ORIGINAL ARTICLE

Study on the Aseismic Performance of the Slope Supported by Energy-consumption Double-limb Anti-slide Piles

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Abstract: In order to improve the seismic behavior of the existing rigid anti-slide piles, a new type of energy-consumption double-limb anti-slide pile was proposed. The new pile is composed of a main pile limb, an auxiliary pile limb and some energy-consumption connecting rods, which can significantly increase the energy dissipation of the slope and its supporting system during earthquake. Three numerical models of s lopes, which are non-supported slope, traditional rigid anti-slide pile supported slope and new energy-consumption double-limb anti-slide piles supported slope, were established respectively by Flac3D finite difference software. The deformation, shear strain increment, point safety factor and earth pressure behind piles of each slope model under earthquake were compared and analyzed. The results is how that the horizontal displacement of the slope supported by energy-consumption double-limb anti-slide piles is similar to that supported by rigid anti-slide piles with the same cross-section, but the horizontal displacement of the soil behind the piles is larger, which increases the dissipation of the seismic input energy. The vertical displacement of the slope supported by energy-consumption double-limb anti-slide piles is smaller than the slope supported by rigid anti-slide piles, which can effectively control the overtopping failure of the slope. The energy-consumption connecting rods yield continuously and plastic deformation occurs during earthquake, which dissipate a lot of energy. Meanwhile, the deformation of the main pile limb is reduced, and the overall safety of the anti-slide pile is guaranteed. The energy-consumption double-limb anti-slide piles can significantly reduce the shear strain and earth pressure behind piles, and improve the point safety factor of the slope supported by it, which have better seismic performance than the rigid anti-slide piles, and can significantly improve the seismic stability of the slope.

Keywords: Energy-Consumption Double-Limb Anti-Slide Pile; Seismic Behavior; Slope; Flac3D

Introduction

China is an earthquake-prone country, and earthquake-induced landslides are the major secondary disasters after earthquakes. They are numerous, large-scale, high-risk and occur mostly in mountainous areas with backward transportation. Common measures for landslide treatment include anchor cable support, anti-slide pile support, retaining wall support, etc. In the aspect of anti-slide pile seismic performance research, Ye Hailin, Zheng Yingren, etc[2-4] etc. have used finite difference software Flac3D, combined with strength reduction dynamic analysis method, considered the dynamic action between pile and soil, obtained the internal force distribution of anti-slide pile, and studied the anti-slide pile seismic performance through vibration table model test. Lai Jie, Zheng Yingren[5, 6] and others used large-scale shaking table model tests to study the seismic effects of embedded anti-slide piles and double-row anti-slide piles. It was found that the slope supported by a single anti-slide pile is prone to tensile failure. With the increase of earthquake action, it is prone to over-top failure at the pile top and shear slip at the slope waist and slope toe. Tu Jiewen and Zheng tung[7, 8] and others have conducted model tests on cantilever anti-slide piles and anchor anti-slide piles. It is found that cantilever anti-slide piles can reduce the acceleration amplification effect of slope to a certain extent under the action of

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earthquake, and the earth pressure behind the piles will increase with the increase of earthquake intensity. At present, most of the researches at home and abroad are based on rigid anti-slide piles. The over-top failure and overall instability inclination of slopes supported by rigid anti-slide piles under earthquake are generally overcome by a combination of various supporting methods.

1. Double-limb energy dissipation anti-slide pile and its numerical model

1.1 Double-limb energy dissipation anti-slide pile structure

The traditional anti-slide pile usually adopts the reinforced concrete pile with equal cross section. Its structure is simple and its rigidity is large. This kind of rigid anti-slide pile is prone to pile toppling or large permanent displacement under earthquake action, which affects its normal use function after earthquake. The effect of earthquake on the slope is essentially a process of energy transmission, transformation and dissipation[9] which inputs the energy of the slope and its supporting system.

If it can be safely converted and dissipated, the slope can maintain its seismic stability. In order to improve the energy dissipation capacity of the slope and its supporting system, and further improve the seismic stability of the supported slope, a new type of double-limb energy dissipation anti-slide pile structure is proposed in this paper.

