Numerical Simulation Study on the Mechanism of Loess Slope Landslide Formation under Rainfall Effects

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Abstract. In the Ili region of Xinjiang, there are a large number of loess slopes. Combined with the high rainfall in the Ili Valley, it often poses hazards to engineering construction. Under the influence of rainfall, the moisture content of the loess increases significantly, leading to sliding and failure at the contact surface between the loess and gravel layers. In order to comprehensively analyze the mechanism of loess surface slope landslide under the effect of rainfall, this study conducted field sampling of typical landslides in the area and performed laboratory direct shear tests and finite element numerical simulation studies. The results showed that: after the increase in moisture content, the cohesive strength of the loess increased to some extent, but the internal friction angle continued to decrease, resulting in a continuous reduction in shear strength. The contact surface between the loess and gravel layers was prone to sliding and failure. Under self-weight conditions, the maximum displacement was 3.7cm, while under rainfall conditions, the maximum displacement reached 56.7cm. This is because rainwater infiltration changes the contact form between the loess particles, reducing its shear strength, and the increase in moisture content makes the loess more prone to plastic deformation. After implementing anchor support measures, the maximum displacement of the slope under rainfall conditions decreased to 27.5cm, demonstrating a significant supportive effect. This study can provide reference for the prevention, early warning, and control of loess surface slope landslides in the Ili region.

Keywords: Loess surface landslide; Shear strength; Rainfall infiltration; Numerical simulation.

1 Introduction

Landslide is a kind of geological disaster, which is universal in the world and has a serious impact on human beings and the environment. Understanding the mechanism of landslide under rainfall is of great significance for predicting and preventing landslide disasters. The sliding surface is an important structure for analyzing the

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mechanism of landslide, and deformation will occur under the traction and shear of the sliding body. He Kun et al.[1] discussed the influence of pre-rainfall and pre-groundwater on landslide movement and deposit morphology. Yu Liangchen et al.[2]found that low-permeability strongly weathered rock can limit the activity of the lower aquifer, resulting in a rapid increase in pore pressure, forming confined water in response to rainfall, resulting in slope failure. Li et al.[3] studied the engineering geological characteristics, influencing factors and failure mechanism through field investigation and geological mapping. Zhou et al.[4] took a landslide as a geological prototype to explore the process and mechanism of slope stability degradation under the combined action of rainfall and slope construction. Xu et al.[5]considering the correlation between loess landslide parameters, established a multivariate model of loess landslide data, and used the multivariate model to predict the statistical and quantitative effects of potential unstable loess slopes from the aspects of landslide width, length and area. Yang et al.[6]compared the infiltration rate of undisturbed loess and disturbed loess in different years and different locations of loess landslide, and summarized the influence of slope failure on the spatial and temporal evolution of infiltration. Yu et al.[7]studied the automatic detection technology of landslides based on GEE and improved YOLOX algorithm by establishing a loess landslide database. Acharya, Govind et al.[8]studied the post-failure sediment yield after a landslide that changes the local slope. Xu et al.[9]analyzed the distribution and scope of the landslide through the inventory of the loess plateau landslide, and studied the main causes of the loess landslide through statistical analysis of the data. Carey, JM et al.[10]carried out a series of innovative dynamic back pressure shear box tests on intact and remolded loess samples, and reproduced the field conditions under different simplified horizontal seismic excitations.

