Study on formation mechanism of granite eluvium landslide by field rainfall simulation

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Abstract

Granite residual soil is a kind of special soil, which is easy to induce geological disasters under the condition of heavy rainfall. Taking the mass landslides in Beiling area, Longchuan County, Guangdong Province as the background, the formation mechanism of typical landslides was explored by means of physical simulation, and the following conclusions were obtained: ① the influencing factors of landslides were rainfall intensity, physical and mechanical properties of rock and soil mass, slope structure; ② Rainfall does not cause the abnormal increase or decrease of soil pressure and pore water pressure in the slope, indicating that the failure of the slope is limited to the local failure of the slope surface and the slope toe, and there is no overall deformation and failure trend; ③ On the surface of the slope, the slope is eroded by rainfall, and on the foot of the slope, the free surface collapses and undergoes erosion. On the whole, the slope shows the characteristics of "step by step retreat and damage in turn"; ④ The evolutionary process of landslide can be divided into the following four stages: original slope evolution stage, soil particle migration stage, slope surface local failure stage and overall instability stage.

1 Introduction

Granite is widely distributed in the southeast coastal area of China. It is a kind of granular intrusive rock mass. Due to its long-term exposure on the surface, under this high temperature, high humidity and rainy environment, granite is strongly weathered, forming different degrees of weathering eluvium. The research shows that the granite residual soil has a high content of sand and gravel, but its hydraulic properties are poor, and it is easy to thixotropy. Under the influence of water immersion, disturbance and other factors, its original stable structure will be rapidly damaged, and its mechanical properties will be rapidly reduced. Therefore, the granite residual soil is a special kind of soil, which has its unique composition, structural characteristics and outstanding engineering characteristics(Zhao et al 2021; Liu et al 2019; Li et al 2020).

On the basis of the study on the failure mechanism of rainfall infiltration of granite residual soil,Roberto Quental Coutinho et al (2019) Studied the failure mechanism of granite residual soil landslide in Pernambuco State, Brazil, considered that rainfall was the most important factor in the initiation of landslide, and attributed the landslide failure to multi-stage failure. Harianto rahardjo et al (2010) Compared the stability of sedimentary soil and residual soil slope under rainfall through numerical simulation method; The results show that when the rainfall intensity is 22, 36 and 80 mm / h, the safety factor of residual soil slope decreases faster than that of sedimentary soil slope. The change of moisture content in granite residual soil will lead to the change of matrix suction, the magnitude of matrix suction will affect the shear strength of soil, and then affect the stability of slope (Lin et al 2011); Jaehong Kim et al (2004) believes that the instability of weathering layer under rainfall is caused by the deepening of wetting zone caused by precipitation infiltration and the decrease of matrix suction. I et al (2002) studied the influence of rainfall intensity, rainfall distribution before rainfall and saturated permeability coefficient of soil on slope safety coefficient by numerical simulation method; Jian et al (2013) and Zhang et al (2016) based on the analysis of the influence of rainfall on the water content of slope soil, through the

relationship between saturation and water content, the effective rainfall of soil from unsaturated to saturated is deduced; Zhang et al (2020) studied the failure mechanism of residual soil slope under rainfall by combining indoor soil column test and numerical simulation, back analyzed the unsaturated hydraulic parameters of residual soil, and then used it to simulate the seepage field and stress-strain field of slope under the action of typhoon Tailim. In addition, the special geological structure of granite residual soil layer plays an important role in the occurrence and development of collapse erosion, and the spatial change of soil physical and mechanical properties along the profile is an important factor affecting the development of collapse erosion (Xia et al 2019).

