Stability Analysis of Slopes Supported by Anti-slip Piles under Different Working Conditions

Zhiquan Wang [1, a], Jian Wu [1, b], Shuaihua Ye [2, c, *], Dong Yang [1, d], Longwei Zhu [2, e]

[1] Gansu Civil Engineering Research Institute Co., Ltd., Lanzhou 730020, China;

[2] School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, China.

[a] zhizhi_3@163.com, [b] ageflyaids@163.com, [c, *] yeshuaihua@163.com,

[d] yd1090256650@163.com, [e] zhulongwei1208@163.com

Abstract. In the reinforcement of slope management measures, the arrangement of anti-slip piles is often used to keep the slope stable, and anti-slip piles, as a typical landslide prevention and control structure, occupy a more important position in landslide management. Relying on a landslide in Gansu Province, this paper carries out numerical simulation research on landslide reinforced by anti-slip piles to study the change rule of the stability coefficient of the landslide under natural, rainfall and earthquake conditions as well as the displacement law under earthquake conditions, and then evaluates the reinforcing effect of anti-slip piles in the management of landslides. The results of the study show that, before the landslide was reinforced by anti-slip piles, the landslide mass was in a stable state and a basically stable state under natural conditions and rainfall conditions, respectively, and the probability of failure was small. Under the earthquake condition, the landslide is in an unstable state and is prone to localized failure, and the displacement of the landslide mass in the X direction is larger; The stability coefficients of the landslide mass under each condition were greatly improved after the stabilization of the landslide by anti-slip piles and the X-direction was limited under the earthquake condition, and the landslide was in a stable state. The effect of anti-slip pile reinforcement is good, and it can provide reference for future anti-slip pile reinforcement slope projects.

Keywords: Anti-slip piles; Rainfall infiltration; Seismic loading; Numerical modeling; Slope stability.

1. Introduction

Factors leading to the occurrence of landslide disaster phenomena include human activities, climate change, earthquakes and rainfall, etc., so the study on the stability of slopes under various working conditions is particularly important. Experts and scholars at home and abroad have conducted a lot of research on anti-slip pile reinforced slopes under different working conditions. Tang Yong [1] simulated and analyzed the mechanism and mode of anti-slip pile reinforcement by using FLAC3D finite element software, and obtained the reasonable parameters of anti-slip pile reinforced slopes. Keefer [2, 3] the relationship between the landslide distribution and the distance from the epicenter and the angle of slopes, etc., and established an earthquake database. Y. Parish et al. [4] studied the dynamic response of concrete rubble dam body under different shear modulus using finite element method and derived the law of shear modulus and self-oscillation frequency. Under the scenario of rainfall condition, Carey et al. [5] analyzed the Lowther Ville landslide and found that the landslide occurred due to the decrease of effective stress in the slope caused by the increase of pore water pressure. Hou et al. [6] found that rainfall was the main cause of induced slope instability based on the phenomenon of landslides on the back dam of Three Gorges Reservoir Area.

Although many scholars have carried out a lot of work on the stability of slopes [7-12], few studies have been conducted to discuss the stability of landslides strengthened by anti-slip piles under various working conditions in combination with engineering examples. Based on this, this paper takes a landslide in Gansu Province as the research object, and with the help of finite element analysis software, numerical simulations were carried out for the landslide before and after the anti-slip pile reinforcement under natural working condition, rainfall working condition and earthquake working condition respectively. With the help of numerical simulation results to analyze the change rule of the safety factor in these three types of conditions, and provide reference for the actual project.

2. Project Overview

2.1 Engineering Geological Condition

The landslide body is located in Gansu Province, a water conservancy hub, both ends of the high mountains, belonging to the near east-west extension of the structure of the high mountainous areas, the overall terrain in the area is high in the west and low in the east, north-south is high in the middle of the two sides of the relatively low, on the plane of the landslide body is an irregular long tongue-like. Northeast of the landslide body for the huge thick layer of tuff, constitute the landslide body peripheral alpine steep terrain, in the lower part of the steep cliff in the southeast and southwest direction for the sandstone, shale strata, but also for the landslide body of the main lithology of the birth. The contact part of these two types of strata has developed a large-scale fault, so the slope structure of the landslide area is more complex.