2 Project overview

Based on the typical loess slope of Jialangpute in Ili River Valley (Figure 1), the surface loess of the slope has obvious particle characteristics, which is obviously affected by rainfall, and the binding force between particles is weaker than that of sand and clay. In addition, due to the prominent characteristics of loess particles, its permeability is relatively low. Under the action of rainwater, the strength of loess will change significantly. When the water content is low, the skeleton structure of loess is relatively stable, showing high strength and stability. However, once the water content exceeds a certain level, the strength of the loess will decrease sharply, which will seriously reduce the stability of the loess slope. In addition, due to the large porosity of the loess, it is easy to destroy the skeleton structure of the soil after rainfall infiltration, which leads to the collapsible behavior of the loess and further reduces the stability of the slope. The mechanical strength of loess itself is relatively low, and it is affected by the type of loess, water content and void ratio, so the mechanical properties of loess are relatively unstable. Combined with the meteorological elements of the region from 2016 to 2020 shown in figure 2 through geological disaster exploration, it is found that many obvious sliding deformations and even landslides in the region occurred during heavy rains, even after continuous light rains. Therefore, this paper mainly studies the influence of rainfall on the strength of loess soil. However, due to the limitation of experimental conditions, this paper indirectly reflects the influence of rainfall, and experiments are carried out by changing the water content.

Fig. 1. Galante ring chair loess landslide

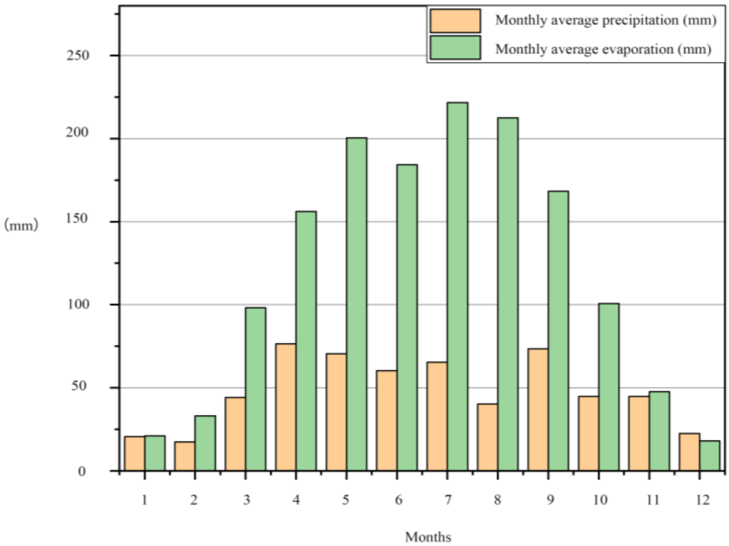

Fig. 2. Map of meteorological elements for 2016-2020

3 Test parameters and model establishment

3.1 laboratory direct shear test

The main work of indoor direct shear of loess in Yili area of Xinjiang selected in this test is the determination of natural water content, as well as the ratio of different water content and indoor direct shear test. The undisturbed loess samples were obtained by drilling soil method to reduce the disturbance to the soil. The loess obtained by drilling soil method and granular soil is shown in Fig.3.

Fig. 3. loess samples

After the remolded soil samples were tested in the laboratory, the physical properties of the undisturbed soil and the remolded soil were obtained through physical and mechanical tests. The ZJ strain-controlled direct shear apparatus was used in the direct shear test. The test pressure level was divided into four grades according to 50 kPa, 100 kPa, 150 kPa and 200 kPa. According to the meteorological conditions in the study area, the prepared loess moisture content was trial-produced according to 10 %, 15 % and 20 %, respectively, and the test shear rate was 1.2 m / min. By analyzing the strength index of soil under different pressure and water content, the influence of water content and pressure on the performance of loess is studied. In order to facilitate further numerical simulation of loess slope, the influence of water content on loess slope is analyzed from engineering practice. The shear process and shear failure surface are shown in Figure 4. The relationship between shear strength and vertical pressure under three water contents is shown in Fig.5 by direct shear apparatus, and the respective C and φ are directly obtained by direct shear apparatus as shown in Fig.5. According to the previous data supplement, the test data of loess under different water content in this area are listed in Table 1.

