable strata. Anti-slide piles are widely used in various slope retaining projects because of their large anti-slide ability, good retaining effect, flexible pile position arrangement, and various combination forms that can be adapted according to the actual situation.

The application of anti-slide piles to slope stabilization began in the 1930s. With the optimization of anti-slide pile design and application, anti-slide piles have gradually become the main way of landslide treatment, and many different types of anti-slide pile structures have been developed [6, 7]. After the 1970s, the development of anti-slide piles entered a new era. The developed countries, such as Japan, adopted anti-slide piles with different sizes and shapes as anti-slide structures to treat large landslides and found the active role of prestressed anchor cables in these circumstances [8]. In China, anti-slide

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piles were first used in 1954 to treat the Shijiaba landslide in the Baocheng Railway. Since the 1980s, the combination use of anchor cables and anti-slide piles has been widely used, transforming anti-slide piles from the passive to the active stress state and effectively reducing the cross-sectional area and burial depth of piles. In engineering practice, due to the differences in landslide types, geological conditions and landform, different types of anti-slide piles are employed to achieve the optimum reinforcing effect. The efficient use of anti-slide piles can significantly save construction costs.

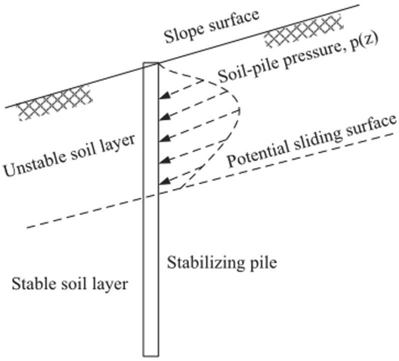

Fig. 1. Stabilizing pile embedded into a semi-infinite slope [5].

Many landslides and pile foundation improvements urge engineers to pay more attention to the design and effectiveness of stabilizing piles [9]. The stability effect of a stable pile is affected by many factors; The driving force acting on the pile and the position of the pile are two important factors. The driving force of pile landslides has an important influence on determining the optimal position of the pile. On the premise of meeting structural safety and stability, it is necessary to fully understand the selection of key parameters and influencing factors in the design of anti-slide piles to reduce the project cost. The design elements of anti-slide piles include the plane position, section size and shape and anchorage depth. Scholars worldwide have researched the design elements and calculation of anti-slide piles in slopes. Among them, the calculation of internal force of anti-slide piles is mainly divided into two methods: displacement method and pressure method, which have their characteristics and scope of application [10–12]. Based on different calculation methods, selecting optimized design parameters, especially pile spacing, landslide stability, and pile plane layout, can improve the stability coefficient of landslide mass and reduce the project cost [13].

The working state of anti-slide piles can be evaluated through field monitoring. At present, the conventional monitoring methods of anti-slide piles mainly include inclinometer, reinforcement gauge, earth pressure gauge, total station and distributed optical fiber technology [14]. Inclinometer, earth pressure gauge and reinforcement gauge belong to point monitoring, and their monitoring results can be directly substituted into the existing design and calculation method of anti-slide piles to evaluate the working state of anti-slide piles. Compared with conventional monitoring methods, distributed optical fiber sensing technology has significant advantages, such as distributed, long monitoring distance, little interference, a large amount of data acquisition, high data acquisition efficiency, real-time monitoring and long-term stability, which can meet the requirements of safety monitoring of slope reinforcement engineering and early warning of landslide [15].

This paper summarizes and evaluates the research progress and some problems existing in the research from the aspects of calculation method of anti-slide piles, pile-soil interaction, optimal layout and field monitoring technology, which can provide a useful reference for future study.

2 Anti-slide Pile-Soil Interaction

The interaction between anti-slide piles and landslide mass is mainly concentrated between anti-slide piles and landslide mass. Under the action of self-weight or upper load of soil between piles, the soil between piles produces uneven displacement, resulting in soil arch between piles. The research history of the soil arching effect can be traced back to the granary effect discovered by Roberst in 1884. In 1895, German engineer H. A. Janssen quantitatively explained this phenomenon with the continuous medium model. The soil arching effect was first proposed by Terzaghi and verified by the movable door test, and then the classical Terzaghi relaxation earth pressure calculation method [16] was derived. With the continuous development of soil arching theory, the arching effect of anti-slide pile and soil around pile has gradually attracted the attention of engineers and technicians, and more and more related research problems are involved.