2.2 Hydrogeological Condition

The district is at a high altitude, the climate is cold and rainy, belonging to the alpine humid climate zone, basically no summer throughout the year, spring and fall are connected, and the winter is long. The average annual precipitation in the district is 596mm, up to 800mm, summer precipitation is more concentrated, precipitation is mainly concentrated in May to September, of which May to June rainfall 65mm-85mm, 7,8,9 three months of rainfall in 100mm-110mm, the maximum daily rainfall of 66mm, annual evaporation of 1259.2mm.

2.3 Reinforcement Scheme Design

According to the preliminary design scheme of the landslide body reinforcement, anti-slip piles are selected for this reinforcement program, pile parameters is Φ2.0m@5.0m, with row spacing of 5.0m, the length of the front row of piles is 20.0m, and the length of the back row of piles is 30.0m, the elevation of the top of the piles of the front row of piles is 2215.00m, and the elevation of the top of the piles of the back row of piles is 2218.00m.

3. Model Building

3.1 Selection of the Constitutive Model

In this model, the anti-slip piles are treated as linear elastic materials and the geotechnical constitutive model is an ideal linear elastic model. Due to the unique properties of Mohr-Coulomb model and its satisfactory results in terms of analysis, computation, and accuracy, this model is chosen as the constitutive model of the soil for this numerical simulation analysis.

3.2 Parameter Values

3.2.1 Soil parameters

After the investigation of the project site by the geological survey company, the soil parameters used in the modeling process are shown in Table 1

Table 1. Soil Parameters

Soil strata	Cohesion (*kPa*)	Internal friction angle (°)	Unit weight (*kN/m³*)	Constrained modulus (*GPa*)	Poisson's ratio
Stony soil	20	31	21	0.3	0.36

Base rock	1000	45	26	60	0.24

3.2.2 Rainfall parameters

Rainfall conditions are calculated for 6 days of rainfall, with the values shown in Table 2

Table 2. Rainfall Parameters

Soil strata	Saturated permeability coefficient (*m/d*)	Humidification paths				Rainfall intensity (*mm/d*)
		a	*m*	*n*	θ_s	
Stony soil	1.728	100	1	2	0.4	100
Base rock	0.04	10	1	2	0.01	

3.2.3 Earthquake parameters

According to the "China Earthquake Parameter Zoning Map" (GB18306-2015), the peak acceleration of ground vibration in the project area is 0.2g, and the intensity of earthquake is VIII. The seismic acceleration coefficient $K_{\mathrm{h}} = 0.2$ is selected for the stability analysis of the landslide under seismic condition by the proposed static method, and the EI-Centro wave with peak acceleration of 0.2g is selected as the example waveform for the analysis of the landslide under seismic condition by the Newmark deformation method.

3.3 Finite Element Modeling

To comprehensively analyze this landslide, the profiles in the plan are selected for numerical simulation under natural, rainfall, and seismic conditions, as shown in Fig. 1.