For the stability and failure mechanism of granite residual soil slope, scholars at home and abroad have conducted a lot of research. It can be found that rainfall is the most direct external factor affecting the stability of this kind of soil slope, and soil properties are the most important internal factor. Scholars mainly use indoor model test, theoretical calculation, numerical simulation and other means to study, which is difficult to accurately reflect the influence of soil structure, Therefore, the physical simulation of in-situ rainfall can reflect the structural effect of rock and soil mass to the greatest extent, but this method is rarely used at present. In this paper, through in-situ rainfall physical simulation test, sensors are used to monitor the internal pore water pressure, soil pressure and water content of the slope, and real-time observation is carried out on the deformation of the slope surface, so as to obtain the internal water content, pressure changes and macroscopic deformation signs of the slope in the process of rainfall, The mechanism of typical slope deformation and failure is explored.

2 Engineering Geological Conditions Of Landslide Area

2.1 General situation of engineering geology

Group landslide in mibeicun ($24^{\circ} 38'37.25''N, 115^{\circ} 18' 18.30'' E$) is located in Beiling Town, Longchuan County, Guangdong Province. The research area is located in the northwest of Beiling Town, with an area of about 10km^2 . There are nearly 200 small landslides in the area, which threaten the safety of life and property in mibei village, and cause a lot of economic losses. The elevation range is mostly 200-500m. Affected by the tectonic movement, the fold is developed in the area. Therefore, the landform has the characteristics of steep mountain potential, sharp peak and narrow ridge. The gully is developed, mostly of which are long strip "V" or "U" type Valley, and there are small-scale inter mountain basins.

The underlying bedrock of the study area is the mixed granite of the lower Paleozoic zone, which is mainly grayish white to grayish yellow. According to the degree of weathering, the exposed bedrock can be divided into three types: completely weathered, strongly weathered and moderately weathered. The Quaternary overburden is mainly residual sandy clay. The slope in the study area has a unified binary structure, i.e. residual soil layer + granite weathering layer (Fig. 1). According to the classification of landslide rock and soil mass and structural factors, the mass landslides in the study area are all soil landslides, which are residual landslides in granite area. It is found that the stability of the slope in the study area is obviously controlled by the free surface formed by the excavation of slope toe and the

erosion and undercutting of water in the channel by human engineering activities. Therefore, this kind of slope is regarded as a typical slope in this study.

2.2 Physical and mechanical properties of rock and soil mass

Since the landslide occurred in the eluvium, it is very important to study the physical and mechanical properties of the rock and soil mass of the completely weathered layer below the eluvium and the residual layer. Through a series of field and indoor physical and mechanical tests, the basic parameters of the whole weathered layer and the residual layer rock and soil are obtained (Table.1).

The residual soil in the study area is characterized by high strength and medium permeability in natural state, and has the characteristics of good permeability, poor grading, large pore ratio, and rapid decrease of soil strength with water content. It is a poorly graded residual clay. The results of X-ray diffraction analysis of mineral composition of geotechnical indicate that granite residual soil is mainly kaolinite, in addition, it contains a small amount of illite and chlorite, The secondary clay minerals of feldspar, bauxite and montmorillonite are formed in the process of weathering, and the proportion of clay minerals in eluvium and completely weathered layer is 67% and 44% respectively.

Table.1 Mechanical parameters of rock and soil mass

Parameter	Completely weathered layer	Residual soil	
c	45.46-66.91kPa	natural	68 kPa
		saturated	20.5 kPa
φ	24.70-29.25°	natural	27°
		saturated	17.5°
Natural density (g/cm ³)	1.62	1.60	
Moisture content(%)	19.88	18.91	
Permeability coefficient	4.83×10 ⁻³ cm/s	4.05×10 ⁻³ cm/s	

3 Experiment Scheme

3.1 Typical point features

The selected typical slope is close to the disaster site and has a typical double-layer structure, that is, the overlying eluvium is about 0.8m thick and the underlying completely weathered layer is 40 ° On the left and right sides, there are shrubs on the surface, which are the slope and structure of high prone slope. The specific location of the test point is shown in Fig. 2.