2.1 Theoretical Analyses

The interaction process between anti-slide pile and soil is very complex. Anti-slide piles are subject to the load transmitted by soil, and the deformation and displacement of soil are also subject to the reaction of anti-slide piles. The interaction process of the two is mutual, which makes it more difficult to analyze the soil arch effect theoretically. At present, some scholars have studied the relationship between longitudinal soil arching and active earth pressure on the back of rigid retaining wall [17], while the soil on the back of the pile sheet wall is more arched in the horizontal direction. Bransby and Shelke respectively studied the deformation and soil arching effect of soil around pile sheet wall and laterally loaded pile group foundation and obtained some regular understanding [18, 19]. In view of the more extensive application of column plate structures such as pile sheet wall in China, and the soil arching effect between piles directly affects the load acting on the retaining structure between piles, some scholars have studied the relationship between the soil arching effect and the earth pressure acting on the baffle.

2.2 Model Tests

Physical model tests can provide the deformation characteristics of the landslides stabilized by anti-slide piles [20, 21]. A series of centrifuge model tests were conducted to investigate the failure mechanism of pile-reinforced slopes under self-weight loading and vertical loading conditions [22]. Hu took the Majiagou landslide and its pile system as a real prototype, and using a model testbed with 57-cm-long test piles made of reinforced concrete and polyesteramide to simulate rigid and flexible piles (Fig. 2), the displacements of two physical models were monitored during progressive loading to simulate the landslide-stabilizing pile system [23].

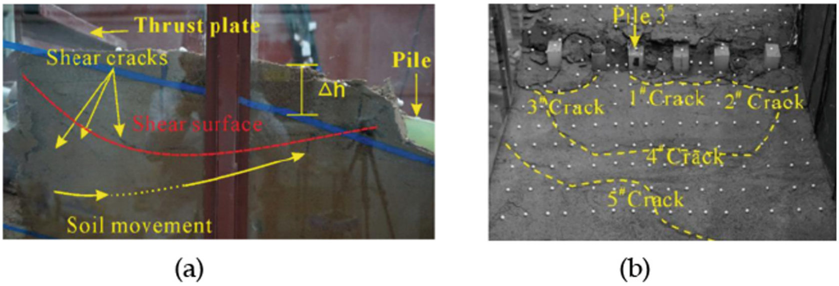

Fig. 2. Deformation characteristics of model piles after failure. (a) Side view of the model between the thrust plate (left) and the piles (right). (b) Oblique front view, looking uphill, showing crack development of the arcuate shear cracks downslope of the piles (after [23]).

3 Designs and Calculation of Anti-slide Piles

After years of development, the calculation theory of ordinary anti-slide pile (laterally loaded pile) has formed a relatively complete system (Fig. 3) [24]. According to different states of foundation, it is mainly divided into elastic theory, foundation reaction, and numerical simulation methods. According to the different assumptions of soil around the pile, the foundation reaction method is divided into limit foundation reaction method, elastic foundation reaction method and composite foundation reaction method.

3.1 Calculation Methods of Internal Forces in Anti-slide Piles

General Calculation Methods

The calculation methods of internal forces of anti-slide piles widely used in many practices include the cantilever pile method, foundation coefficient method, finite element method and matrix analysis method. These methods only consider the stress of an anti-slide pile when the soil around the pile is in the linear elastic stage.

The elastic foundation coefficient method is generally used abroad, and the internal force calculation of anti-slide piles is divided into two parts above and below the sliding surface. The static equilibrium structure method is used to calculate the internal force of anti-slide piles on the sliding surface, and the finite difference method is used to calculate the internal force below the sliding surface.

The traditional cantilever pile method and foundation coefficient method are widely used in China. The cantilever pile method is characterized by the pile section above the sliding surface as a cantilever beam. The pile section below the sliding surface is calculated according to the Winkler elastic foundation beam model. However, the simplification of the actual stress state of the pile by this method is safe, so the calculation