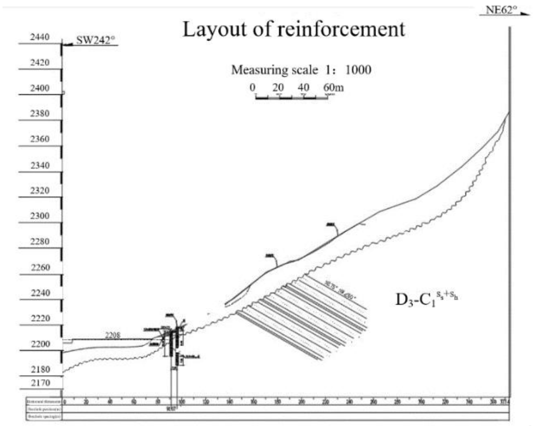


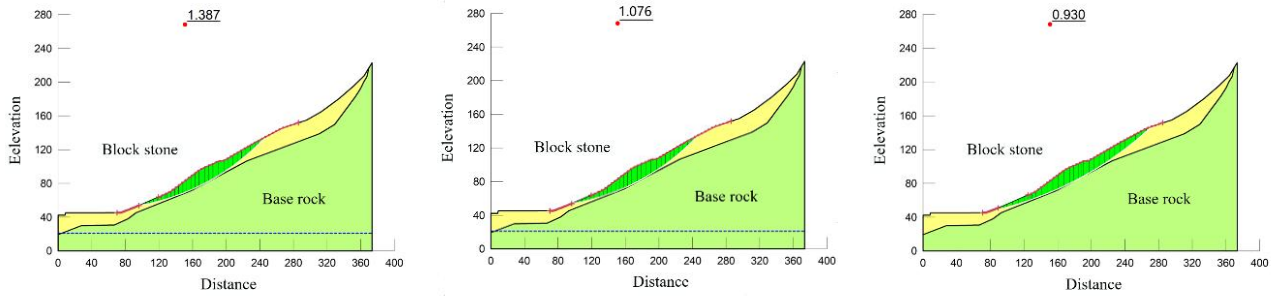
Fig. 1 Landslide profile

In the process of landslide modeling, rainfall conditions are set up: a) Consider the effects of rainfall and landslide slope loading; b) Set the duration of rainfall as 6 days. Setting up the seismic condition: a) using the proposed static method to calculate the safety coefficient of the slope; b) using the Newmark deformation method to analyze the displacement of the landslide under the seismic condition and inputting the EI-Centro waveform as the example waveform.

4. Analysis of Calculation Results

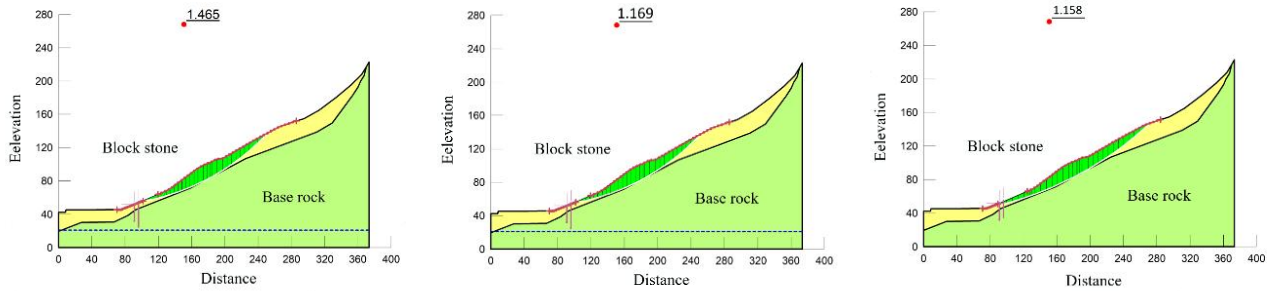
4.1 Stability Analysis of Landslides Under Each Working Conditions

The stability coefficients of the landslide profile before and after stabilization under natural, rainfall, and earthquake conditions are shown in Fig. 2 and Fig. 3.



(a) Natural condition (b) Rainfall condition (c) Earthquake condition

Fig. 2 Calculation results of each working condition before landslide stabilization



(a) Natural condition (b) Rainfall condition (c) Earthquake condition

Fig. 3 Calculation results of each working condition after landslide reinforcement

The stability coefficients of the profile before and after reinforcement for natural, rainfall and earthquake conditions are shown in Table 3.

