Investigating the Effect of the Rock-Socketed Depth of the Hinged Cable-Anchored Pile on the Earthquake Response Characteristics of Supporting Structures

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In order to meet the design requirements of the anti-slide pile, the form of the anchor-pull pile is often adopted in engineering applications. In the present study, the seismic response characteristics of hinged cable-anchored piles with different rock-socketed depths are analyzed using a large-scale seismic model test platform and numerical simulations. The obtained results show that the rock-socketed depth significantly affects the seismic response of the pile-anchor system. It is found that, as the rock-socketed depth increases under the same seismic conditions, the peak acceleration at the top of the anchored pile, the peak dynamic Earth pressure behind the pile, the axial force of the anchor rod, and the bending moment of the pile body decrease and the seismic stability of the anti-slide pile improves. It is concluded that, in the seismic design of anchor-pulled piles, increasing the rock-socketed depth of the anchor is an appropriate scheme to improve the seismic performance of anchor-pulled piles. The research results have a certain significance for improving the understanding of the seismic response law of hinged cable-anchored piles and improving the seismic design.

1. Introduction

Studies show that the rock-socketed depth of the anchor section is an important parameter that affects the anti-slide pile design, thereby affecting the whole supporting system. When the rock-socketed depth is insufficient, the anti-slide pile will not have sufficient resistance to the thrust load of the sliding body and will easily fail. Excessive rock-socketed depth, on the contrary, imposes additional engineering expenses and increases the construction difficulty. Accordingly, obtaining a safe and economical rock-socketed depth has become one of the most concerning issues for geotechnical engineers. In this regard, many investigations have been carried out on anti-slide piles. However, most scholars have focused on the load-bearing mechanism and pile-soil interaction under static conditions and calculating the anchorage depth [1–11]. For example, Jiang et al. [12] studied rigid piles in different conditions and proposed an expression to calculate the anchorage depth of the rigid pile. Although the proposed expression yields promising achievements, there are some limitations. Moreover, Chunmei and Yin [13] determined different embedded depths by changing the structural form and section size of the anti-slide pile. However, since the influence of rock characteristics of the embedded section was not considered in the calculations, the proposed expression had certain limitations. Hu and Wang [14] demonstrated that the anchorage depth of an anti-slide pile is affected by random variables and used the cantilever pile method to calculate the anchorage depth of a rigid anti-slide pile. Based on the lower limit theorem of the plastic limit analysis, Ting-kai et al. [15, 16] derived analytical solutions for active and passive Earth pressure before and after the anti-slide pile, determined the lateral allowable bearing capacity of the soil
around the anti-slide pile, and calculated the anchorage depth of the elastic anti-slide pile. Wu K. [17] established the reliability analysis model to calculate the anchorage depth of rigid piles based on the strength reduction finite element method. Zhang et al. [18] considered different parameters in calculations and established a model to analyze the anchorage depth of rigid piles. Yuan-you et al. [19] introduced the nonlinear optimization theory in the optimal design of anti-slide piles. Furthermore, Chen and Xiao [20] derived an expression to calculate the allowable resistance at the side soil of an anti-slide pile in the anchor section and determine the optimum anchorage depth.

Reviewing the literature indicates that most investigations on the seismic dynamics of anchor-drawn anti-slide piles have focused on the structural responses [21–29]. These investigations are often carried out using numerical simulations and physical tests [30–39]. For example, Kong et al. [40] studied the embedded depth of anti-slide piles under the action of earthquakes and determined the optimal embedded depth of anti-slide piles in gravel soil. Currently, there is a lack of knowledge on the difference in response characteristics of anchorage piles caused by different rock–socketed depths in anchorage sections under the action of an earthquake.