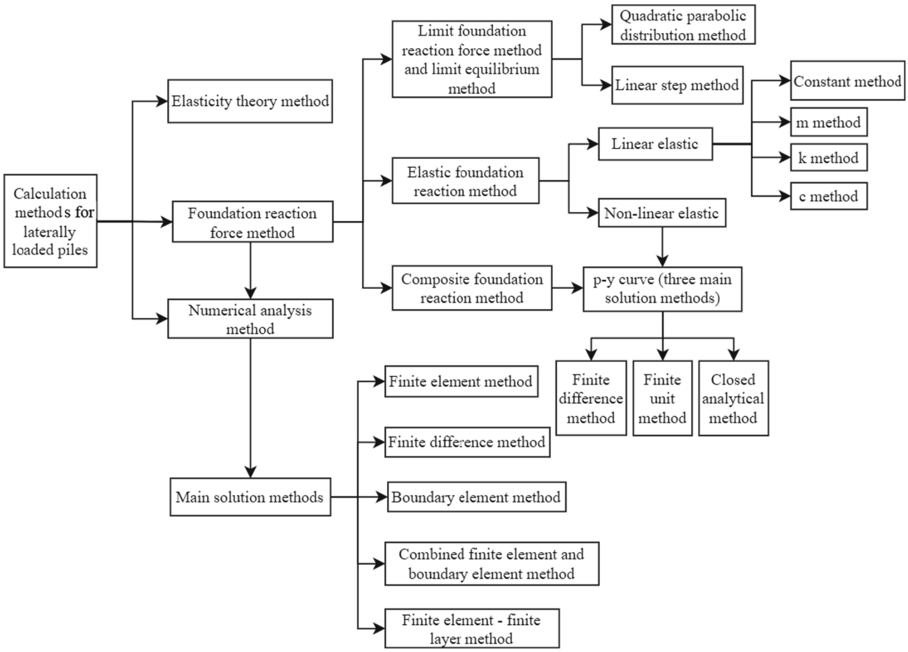

Fig. 3. Current calculation theories of anti-slide pile

results are conservative. The foundation coefficient method regards the whole pile as an elastic foundation beam, which is relatively close to the actual stress state of anti-slide piles.

Recent Developments in Calculation Methods

Although the existing design method of anti-slide piles can meet practical engineering requirements, it does not mean that it meets the actual stress state of anti-slide piles. Therefore, relevant researchers have made many efforts to find a more reasonable calculation mode and method for anti-slide piles.

Improved Cantilever Pile Method

Dai and Shen (2003) assumed that the part of anti-slide piles above the sliding surface is an elastic directional hinged cantilever beam and the part below the sliding surface is a Winkler elastic foundation beam [25]. The improved foundation coefficient "m" method is used to calculate the internal force of the pile. The displacement of the pile at the sliding surface depends on the calculation results below the sliding surface. Therefore, the displacement of anti-slide piles above the sliding surface is superimposed by the calculation results of the upper cantilever beam and the calculation results at the sliding slide to establish a unified coordinate system and make the calculation results more in line with the actual stress and deformation. Compared with the traditional cantilever beam method, this method improves the calculation accuracy and analysis efficiency of internal forces in anti-slide piles.

Finite Element Method
For anti-slide piles, whether the general cantilever beam method or the improved method, the calculation process is also quite cumbersome, and the calculation results will produce errors. The finite element method is convenient in dealing with complex structures, complex boundary conditions, complex stratum conditions and complex load conditions, and pile-soil interactions can be considered. Dai et al. (2012) used finite element software to establish a three-dimensional finite element model, adopted the finite element strength reduction method, set the interface between the pile and soil, and fully considered the pile-soil interaction [26]. This method can provide a reliable reference for the internal force design and calculation of anti-slide piles. Zhu et al. used the strength reduction finite element method to analyze the different factors affecting the stability of the slope strengthened by anti-slide piles and calculated the pile bending moment, shear force, displacement and slope safety factor of the slope anti-slide piles in the process of graded loading at the top of the slope [27].

Finite Difference Method
Dai et al. (2003) proposed a new calculation model and corresponding calculation method for elastic anti-slide piles [25]. First, the finite difference method is used to analyze the internal force of the whole pile, the corresponding calculation method is deduced, and the program for calculation and graphic processing is compiled. The calculation results of this method are consistent with the laws obtained from theoretical analysis and field tests. At the same time, compared with the existing common calculation methods, the maximum bending moment is significantly reduced, which releases the application potential of anti-slide piles. This makes anti-slide piles design and calculation more economical, reasonable and effective.

Finite Difference Method
Cundall proposed the particle discrete element method for rock mechanics in 1971, proposed the particle discrete element method for soil mechanics in 1979, and introduced the soft particle model [28, 29]. The particle discrete element method can overcome the problems that the finite element method cannot predict fracture development and large deformation.