As shown in Figure 1, the new energy dissipation anti-slide pile adopts a split structure and consists of a main limb pile body, an auxiliary limb pile body and an energy dissipation connecting rod. The main limb pile body is an L-shaped deformed section column, the large section part at the lower part of the main limb pile body is the anchoring section of the anti-slide pile, and the small section part at the upper part is the loading section of the main limb pile body. The auxiliary limb pile body is a cuboid column and is positioned on one side close to the mountain. The main and auxiliary limb piles are arranged on the main limb pile.

The variable cross-section of the 75 body is connected by a positive and negative l shaped clamping groove sliding pair (Figure 1c). the auxiliary limb pile body can generate a certain horizontal displacement relative to the main limb pile body along the sliding pair. The energy dissipation connecting rod is used for connecting the loading section of the auxiliary limb pile body and the main limb pile body, and comprises a horizontal connecting rod and an inclined connecting rod, wherein the inclined connecting rods are arranged crosswise along the vertical direction and the horizontal direction, so that the auxiliary limb pile body and the main limb pile body are stressed together as a whole structure, and the auxiliary limb pile body, the energy dissipation connecting rod and the loading section of the main limb pile body form the loading section of the anti-slide pile to jointly resist landslide thrust.

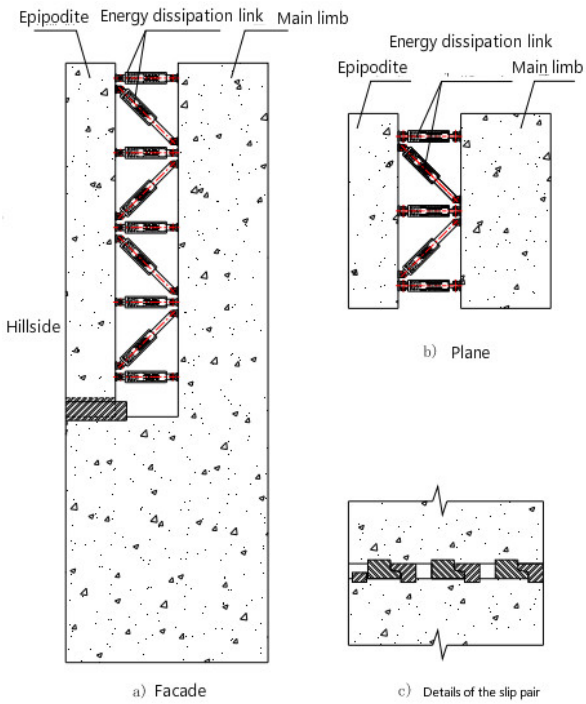


Figure 1. The structure of the energy-consumption double-limb anti-slide pile.

1.2 Numerical model of double-limb energy dissipation anti-slide pile

In the FLAC numerical model, the main and auxiliary limb piles adopt hexahedral solid elements and elastic constitutive model. Energy dissipation link has complex structure and double energy dissipation mechanism, which is approximately simulated by bolt element of ideal elastoplastic constitutive model. The sliding pair of the L shaped clamping groove between the main and auxiliary limb piles is simulated by a contact surface unit, and the L shaped clamping groove is realized by controlling parameters such as tensile strength, friction angle, cohesion and the like of the contact surface.

The sliding pair has the characteristic of only sliding but not cracking. The connection between the anchor rod unit and the solid unit is realized through link, all links adopt the form of hinges, releasing three rotational degrees of freedom. The model of the double-limb energy dissipation anti-slide pile and its energy dissipation connecting rod is shown in Figure 2.