Table 3. Coefficients of safety for different operating conditions

Work conditions	Pre-reinforcement F_S	After reinforcement F_S
Natural condition	1.387	1.465
Rainfall condition	1.076	1.169
Earthquake condition	0.930	1.158

From the above table, the stability coefficients of the profile before and after reinforcement are 1.387 and 1.465 respectively under natural condition, which shows that the profile is in stable condition and the reinforcement effect of anti-slip piles under natural working condition is about 5.6%.

Under the rainfall condition, the stability coefficient of the profile before and after reinforcement is 1.076 and 1.169, respectively, which shows that the stability coefficient of the profile has decreased relative to the natural condition, and the profile is in a basically stable state, and the reinforcement effect has been enhanced by about 8.6%. The existence of anti-slip piles can reinforce the slope better, and if the subsequent rainfall time continues to increase, the slope before reinforcement may be in danger of localized damage.

The stability coefficient of the landslide was only 0.930 when the seismic load was applied to the landslide before the anti-slip pile reinforcement under the earthquake condition, which shows that the landslide is in an unstable state under the current condition, and it is very easy to be damaged locally and evolve into a landslide disaster, so the anti-slip piles should be designed for the landslide to enhance the safety and stability of the landslide. After the anti-slip pile support, the stability coefficient of the landslide body reaches 1.158, compared with the stability coefficient before reinforcement increased by about 24.5%, and the slope body reaches a stable state.

Under rainfall conditions, rainwater will infiltrate into the landslide body from the surface of the slope body, so that the water content of the landslide soil body increases, the pore water pressure increases, the matrix suction decreases, which changes the mechanical properties of the soil body, and the shear strength of the slope body decreases, which makes it difficult to resist the downward force of the slope. At the same time, the heaviness of the soil body will also increase to a certain extent, which in turn increases the sliding force of the soil mass and is more likely to induce landslide phenomenon. The existence of anti-slip piles can better increase the sliding force of the soil body, transfer the upper thrust to the lower bedrock, and can play a certain supporting role.

4.2 Displacement Analysis of Landslides Under Earthquake Condition

The displacement of the landslide body in x-direction under seismic loading before and after the stabilization of the anti-slip pile is shown in Fig. 4.

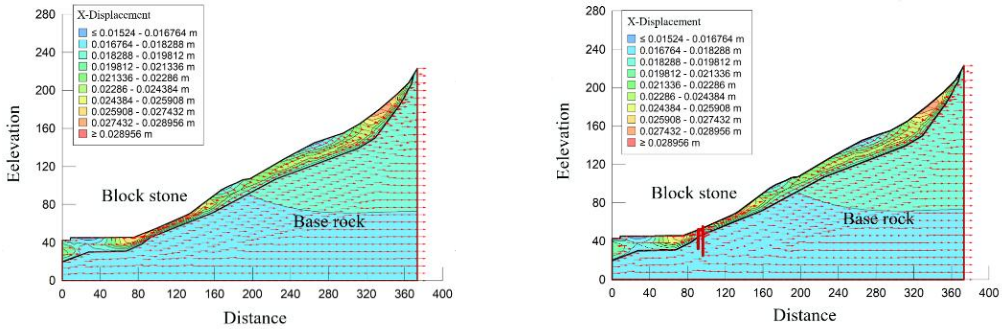


Fig. 4 Displacement map in X direction before and after reinforcement

From the above figure, under the earthquake condition, the displacement of the landslide mass before reinforcement is more than 28.96mm, while the displacement after reinforcement is about 19.81mm, which is reduced by 31.60% relative to the pre-reinforcement, so it can be seen that the installation of anti-slip piles significantly reduces the displacement of the landslide mass. The anti-slip pile support structure changes the stress state of the landslide mass, on the one hand, it limits the displacement trend of the latent soil mass under seismic action and changes the stress system of the whole landslide mass; On the other hand, as a rigid anti-slip pile will be embedded in the bedrock through the landslide mass, when the seismic load is transferred to the soil mass, the anti-slip pile will be extruded with the soil layer each other, which will form a buffer-like effect, and can absorb the energy of the seismic load to a certain extent, which ensures the stability of the landslide mass.