Calculation of the Lateral Force Acting on the Pile
The evaluation of earth pressure under the action of stable piles is of great significance to the study of slope stability. The lateral force acting on the pile depends largely on the relative movement between the pile and soil (Fig. 4) [5]. In the design and calculation of anti-slide piles, the first step is to determine the failure mode, and the failure mode is the basis for establishing the calculation method [30]. There are two types of failure modes of slope strengthened with anti-slide piles: pile structure failures, such as pile dumping or damage; The other is the failure of slope soil, which slides away from the pile. Based on the assumptions of different failure modes and pile-soil interaction methods, a series of calculation methods for the lateral force acting on the pile and corresponding

design methods of anti-slide piles have been developed. The common methods are the load-structure method, Viggiani method, Ito method, and Poulos method.

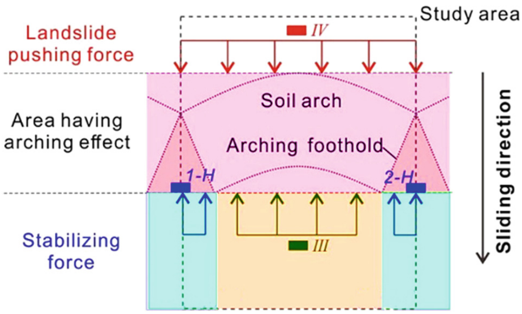

Fig. 4. Calculation of the lateral force acting on the pile

Load-Structure Method
The load-structure method is currently commonly used in anti-slide piles in China. The forces acting on piles are calculated in the two parts below and above the sliding surface, respectively. Then, the sliding force behind the pile and the anti-slide force before the pile were calculated according to the limit equilibrium method of the rigid body. The recursive method is widely used to calculate the sliding force and anti-sliding force in China.

Viggiani Method
The Viggiani method assumes that 1) the pile is rigid; 2) the soil around the pile and the sliding bed is saturated clay; 3) the cohesion of the saturated undrained shear is c_1 and c_2, respectively; 4) the lateral ultimate bearing capacity between piles and soil is $P_y = k{\cdot}c{\cdot}d$ (k is the lateral bearing capacity coefficient, and d is the pile diameter) [31]. Viggiani later proposed a calculation model of pile-soil failure and improved the Viggani method [32]. However, the modified Viggiani method still takes the yield value of pile-soil and materials as the constraint condition of static equilibrium and does not consider the pile-soil interaction.

Ito Method
Ito and Matsui (1975) established an equation for calculating the ultimate lateral pressure of sliding soil based on plastic deformation theory and the force model of a single row of piles [33]. The model is suitable for the infinite rigid pile. It is assumed that the soil around the pile is in a plastic state and meets the Mohr-Coulomb yield criterion. The method considered the effects of pile diameter, pile spacing and parameters of the surrounding soil. The Ito Tomio method considers the rigidity of piles and the bearing capacity of the soil and does not consider the pile-soil interaction. Kumar and Hall (2006) studied the lateral landslide thrust behind the pile in the process of landslide instability, and failure strengthened by anti-slide pile and pointed out that when considering the horizontal soil arching effect behind the pile, the lateral landslide thrust behind the pile

was calculated according to the local plastic deformation theory (Fig. 5) is significantly greater than the measured value [34].

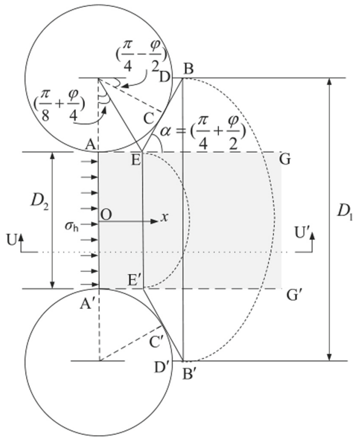

Fig. 5. Soil arch between neighboring piles [33].

Poulos Method

The Poulos method takes the displacement between piles and soil as the basic unknown quantity to analyze the whole pile above and below the sliding surface. In this method, the continuity and behavior of soil with depth are added into the analysis, and various diagrams for calculating the stress of a single pile are obtained. At the same time, the soil properties, boundary conditions, and stiffness of piles are considered. Poulos used an analysis method in which a simplified form of the boundary element method was employed to study the response of a row of passive piles incorporated in limit equilibrium solutions of slope stability [35]. This method revealed the existence of three modes of failure: (1) “flow mode”, (2) “short-pile mode”, and (3) “intermediate mode”. This finding contributed to the practical design of stabilizing piles. Poulos highlighted that the flow mode created the least damage effect of soil movement on piles; if the piles required protection, efforts should be made to promote this mode of behavior.