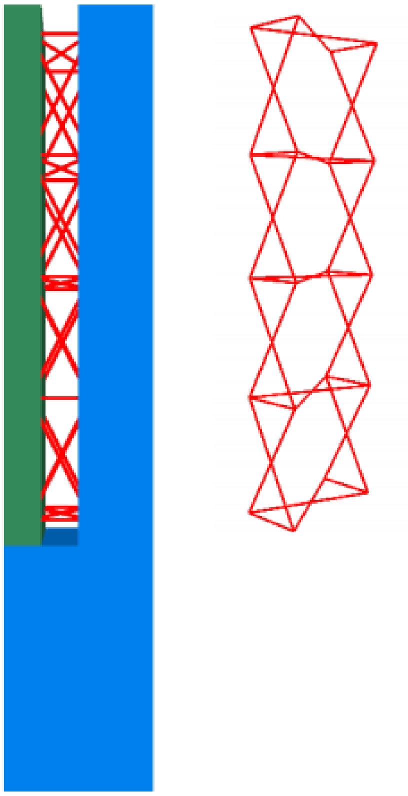


Figure 2. Numerical model of energy-consumption double-limb anti-slide pile and its energy-consumption connecting rods.

2. Numerical simulation analysis

2.1 numerical simulation scheme

In order to investigate the anti-seismic performance of the slope supported by double-limb energy dissipation anti-slide piles, three numerical models were established, i.e. unsupported slope, traditional rigid anti-slide pile supported slope and new double-limb energy dissipation anti-slide pile supported slope.

The double-limb energy dissipation anti-slide pile model replaces the rigid anti-slide pile in the rigid anti-slide pile model with the double-limb energy dissipation anti-slide pile. The length of the main limb of the double-limb energy dissipation anti-slide pile is 12m, the cross section is 2.4m×2.4m, and the cross section of the loaded section is 1.4m× 2.4m; The length of the auxiliary limb pile is 7m and its cross section is 0.4m×2.4m. The cross-sectional dimension of the anchoring section and the outer contour dimension of the cross-section of the loading section of the double-limb energy dissipation anti-slide pile are the same as the cross-sectional dimension of the rigid anti-slide pile.

When simulating a semi-infinite body such as a slope, numerical methods that rely on discretization of finite regions in space need to impose appropriate conditions on artificial numerical boundaries. The fixed boundary or elastic boundary used in static analysis will cause outward propagating waves to be reflected back to the model in dynamic analysis and will not allow necessary energy divergence. To solve this problem, FLAC3D uses static boundary and free field boundary in dynamic analysis. The three models in this paper adopt static boundary at the bottom and free field boundary around. The calculation model and boundary condition settings are shown in Figure 3.

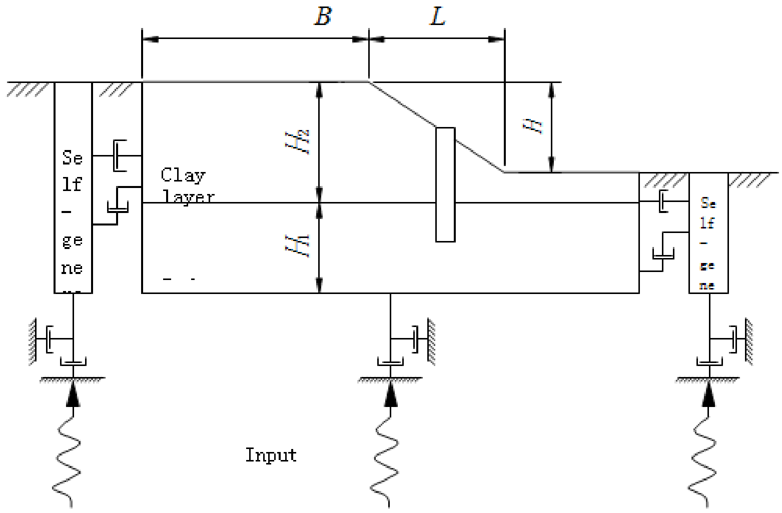


Figure 3. Dynamic numerical simulation model of the slope.

2.2 Input seismic wave

The same seismic action is applied to the three numerical models, and the former 18s record of El-Centro wave (1940, N-S direction) is taken as the input seismic wave, and the peak acceleration is adjusted to 0.2g. The input seismic acceleration time history is filtered and baseline corrected, then converted into stress time history and applied to the static boundary at the bottom of the model. The acceleration time history near the bottom of the model is monitored, and the results are in good agreement with the input acceleration time history curves. The input acceleration time history curve is shown in Figure 4.