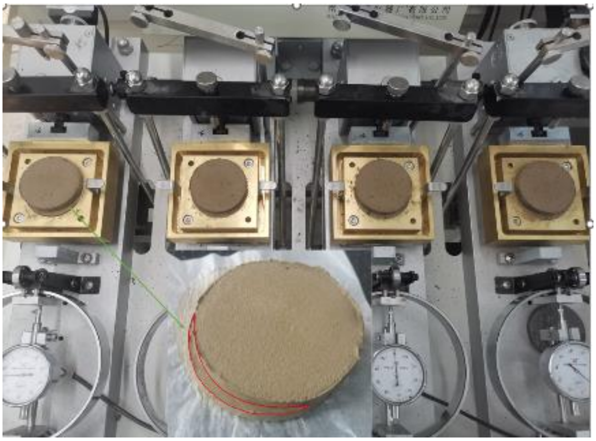

Fig. 4. Shear failure diagram of loess

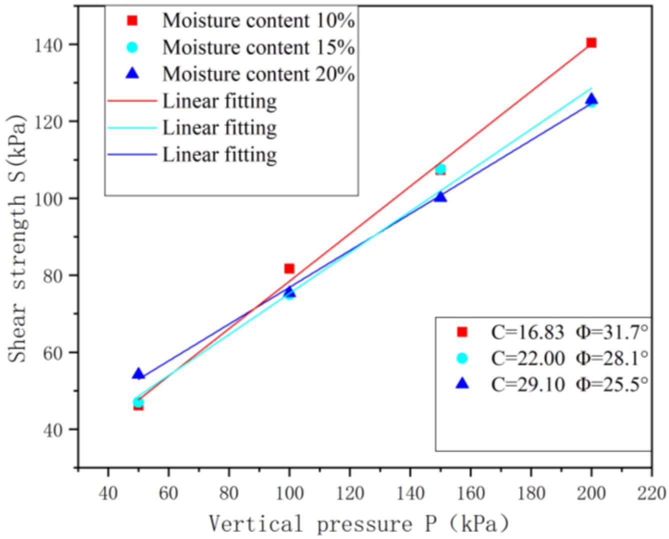

Fig. 5. Shear strength and vertical pressure relationship curve

Table 1. The parameter table of loess

soil sample	density(g/cm³)	young's modulus(MPa)	poisson ratio	friction(°)	cohesion(kPa)
Undisturbed loess	1.6	30	0.40	35	25
Saturated loess	1.73	7.3	0.45	25.5	29.1

3.2 Establishment of the model

Model assumptions

The loess slope is taken from a section of the Galangput landslide, which simplifies the calculation model. It is feasible to make reasonable assumptions on practical engineering problems. The assumptions of the calculation model are as follows : the soil is continuous, isotropic and linear elastic material ; the soil properties, groundwater conditions, load conditions and other parameters of the slope are uniform and unchanged in the whole slope area ; the deformation behavior of the slope is a small deformation hypothesis, that is, the deformation of the slope is relatively small in size and will not cause major shape changes ; the material behavior of the slope is linear, and the nonlinear effect is not considered during the whole loading process.

Parameter selection

Numerical experiments were carried out by FLAC3D finite element method, and the Mohr-Coulomb strength theory was used as the strength criterion. The displacement cloud map and the maximum plastic strain zone cloud map obtained by the numerical analysis determine the appropriate slope support position, select the appropriate support method, provide good data support for the prevention of geological disasters such as landslides, and can greatly reduce the losses caused by these geological disasters. In order to establish a more reasonable model parameters, on the basis of this experiment, with reference to relevant literature and normative standards, the parameters of each soil layer in this numerical simulation are determined as shown in Table 2.

Table 2. Initial numerical simulation parameter table

Rock and soil Type	Denst-y(g/cm^3)	void ratio	young's modu-lus(MPa)	Poisson ratio	friction(°)	cohesion(kPa)
loess	1.6	0.31	30	0.40	20	30
pebble gravel	2.0	0.42	100	0.25	35	35
mudstone	2.4	0.001	400	0.27	45	45

Establishment of calculation model

This simulation experiment uses Midas GTS software. The selected slope is a natural slope in Yili, Xinjiang. The overlying soil layer of the slope is loess, and the lower part is composed of gravel and mudstone. This paper mainly considers the mechanism analysis of the loess slope forming landslide under this condition from the perspectives of groundwater and earthquake, and carries out stability analysis. The slope modeling is shown in Figure 6.