Anti-slide pile with hinge support at the base refers to an anti-slide pile with complete basement strata but a small rock–socketed depth where the pile bottom is supported with a hinge. In order to control the displacement of the pile top and limit the lateral wall stress of the anti-slide pile to the lateral allowable compressive strength, anti-slide piles are usually anchored. In practical applications, the slope reinforced with prestressed anchor cable and anti-slide piles has a reasonable seismic capability [41, 42]. The main objective of the present study is to investigate the performance of hinged-supported anchor piles and the ground motion response characteristics of its support structure under different rock–socketed depths. To this end, tests are carried out on the seismic shaking table and numerical simulations are performed to develop the anti-slide design method of the hinged-supported anchor pile.

2. Model Design

2.1. Similarity Principle. According to similarity criteria [43], physical variables can be mainly divided into three categories, including general geometric similarity, dynamic similarity, and kinematic similarity. General geometric similarity refers to elementary geometric similarity, where a specific length is generally taken as the dimension of physical variables. Combining similar characteristics of various physical systems, the positions and significances of three categories can be described as if any two systems that are similar in geometry, dynamics, and kinematics have similar performances. It is worth noting that geometric similarity can be simply achieved, while the kinematic similarity is achieved only when geometric and dynamic similarities are achieved simultaneously. Therefore, the kinematic similarity is the most challenging one among the three similarities. Meanwhile, under the condition of geometric similarity, an arbitrary solution obtained from the dynamic similarity satisfies the kinematic similarity.

Pursuant to these principles, geometric similarity and dynamic similarity of the anchor pile support landslide were taken as the basic conditions in this model. Due to limited data, including the selection criteria, about the characteristics of the prototype material, it is a challenge to achieve a complete similarity between the materials of the model and the prototype. Consequently, it is a challenge to achieve consistency between the test results and the prototype failure results. Therefore, law similarity was taken as the basic criterion in the model test.

2.2. Experimental Equipment and Model Making. In the present study, the 3-DOF shaking table of Yunnan Institute of Engineering Aseismic with dimensions of 4 m × 4 m was used in all tests. In this table, the maximum load is 30 tons. Moreover, the maximum displacement and velocity are 250 mm and 0.8 m/s, respectively. The maximum acceleration is 1 g under a load of 20 tons, while it reduces to 0.8 g when the load increases to 30 tons. The operating frequency can be set in the range of 0 – 100 Hz and the maximum overturning moment is 30 tm.

The whole test consists of many materials, including landslide materials, model box, retaining plate, anti-slide pile, anchor rod, and concrete. The landslide model is made of three parts, including the sliding bed, sliding surface, and sliding body. Silty clay is used as the soil during tests and the sliding-bed soil is compacted. When making the sliding surface, the soil is first screened with a sieve of about 2 mm in diameter, and then, it is dried. In this way, impurities are picked out and 50% of the fine sandy soil is mixed. The prepared sliding surface soil is evenly distributed over the sliding bed with a thickness of 5 cm. The silty clay is used as the slime soil. It is worth noting that instead of sieving, drying, and tamping, the silty clay is stacked above the slime surface and leveled evenly in the present study. The bedrock of the anchoring section of the anti-slide pile is made of C40 concrete. Table 1 shows the physical and mechanical properties of the test materials.

The studied anti-slide pile is made of wood and has a cross section of 80 mm × 80 mm and a length of 60 cm. The bottom part of the anti-slide pile is placed in the concrete cast in a steel channel to simulate the rock–socketed depth. Each anti-slide pile has a hole with a diameter of about 15 mm at a position 5 cm in front of the pile from the pile top to place anchor rods. The retaining plate is 1.66 m long, 1.5 cm thick, and 0.45 m high. During the tests, the rock–socketed depth of No. 1, No. 2, and No. 3 anti-slide piles is set to 0.05 m, 0.1 cm, and 0.15 m, respectively. The three bolts are made of reinforced steel with a diameter of 14 mm, and the anchoring section is fixed on the angle steel with screws. All bolts are 2.12 m long and are connected to No. 1, No. 2, and No. 3 anti-slide piles and retaining plates, respectively. The four surfaces of the bolt at a distance of 0.08 m from the retaining plate are polished to arrange the strain gauge. The whole model box is 1.5 m high, 3.5 m long, and 1.66 m wide. The schematic of the model is shown in Figure 1.
Figure 2 shows that an acceleration sensor is arranged on the pile top to measure the acceleration and convert the displacement of the pile top into xxx. Moreover, strain gauges are arranged on four sides of the anchor cable 0.08 m from the retaining plate to measure the axial force. Figure 3 shows the installed acceleration sensors.