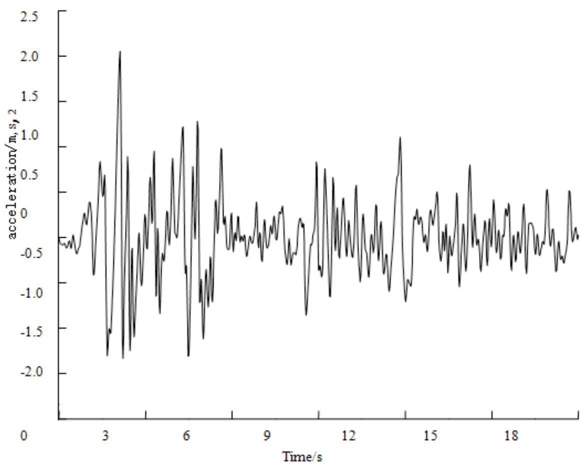


Figure 4. Input acceleration time history curve.

2.3 Monitoring point arrangement

To monitor the response of the model slope under earthquake. Corresponding monitoring points are arranged at the same positions of the three models, of which: monitoring point O is arranged at the bottom of the model; Monitoring point A1 is arranged on the slope surface in front of the pile, and monitoring point A2-A5 is evenly arranged on the slope surface behind the pile; The monitoring point Z1 is close to the slope behind the anti-slide pile and is used for monitoring the vertical displacement of the slope behind the pile. Monitoring points F1-F3 are determined according to the calculated shear strain increment nephogram of the final state slope and are arranged on relatively dangerous sliding belts for monitoring the number of safety systems at the slope points. All monitoring points are arranged on the central section in the width direction of the model, and the specific position is shown in Figure 5.

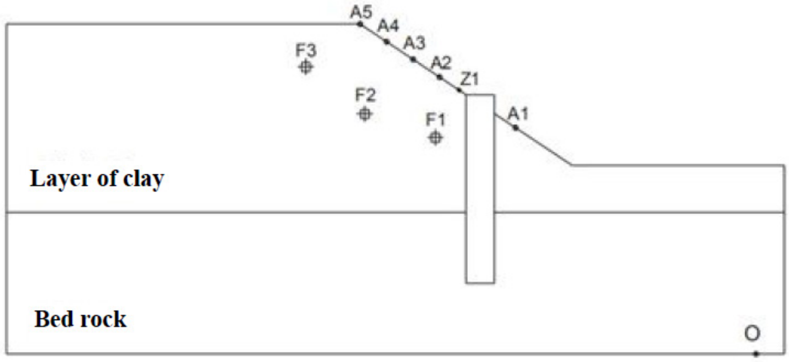


Figure 5. Locations of the monitoring point.

2.4 Slope stability evaluation

In slope stability analysis, there has been a relatively unified evaluation standard for slope safety evaluation under static load, but there is no unified understanding[10, 11] for slope stability evaluation under dynamic load.

In this paper, the horizontal displacement of slope monitoring points during earthquake and the vertical displacement of final slope monitoring points are calculated to judge the degree of slope slip and over-top failure. Judging the slope stability and supporting effect through the point safety factor and shear strain increment of monitoring points; The seismic dynamic response of the slope and the stress state of the supporting structure are judged by the earth pressure behind the pile.

3. Analysis of simulation results

During the earthquake, the maximum horizontal displacement of the unsupported slope occurred at 17.4s and reached 44.5cm. At the end of the earthquake, the displacement of the slope has no convergence trend.

Figure 6 shows the horizontal displacement of A3 monitoring point under three working conditions of no support, rigid anti-slide pile support and double-limb energy dissipation anti-slide pile support during the earthquake. As can be seen from the figure, after the slope is supported, the displacement of the slope surface is effectively controlled, and the reinforcement effect of the two support schemes is approximately the same, and the displacement of the slope supported by the double-limb energy dissipation anti-slide pile is slightly larger.