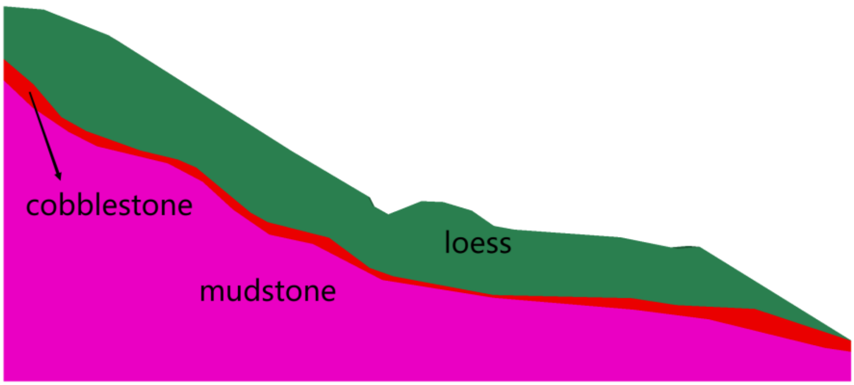

Fig. 6. slope modeling

4 Simulation result analysis

4.1 Comparative analysis of displacement cloud map

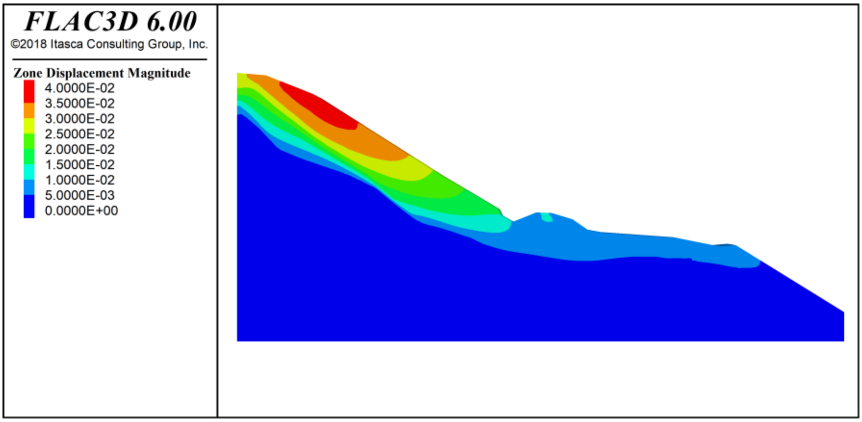

Fig. 7. Displacement cloud diagram in natu-ral state

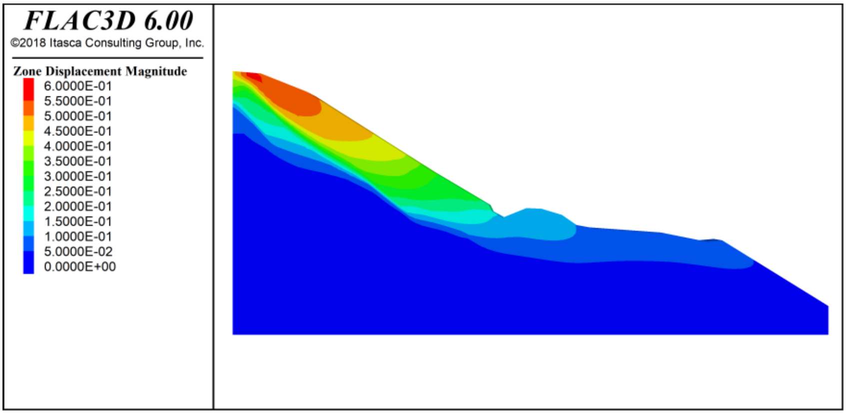

Fig. 8. Displacement cloud diagram under the action of rainfall

As shown in Figure 7, the displacement cloud diagram in the natural state is shown in Figure 8, which is the displacement cloud diagram under the action of rainfall. In both states, a large displacement occurs at the trailing edge of the landslide. In the natural state, the maximum displacement of the trailing edge of the landslide is 3.7cm, and the displacement of the leading edge of the landslide is only 0.5cm, and the displacement from the trailing edge to the leading edge of the landslide gradually decreases. Under the action of rainfall, the maximum displacement of the trailing edge of the landslide is 56.7cm, the displacement of the leading edge of the landslide is also 10cm, and the displacement from the trailing edge of the landslide to the leading edge is gradually decreasing. Through comparative analysis, it is found that the strength of loess decreases obviously after rainfall, and there is obvious slip at the trailing edge. Combined with the reference of indoor direct shear test literature, it is concluded that the higher the moisture content, the lower the elastic modulus of loess, but the cohesion increases, but the overall strength of loess is decreasing, which leads to the displacement of loess slope under the action of rainfall. The change is relatively large, which leads to the occurrence of landslide.