5. Conclusion

The article uses finite element software Geo-studio to simulate and analyze the stability change law of a landslide in Gansu Province under natural, rainfall and earthquake conditions using anti-slip pile reinforcement treatment, and obtains the following conclusions:

(1) Under the natural condition, the landslide is in a stable state and does not need reinforcement treatment. When the landslide is in saturated rainfall condition, the stability coefficient of the landslide is greatly reduced, and the stability coefficient of the landslide is enhanced by about 8.6% after the anti-slip pile reinforcement treatment.

(2) Under the earthquake condition, the safety coefficient of the landslide mass before reinforcement is less than 1, and the landslide mass is in the state of instability. After reinforcement, the safety coefficient of the landslide mass reaches 1.158, which is improved by about 24.5%, and the landslide mass reaches a stable state.

(3) The installation of anti-slip piles can effectively reduce the displacement of the landslide mass in the X direction under earthquake condition and can better improve the force characteristics of the landslide mass. If the anti-slip piles are analyzed in terms of parameters such as pile length, pile diameter, and pile spacing, the reinforcing effect of anti-slip piles can be further exerted.

References

[1] Tang Yong, Yu Xin, Sun Zhihui. Study on seismic reinforcement mechanism and model of anti-slide Piles based on FLAC 3D. Water Power, 2019, 45(7):33-37.

[2] Keefer D K. Landslides caused by earthquakes. Geological Society of America Bulletin, 1984, 95(4): 406-421.

[3] Keefer D K. Statistical analysis of an earthquake-induced landslide distribution—the 1989 Loma Prieta, California event. Engineering geology, 2000, 58(3-4): 231-249.

[4] Parish Y, Abadi F N. Dynamic behaviour of earth dams for variation of earth material stiffness. Proceedings of World Academy of Science: Engineering and Technology. 2009, 50: 606-611.

[5] Carey J M, Petley D N. Progressive shear-surface development in cohesive materials; implications for landslide behaviour. Engineering geology, 2014, 177: 54-65.

[6] Hou Tianshun, Wang Xingang, Pamukcu Sibel. Geological characteristics and stability evaluation of Wanjia middle school slope in Wenchuan earthquake area. Geotechnical and Geological Engineering, 2016, 34: 237-249.

[7] Xue Tao, Ye Shuaihua, Cao Chengming. Permanent displacement analysis of multistage loess slopes with multiple slip surfaces based on energy methods. International Journal of Geomechanics, 2023, 23(11): 04023192.

[8] Ye ShuaiHua, Zhao Zhuangfu. Allowable displacement of slope supported by frame structure with anchors under earthquake. International Journal of Geomechanics, 2020; 20(10): 04020188.

[9] Ye Shuaihua, Xue Tao, Zhang Wuyu. Multi-stage slope displacement analysis based on real-time dynamic Newmark slider method. Soil Dynamics and Earthquake Engineering, 2023, 174: 108209.

[10] Zhang Ruihuan, Ye Shuaihua, Tao Hui. Stability analysis of multistage homogeneous loess slopes by improved limit equilibrium method. Rock and Soil Mechanics, 2021, 42(3): 813-825.

[11] Fang Guangwen, Zhu Yanpeng, Ye Shuaihua, Wu Qiang. Reliability analysis of soil nailing - reinforced slopes considering fuzzy randomness. Chinese Journal of Geotechnical Engineering, 2021, 43(S1): 122-126.

[12] Zhao Shangyi, Zheng Yingren, Shi Weimin, Wang Jinglin. Analysis on safety factor of slope by strength reduction FEM. Chinese Journal of Geotechnical Engineering. 2002,24(3):343-346.