Figure 7 shows the calculated final permanent displacement of the slope surface and post-pile monitoring points. as can be seen from the horizontal displacement of the slope surface in figure 7a, the horizontal displacement of the slope surface is controlled within the range of 10-20cm after the supporting measures are taken, and the horizontal displacement of the slope surface supported by rigid anti-slide piles and double-limb energy-consuming anti-slide piles are not much different. As can be seen from the horizontal displacement of the soil behind the 7b pile in Figure 1, the horizontal displacement of the soil in the deep part of the slope supported by rigid anti-slide pile is small and increases sharply when approaching the slope surface. After the double-limb energy dissipation anti-slide pile supports the slope, the soil body has a certain controllable horizontal displacement along with the auxiliary limb pile body, and the horizontal displacement at the slope surface tends to be consistent with that of the rigid anti-slide pile supports the slope. This safe and controllable displacement generates a large amount of energy consumption of connecting rods, and at the same time increases the energy consumption of the slope itself, thus improving the seismic stability of the slope. From figure 7c to calculate the final vertical displacement, it can be found that the settlement of the slope far away from the supporting structure is larger than that near the supporting structure. on the whole, the settlement of the slope supported by the double-limb energy dissipation anti-slide pile is larger than that of the rigid anti-slide pile. Comparing the vertical displacement of Z1 point, it can be found that the vertical displacement of the slope supported by the double-limb energy dissipation anti-slide pile is -0.03cm and the vertical displacement of the rigid anti-slide pile is 4.75cm, which shows that the double-limb energy dissipation anti-slide pile can obviously reduce the degree of over-top failure of the slope.

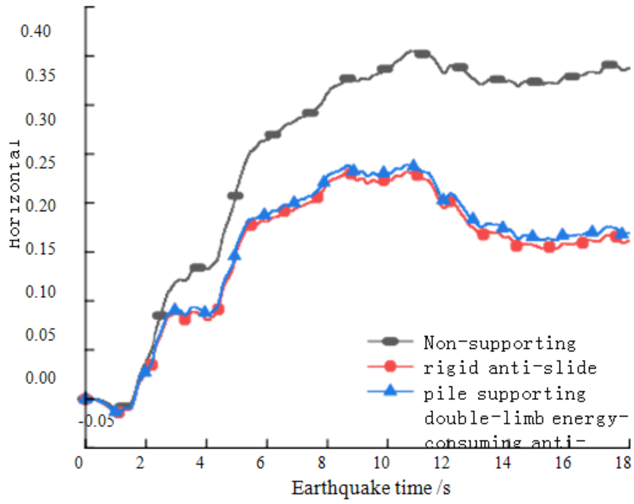
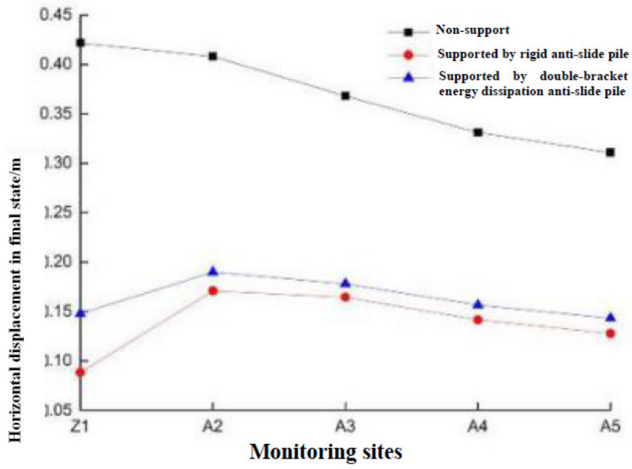
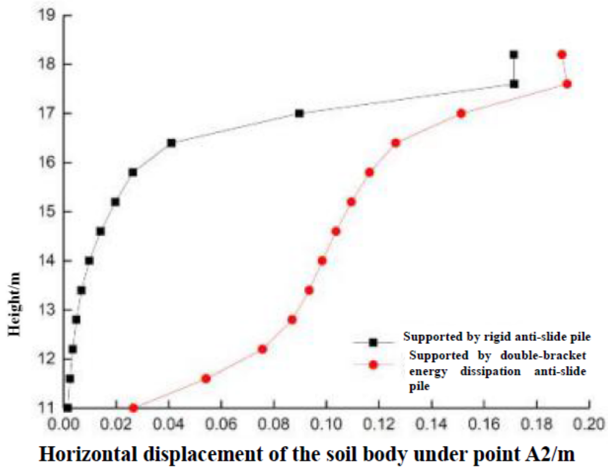