4.2 Comparative analysis of the maximum plastic zone

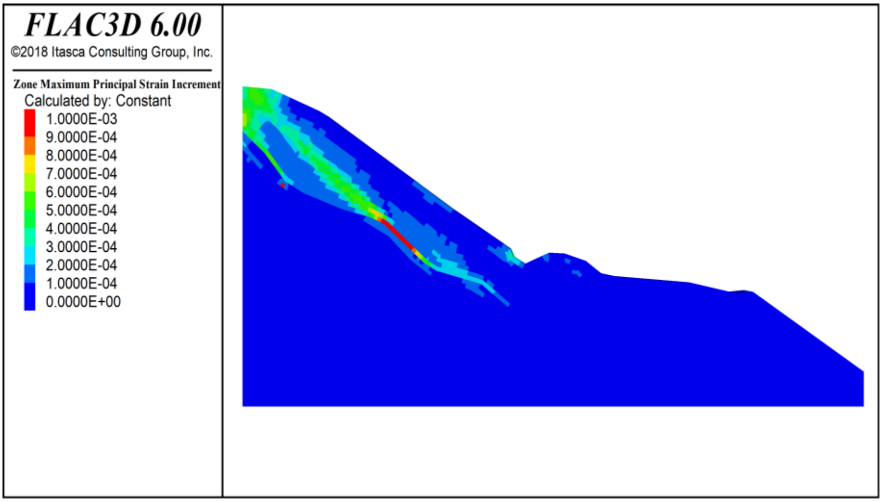

Fig. 9. Plastic strain cloud diagram in natu-ral state

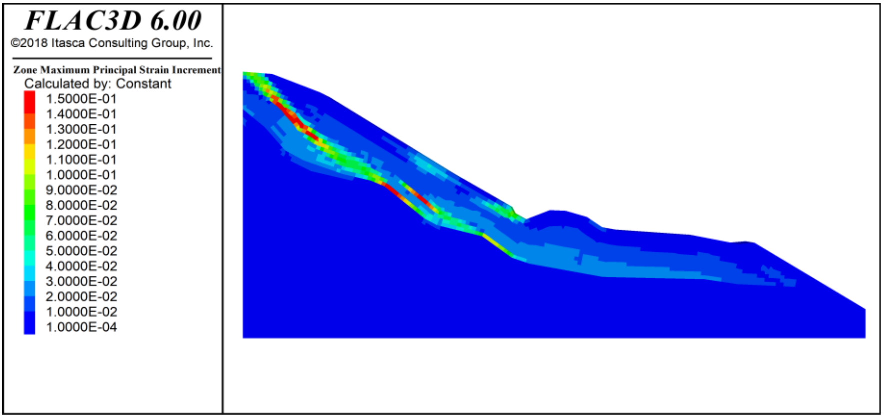

Fig. 10. Plastic strain cloud diagramunder rainfall

The plastic strain cloud diagram shows the degree of plastic deformation of the slope. Plastic deformation usually occurs in the weak area or high stress concentration area of the slope, which reflects the failure and deformation characteristics of soil or rock mass. By comparing the plastic strain cloud images under different conditions, the distribution and range of plastic strain can be observed. As shown in Figure 9, the plastic strain zone in the natural state is mainly concentrated in the trailing edge of the landslide body, and the plastic strain zone is more dispersed. As shown in Figure 10, the plastic strain zone under rainfall begins to gradually penetrate the whole slope compared with the natural state, and the slip surface is relatively concentrated at the interface between the loess layer and the gravel layer. This is mainly due to the obvious changes in the physical and mechanical properties of the loess under the action of rainfall, and the gravel layer forms an obvious interface, so the plastic zone begins to penetrate the entire landslide area.