In all experiments, El Centro waves are used. It is worth noting that the El Centro wave is extensive and representative, which is of great significance for seismic research. In this regard, studies show that the horizontal component of the seismic wave reflects the fundamental force that causes the crack propagation and even failure of the landslide and its retaining structure. During the tests, 5 seismic conditions were designed to simulate a 7-degree medium earthquake, 8-degree medium earthquake, 8-degree large earthquake, 9-degree large earthquake, and over 9-degree earthquake. Figure 4 shows that the control peak of horizontal acceleration in each test condition is 0.1 g, 0.2 g, 0.4 g, 0.62 g, and 1.0 g, respectively. The data of slope acceleration, pile tip displacement, and anchor shaft force are collected.

3. Analysis of the Test Results

3.1. Seismic Displacement Response. Figure 3 shows that an acceleration sensor is installed on the top of the anti-slide pile to measure the seismic acceleration response of the pile under the action of an earthquake. The pile top displacement under five working conditions is obtained using the quadratic integration.

Then, the pile top displacement of seismic waves was analyzed, and the results are presented in Table 2.

Figure 5 illustrates the displacement at the pile top under different working conditions and the same hinge support. It is observed that the peak displacement of the three anchor piles with different rock-socketed depths increases with the increase of the acceleration of the input seismic wave. When the acceleration peak value of the input seismic wave varies
from 0.1 g to 0.6 g, the displacement peak value increases linearly, and then, it decreases when the acceleration exceeds 0.6 g. It is found that, as the acceleration peak of the input seismic wave increases, the corresponding pile-anchor-soil interaction becomes more significant.

The comparison of displacements at the top of the anchor-pull pile with different rock-socketed depths reveals that the rock-socketed depth affects the displacement of the top of the anchor-pull pile under the same seismic condition. More specifically, the biggest peak displacement occurs in anchor-pull pile No. 1 with a rock-socketed depth of 5 cm, while the lowest peak displacement occurs in the anchor-pull pile No. 3 with a rock-socketed depth of 15 cm. The stress mechanism of the anti-slide pile with hinged bearing is analyzed to interpret these results. The schematic diagram of the anti-slide pile with a hinged bearing in Figure 6 can be characterized by the integrity of the rock stratum at the bottom of the pile and the hard rock in section AB. However, the embedded pile in this layer is not deep, so the displacement and the bending moment at point B are \( x_B = 0 \) and \( M_B = 0 \), respectively. When the base of the pile is the hinge end, the displacement and rotation angle at point A can be calculated using the following expression:

\[
\begin{align*}
x_A &= \frac{M_A}{\beta^2 EJ} \left( \frac{4\varphi_3\varphi_4 + \varphi_1\varphi_2}{4\varphi_1\varphi_3 - 4\varphi_1\varphi_4} + \frac{Q_A}{\beta^2 EJ} \right), \\
\varphi_A &= \frac{M_A}{\beta EJ} \left( \frac{\varphi_1^2 + 4\varphi_2^2}{4\varphi_2\varphi_3 - 4\varphi_1\varphi_2} + \frac{Q_A}{\beta^2 EJ} \right).
\end{align*}
\]

Equation (1) indicates that the height \( h \) of the segment AB decreases with the increase of the rock-socketed depth of the anti-slide pile under the hinged bearing, which is equivalent to the decrease of the effective arm of the anti-slide, decrease of the bending moment \( M_A \), and the displacement of the rotation angle at point A. Finally, the experimental results are verified with the theoretical results.

3.2. Strain Response of the Bolt. In this section, axial strain peaks of three bolts embedded in rock with depths of 5 cm, 10 cm, and 15 cm under different working conditions were statistically analyzed, and the results are presented in Table 3. Figure 6 schematically presents the pile diagram.