Limit Equilibrium Method (LEM)

However, these methods are limited to homogeneous soil slopes, where the ground or sliding surface geometry is relatively regular and has no special characteristics (e.g., uneven ground or sliding surface). In addition, these studies do not consider the effects of pore water pressure and shear strength in the slip zone on the lateral force and its distribution. In actual landslide engineering, the most widely used method to evaluate the slope stability and the lateral force acting on the pile is still the limit equilibrium method (LEM) combined with the slice method (Fig. 6) [36, 39]. This technology can adapt to complex slope geometry with different soil properties, pore water pressure conditions, different sliding surface shapes and the effects of external boundary loads [37].

The finite element model combined with the shear strength reduction method (FE-SRM) is widely used in comprehensive slope stability analysis. One of the advantages of FE-SRM is that there is no need to assume the shape and location of the critical failure surface. The location, shape and size of the plastic deformation area can be used to quantify the sliding surface and safety factor [38].

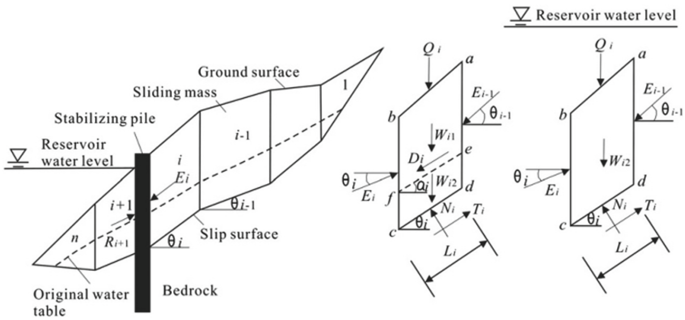

Fig. 6. Schematic representation of the LEM method. [39]

4 Optimal Designs of Anti-slide Piles

4.1 Optimum Pile Spacing

The formation of soil arch between piles is mainly due to the uneven displacement of soil between piles under the action of self-weight or upper load of soil between piles. The soil arching effect is realized through the exertion of the shear strength of the soil. At present, the works on the strength design of anti-slide piles have been relatively mature, but the arching effect is not fully considered in the design and calculation of anti-slide piles. The calculation of the critical spacing of anti-slide piles is a key problem in the design of anti-slide piles, which involves the safety and economy of anti-slide piles. Making full use of the soil arching effect between anti-slide piles can achieve the purpose of economy and efficiency. In recent years, studies on pile spacing under the soil arching effect have been hot, and many results have been obtained.

Wang et al. (2001) deduced the calculation method of pile spacing according to the fact that the sum of total friction resistance between anti-slide piles is beyond the thrust force between piles [40]. Zhou et al. (2004) analyzed the soil arching effect of anti-slide piles using theoretical analyses. They concluded that the static balance condition, the strength condition of the across-section at the arch crown and the arch toe are critical factors that must be considered when determining the pile spacing [41]. Zhao et al. (2010) assumed that the soil arch has the shape of a parabola, and the static balance and strength conditions are met in the horizontal and vertical planes. Then, they deduced the pile spacing calculation equation and obtained the optimal pile spacing [42]. He et al. (2014) inferred the maximum anti-slide pile spacing according to the restriction that the soil strength of the arch toe and the soil shear stress at any point on the pile-soil contact surface should be less than the maximum anti-slide force of the piles [43].

4.2 Optimal Pile Position

The position of anti-slide piles significantly influences the effect of anti-slide piles in stabilizing slopes. Zhu et al. claimed that the factor of safety of the slope is the largest when the pile is located between the middle of the slope and the slope top, and the safety margin of the pile is large (Fig. 7). In this case, the efficiency of anti-slide piles is the highest [27]. Based on the analyzing results of the strength reduction method, Cai and Ugai (2000) observed similar phenomena [44]. Won et al. (2005) considered that when anti-slide piles were installed in the middle of a slope, the earth pressures on the pile sides were the largest, and thus they can provide the greatest reinforcing loading [45]. In the study of Shooshpasha et al. (2020), the performance of a homogeneous slope reinforced with one row of piles is investigated using coupled numerical analysis and the method of shear strength reduction. They claimed that the optimum pile location depends on the pile length, but no matter what the piles head type is, the maximum increase in the factor of safety is obtained if the pile is located in the mid-section of the slope [46].