4.3 Comparative analysis of safety factor

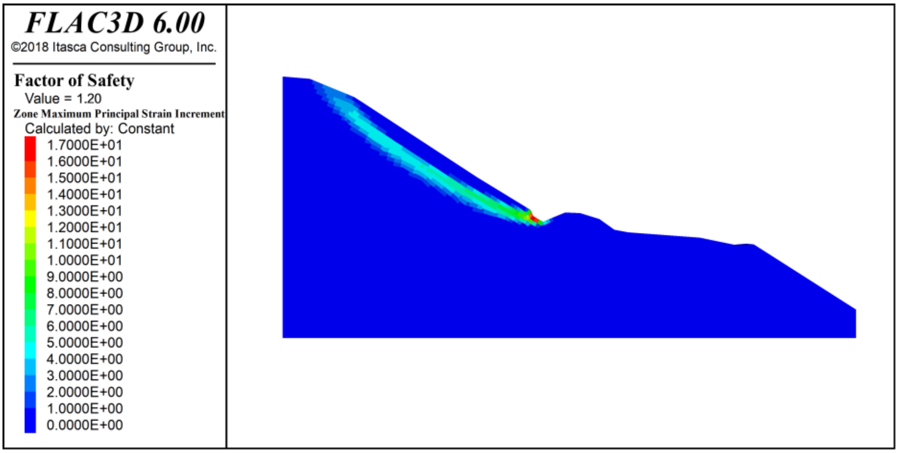

Fig. 11. Safety factor in natural state

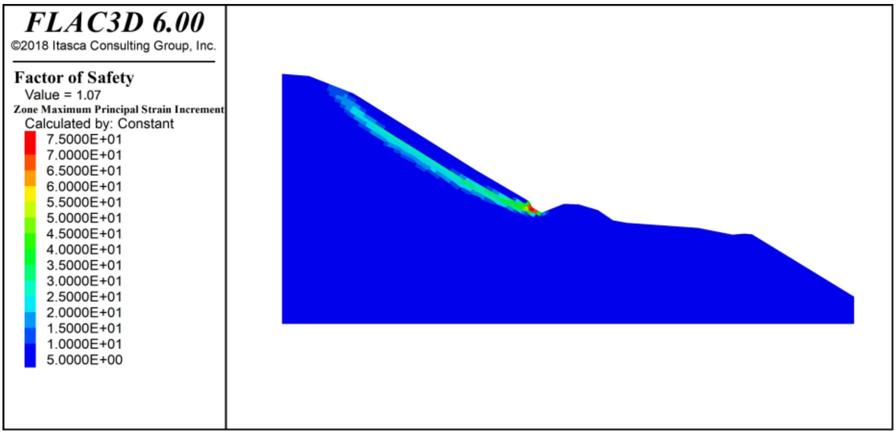

Fig. 12. Safety factor under rainfall

The safety factor in the self-weight state is 1.20 (as shown in Fig.11), which indicates that the slope has certain stability without external load, but there is still a certain risk. The safety factor greater than 1 indicates that the slope is stable, but there is still a certain distance from the ideal safety factor of 1.5, so the stability of the slope needs to be further evaluated and improved. The safety factor under rainfall is 1.07 (as shown in Fig.12), which indicates that the slope is less stable when subjected to rainwater infiltration and rainfall load. The safety factor is less than 1.5, indicating that the slope may have a high risk after rainfall, and further safety measures need to be taken to ensure the stability of the slope. By comparing the safety factor under gravity and rainfall, we can see that the stability of the slope under rainfall is weaker than that under gravity. This shows that the rainfall has a great influence on the stability of the slope, which needs special attention and effective measures to reduce the adverse effects of rainfall on the slope.