Figure 7 shows that, as the rock-socketed depth of anchor piles with hinged supports under the same seismic conditions increases, the corresponding strain of the anchor rod decreases. This may be attributed to the elongation of the anchor cable, which is equal to the horizontal displacement of the pile. This analysis is also consistent with the achieved conclusions in the previous section regarding the seismic displacement response.

The obtained results indicate that, under different seismic conditions, as the peak acceleration of the input seismic wave increases, the corresponding strain values of the anchor rod increase at different rock-socketed depths. It is inferred that, with the increase of the peak acceleration of the input seismic wave, the pile-anchor-soil interaction becomes more significant. These results are also consistent with the conclusions of the seismic displacement response in the previous section.
In this section, Fast Lagrangian Analysis of Continua in 3-Dimension (FLAC3D) software, which is a powerful tool to perform geotechnical analyses of soil, rock, groundwater, constructs, and ground support [44–46], is applied to carry out numerical analyses. Such analyses include engineering design, setting the safety factor, analysis of the test results, and back analysis of failures. In this software, the governing equations are solved using an explicit finite volume method to study the complex behaviors of models. Calculations in this software mainly consist of several stages, including detecting large displacements and strains and calculating nonlinear material behavior, yield/failure over large areas, and total collapse. Studies show that Flac3D software has remarkable advantages. First, it uses the “mixed discrete method” to simulate plastic failure and plastic flow. It is worth noting that this method is more accurate than the “discrete integration method,” which is usually used in the finite element method [xx]. Second, even though the

**Figure 4:** El Centro waves under five conditions. (a) 0.1 g El Centro wave, (b) 0.2 g El Centro wave, (c) 0.4 g El Centro wave, (d) 0.62 g EL Centro wave, and (e) 1 g El Centro wave.

**Table 2:** Peak displacement of piles under different working conditions (mm).

| No.                  | 0.1 g | 0.2 g | 0.4 g | 0.62 g | 1.0 g |
|----------------------|-------|-------|-------|--------|-------|
| Pile no. 1 (rock-socketed depth of 0.05 m) | 14.59 | 29.05 | 60.08 | 90.66  | 98.28 |
| Pile no. 2 (rock-socketed depth of 0.10 m) | 13.73 | 27.22 | 56.8  | 85.27  | 92.43 |
| Pile no. 3 (rock-socketed depth of 0.15 m) | 11.36 | 22.41 | 46.41 | 70.49  | 76.11 |
simulated system is static, the dynamic equations of motion should be solved, which makes FLAC3D have no numerical obstacles in simulating the physically unstable process. Last, it adopts an explicit solution scheme. Therefore, the explicit solution takes almost the same time to obtain the nonlinear stress-strain relation as the linear constitutive relation, while the implicit solution takes a longer time to solve a nonlinear problem. Meanwhile, there is no need to store the stiffness matrix so multielement structures can be solved with less memory capacity. Therefore, it is feasible to simulate large deformations because there is no stiffness matrix to be modified. Accordingly, the FLAC3D software is selected in the present study to analyze the problem.

To avoid being affected by boundary conditions, three models are established in this numerical simulation. Each model has three anti-slide piles. The rock-socketed depths of the three models are 5 cm, 10 cm, and 15 cm, respectively. In each model, the anti-slide pile in the middle position was selected for data analysis.

Table 4 shows the physical and mechanical parameters of the studied materials. During calculations, the retaining plate, anti-slide pile, and anchor rod were considered elastic materials to improve the calculation accuracy and efficiency. The whole 3D dynamic model is divided into 30,000 elements. The meshed model is shown in Figure 8.

### 4.1. Analysis of the Acceleration Response
Three anti-slide piles are established in each model, and the acceleration-time curve is obtained at the top of the anti-slide piles at the middle position. Figure 9 reveals that, under the same conditions, the largest and the smallest peak accelerations occur at the top of the anchor-pull pile with a rock-socketed depth of 5 cm and 15 cm, respectively. It is found that, as the rock-socketed depth increases, the corresponding peak acceleration at the top of the anchor-pull pile decreases. This is also consistent with that obtained results from the shaking table test.