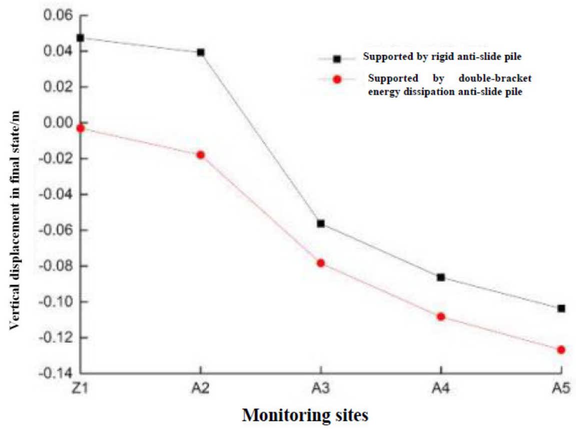
Figure 6. Horizontal displacement of point a3.



(a) Horizontal displacement of slope monitoring points



(b) Horizontal displacement behind pile directly below point



(c) Vertical displacement diagram of slope monitoring points

Figure 7. Displacement at the end of calculation.

4. Conclusion

(1) Under the action of earthquake, anti-slide pile support can effectively control the slope displacement and improve the seismic stability of the slope. The horizontal displacement of slopes supported by rigid anti-slide piles with the same cross-section and double-limb energy dissipation anti-slide piles is approximately the same. The horizontal displacement of the soil behind the double-limb energy dissipation anti-slide pile is larger than that of the rigid anti-slide pile. This safe and controllable displacement can generate a large amount of connecting rod energy consumption, and at the same time increase the energy consumption of the side slope itself, thus improving the seismic stability of the side

slope. The vertical displacement of the slope supported by the double-limb energy dissipation anti-slide pile is obviously smaller than that of the slope supported by the rigid anti-slide pile, which can significantly reduce the over-top damage degree of the soil body behind the pile.

(2) During the earthquake, the point safety factor of the slope with support is significantly higher than that of the slope without support, and the point safety factor of the slope with double-limb energy dissipation anti-slide piles is higher than that of the slope with rigid anti-slide piles. After the earthquake, the shear strain increment of the slope supported by the double-limb energy dissipation anti-slide pile is reduced by nearly half compared with that of the rigid anti-slide pile, which indicates that the double-limb energy dissipation anti-slide pile can significantly reduce the shear strain of the slope supported. The results of point safety factor and shear strain increment show that the double-limb energy dissipation anti-slide pile has better seismic performance than the rigid anti-slide pile, which can significantly improve the seismic stability of the supported slope.

(3) During the earthquake, the maximum earth pressure borne by the double-limb energy dissipation anti-slide pile is far less than the maximum earth pressure borne by the rigid anti-slide pile. The double-limb energy dissipation anti-slide pile can effectively reduce the earth pressure behind the pile, reduce the earthquake action borne by the pile body, and has better anti-earthquake performance and larger safety reserve.

(4) During the earthquake, the energy-consuming connecting rod of the double-limb energy-consuming anti-slide pile continuously yielded and produced plastic deformation, and the reciprocating deformation of the energy-consuming connecting rod produced a large amount of energy dissipation. The displacement of the auxiliary limb pile body and the energy dissipation connecting rod reduces the deformation of the main limb pile body and ensures the overall safety of the anti-slide pile.

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