5 Discussion

Combined with field sampling, laboratory test and numerical simulation, under normal circumstances, the water content of the loess layer is low, the soil strength is high, the landslide is in a relatively stable state as a whole, and the gravel layer and the mudstone layer are always in a relatively saturated state, so the rainfall has little effect on the gravel layer and the mudstone layer. Whether it is natural or under the action of rainfall, the displacement mainly occurs in the loess layer at the trailing edge of the landslide, but the maximum sliding displacement under the action of self-weight is only 3.7cm, but under the action of rainfall, it reaches more than ten times under the action of self-weight, with 57.6cm. It can be seen that the effect of rainfall on the strength reduction of loess is very obvious; The distribution of the plastic zone is distributed at the interface between the gravel layer and the loess layer. The difference is that the plastic zone under the action of self-weight is mainly located at the trailing edge of the landslide, while the plastic zone under the action of rainfall almost runs through the entire slope, and the sliding surface is located at the contact surface between the loess and the gravel. This is because the rainfall infiltration leads to the weakening of the contact between the loess and the gravel, and the weak surface is formed on the contact surface, so that the loess slips along the weak surface after the rainfall. Rainfall infiltration has a great change in the physical and mechanical properties of the loess, and the actual pore water pressure will increase, but this simulation test does not reflect the change of this pore water pressure. However, it can be concluded from the test that rainfall causes the shear strength of loess to decrease, making it prone to sliding and deformation. In summary, rainfall will have an impact on the physical and mechanical properties of loess, so it is necessary to fully consider the impact of rainfall on loess in engineering design and construction, and take corresponding measures to ensure the stability and safety of loess engineering.

6 Conclusions

Taking a loess landslide in Yili area as an example, this paper uses FLAC3 D to carry out numerical simulation research, and analyzes the deformation characteristics and safety factor of the landslide under the action of self-weight and rainfall. The conclusions are as follows:

1) It can be concluded from the indoor direct shear test that the cohesion increases with the increase of water content, the internal friction angle decreases, and the shear strength decreases with the increase of water content.

2) Under the action of self-weight, the slope only has a large displacement at the trailing edge, and the plastic zone formed is also at the trailing edge of the landslide, without forming a penetrating landslide zone. The landslide safety factor is 1.20, and the landslide is basically in a stable state; under the action of rainfall, the water content of the loess layer increases, and it is close to saturation. The displacement of the unstable slope at the trailing edge of the landslide becomes larger, and the maximum reaches 56.7cm. There is a relatively penetrating plastic zone sliding surface on the contact surface between loess and gravel, and the safety factor also decreases from 1.20 under the action of self-weight to 1.07. The unstable slope is difficult to slide and is in a critical stable state, but there is also a great risk. Therefore, anchor cable support is selected for the slope to effectively improve the stability of the slope and prevent the occurrence of landslide accidents.

3) Through comparative analysis, it is found that rainfall has a great influence on the physical and mechanical properties of loess. From the side, it reflects that rainfall leads to rainwater infiltration, which destroys the internal structure of loess, and the skeleton system of loess is also destroyed, which further reduces the shear strength of loess and makes the surface loess more prone to sliding and deformation. In this study, the process of rainfall is simulated by changing the parameters. By using FLAC3D for numerical simulation, a small amount of indoor test data can be used for numerical simulation to achieve ideal results in the future understanding of landslide disasters.

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