### 4.2. Response of Dynamic Earth Pressure behind the Pile
In the three models, the anchor piles at the middle position are selected to monitor the dynamic Earth pressure along the
4.3. Axial Force Response of the Anchor Rod. There are three anchors with the same inclination angle and the middle anchor piles are selected to analyze numerically. Axial force monitoring points are set on each bolt, and the time-history curves of the axial force under the same seismic condition are shown in Figures 14–16. Peak axial forces of the anchor rod are presented in Table 6.

Figures 14–16 and Table 6 show that the time-history curves of axial force values of the three bolts have the same changing trend. Moreover, the comparison of the peak axial force between Table 6 and Figure 17 reveals that the axial force of the anchor rod decreases with the increase of the
depth of rock-socketed anchor piles, which is consistent with the results of the strain response of the anchor rod in the seismic model test.

4.4. Moment Response of the Anti-Slide Pile. In this section, the anchor piles in the middle of the three models are selected and analyzed. Based on the time-history curve data at 0.3 m of the anti-slide pile, the moment response with

| Pile number | Peak values of dynamic Earth pressure (Pa) |
|-------------|------------------------------------------|
| No. 1 (rock-socketed depth of 5 cm) | -1051294 |
| No. 2 (rock-socketed depth of 10 cm) | -1051023 |
| No. 3 (rock-socketed depth of 15 cm) | -1046292 |

Figure 12: The time-course curve of the Earth pressure at the anti-slide pile No. 3.

Figure 13: Peak values of dynamic Earth pressure under different rock-socketed depths.

Figure 14: Axial force diagram of the anchor pile No. 1 with a rock-socketed depth of 5 cm.

Figure 15: Axial force diagram of the anchor pile No. 2 with a rock-socketed depth of 10 cm.

Figure 16: Axial force diagram of the anchor pile No. 3 with a rock-socketed depth of 15 cm.
different rock-socketed depths is analyzed and the results are presented in Figure 18. Figure 18 shows that, under the same seismic conditions and at the same height, different rock-socketed depths result in different peak moment values in the anchor pile. The maximum bending moment time curve of the anchor-pull piles No. 1, No. 2, and No. 3 are 350.8 N·m, 349.8 N·m, and 348 N·m, respectively. The results show that the greater the rock-socketed depth, the smaller the bending moment. This is also consistent with the test results and the theoretical analysis of the anti-slide pile with a hinged bearing.

5. Conclusions

In the present study, the seismic response characteristics of the anchor pile with hinged support at different rock-socketed depths are studied using a large-scale seismic model test platform and numerical simulations. Based on the obtained results, the main conclusions can be summarized as follows:

(1) The rock-socketed depth has a significant impact on the seismic response of anchor piles. It is found that, under the same seismic condition, the peak acceleration at the top of the pile, the peak dynamic Earth pressure behind the pile, the axial force of the anchor rod, and the bending moment of the pile decrease with the increase of the rock-socketed depth. This is because the effective force arm and bending moment of the anti-slide pile, and the displacement and rotation angle of the anti-slide pile decreases with the increase of the rock-socketed depth.

(2) With the increase of the acceleration peak value of the input seismic wave, the pile-anchor-soil interaction becomes more significant. The performed analyses demonstrate that the displacement of the pile top is limited by the anchor cable.

(3) Increasing the rock-socketed depth improves the seismic stability of the anti-slide pile. This is a promising way to improve the seismic performance of the anchor-pull pile with hinged support.

The studied test model for the seismic response of the anchor pile retaining structure subjected to the earthquake load is an effective way to understand the dynamic interactions between the pile-anchor and the pile-soil mass and can provide theoretical support for the seismic design of the slope. However, the dynamic interactions between the pile and soil are complex and further investigations are required in this area.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest, financial, or otherwise.

Authors’ Contributions

Fayou A. and Mingchang Hei are contributed equally to this work.
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