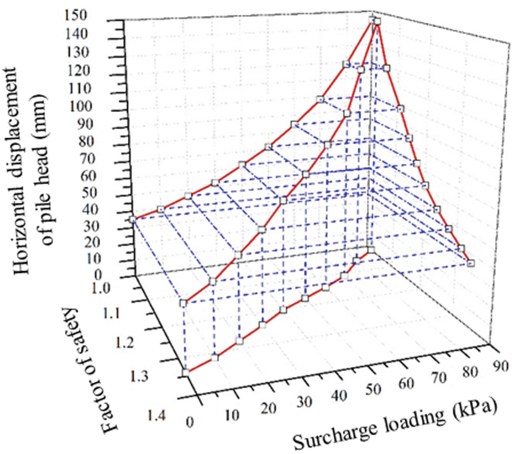

Fig. 7. Relationship curve of surcharge loading-horizontal displacement of pile head-factor of safety [27].

5 Monitoring Techniques of Anti-slide Piles

Slope monitoring has always been an important issue in the field of modern geology and rock engineering. It is an important means to understand and master the evolution process of the slope, timely capture the information of landslide disaster, and provide reliable data and scientific basis for the correct analysis, evaluation, prediction, prediction and treatment of landslide. Because the deformation field of the slope, especially the reservoir bank slope, is the result of the comprehensive influence of many factors, the effects of groundwater, rainfall, temperature, geophysics, chemistry and other field factors cannot be ignored. At present, slope monitoring focuses on deformation monitoring and begins to develop towards multi-field and multi-parameter monitoring. In addition, the monitoring technology is also developing from simple observation of ground macro features and ground instrument monitoring to deep slope monitoring. The development of space telemetry and remote sensing technology provides a new means for mastering slope stability and timely evaluating landslides [47].

The working state of anti-slide piles can be evaluated through field monitoring. At present, the conventional monitoring methods of anti-slide piles mainly include inclinometers, reinforcement gauges, earth pressure cells, total stations and distributed fiber optic sensing technologies. Inclinometer, earth pressure cells and reinforcement gauges are based on point measurement, and their monitoring results can be directly substituted into the existing design and calculation method of anti-slide piles to evaluate the working state of anti-slide piles. These monitoring methods are relatively widely used and mature in engineering with many results. Conventional monitoring methods often have problems in the monitoring process, such as large error, low data acquisition efficiency, improper number of monitoring points, easy-to-produce structural effects [32]. At present, the deep displacement of an anti-slide pile is mainly obtained by an inclinometer. However, the inclinometer sampling interval and data acquisition efficiency are low, and the comparison error of the manual inclinometer at different time points is relatively large.

With the development of DFOS technology, it has been widely used in geotechnical field tests. At present, fiber optic sensing technology has been used to study on-site monitoring of anti-slide piles [48, 49]. Compared with conventional monitoring methods, distributed fiber optic sensing technology has significant advantages, such as full distribution, long monitoring distance, little interference, a large amount of data acquisition, high data acquisition efficiency, real-time monitoring and long-term stability, which can meet the requirements of safety monitoring of slope reinforcement engineering and early warning of landslides [50, 51]. Zhu et al. (2009) investigate the application of fiber Bragg grating technology to monitoring the stability of a reinforced highway slope in Hong Kong [52]. The DFOS technologies are becoming more refined through many trial tests and have shown great potential in capturing anti-slide pile behavior in different working conditions.

6 Conclusions

Anti-slide piles have been widely used in various slope stabilization. Based on the summary and discussion of the current results, this paper analyzes the research status of anti-slide piles and proposes some problems to be solved in the design and field test of anti-slide piles.

(1) The design of anti-slide piles needs to consider the pile-soil interaction and make full use of the soil arching effect between anti-slide piles to achieve the purpose of economy and efficiency.
(2) The calculation methods of internal force of anti-slide piles widely used in engineering practices mainly include the cantilever pile method, foundation coefficient method, finite element method, matrix analysis method, etc. Among them, the discrete element method have great potential in simulating the failure mechanism of

anti-slide piles, which can effectively solve the shortcomings of traditional methods in modeling large deformations.

(3) The working state of anti-slide piles and slope stability can be evaluated through field monitoring. The capability of the DFOS technique in measuring strain profiles is highly advantageous in understanding and detecting any abnormalities in anti-slide piles behavior.

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