3.2 Design of rainfall test system

The test selects a rectangular area of 1.5 * 2m on the original slope for rainfall. The whole rainfall simulation system consists of five parts: the reservoir in the upper right corner, the rainfall system which can control the rainfall intensity in real time, the in-situ slope, the collecting tank and the collecting pool, data collection and collection system. The instrument and equipment required for the test are shown in Fig. 3a.

Artificial rainfall simulation is designed for the field test conditions to achieve a spray system, which consists of a micro pressure pump, four atomizing nozzles, a flowmeter, a main pipe and a return pipe, which can realize real-time control of different rainfall intensity. The instruments used for data collection on site are mainly soil pressure gauge, pore water pressure gauge, water content sensor and flowmeter (Fig. 3b). See Table.2 for model and parameters of each sensor.

Table.2 Some monitoring instruments and parameters

Measurement items	Measuring instrument	number	range	accuracy
Increment of earth pressure	Earth pressure sensor	4	0-50kPa	≤ 0.5%F•S
pore water pressure	Pore water pressure sensor	4	0-30kPa	≤ 0.5%F•S
Moisture content	Water content sensor	4	0-100%	± 3%
rainfall intensity	Flowmeter	1	0.16-1.6L/min	± 5%

The sensor is mainly used to measure the pressure and moisture content changes at the top and toe of the slope inside the slope. The sensor layout plan and profile are shown in Fig. 4 (the unit marked in the figure is cm). The profile is divided into two layers, which are respectively arranged at the depth of 30cm and 80cm. The pore water pressure sensor is arranged on the left side of the plane and the earth pressure sensor is arranged on the right side, The moisture content sensors are arranged in the upper left corner and the lower right corner, in which the buried depth of MS1 and 3 is 30cm and that of MS2 and 4 is 80cm. Each sensor starts to collect data at the beginning of rainfall. Since the rain continues to infiltrate inside the slope after rainfall, the collection ends when it is observed that the sensor data fluctuates little after rainfall. In order to avoid the disturbance of the embedded sensor to the undisturbed slope as far as possible, Luoyang shovel with a diameter of 5cm is used to form a hole horizontally, and the undisturbed soil is backfilled after the sensor is embedded. See Fig. 5 for the layout of the test site. After the rainfall, it is planned to excavate the profile along L1, L2 and L3 shown in Fig. 4a to more accurately obtain the internal water content distribution of the slope after the rainfall.

3.3 Rainfall scheme design

In order to observe the changes of pressure and moisture content in the slope during rainfall and rain stop, the rainfall scheme of continuous multiple rainfall and intermittent rainfall under the working conditions of heavy rain - rainstorm - heavy rainstorm - severe rainstorm is designed in order to obtain the test results under various working conditions. The rainfall solution adopts bright blue staining solution with a concentration of 4g / L (it is an edible dye and has no pollution to the soil), See Table.3 for specific rainfall intensity and rainfall time.

Table.3 Rainfall scheme design

Time	Rainfall condition	rainfall	Rainfall duration
Day1	heavy rain	90L	1.5h
Day2	rainstorm	180L	2.1h
Day3	heavy rainstorm	360L	4.2h
Day4	severe rainstorm	880L	6h

4 Analysis Of Artificial Rainfall Simulation Results

4.1 Dynamic characteristics of rainfall infiltration and characteristics of volumetric water content distribution

During the test, the downhill surface runoff of different rainfall intensities in different periods is recorded. According to the calculation of total rainfall and surface runoff, the relationship curve between the ratio of surface runoff and total rainfall and time during rainfall can be obtained (Fig. 6). The results show that after Day1 heavy rain condition, the proportion of surface runoff is only 9%, and after switching to heavy rain condition, the proportion of surface runoff is stable at about 50%, It shows that the soil permeability coefficient of the slope is high. Under the condition of heavy rain, most of the rainwater can penetrate into the soil. After increasing the rainfall intensity, the surface runoff increases and the water head at the infiltration interface also increases. At the same time, the permeability coefficient of the shallow layer of the slope also increases due to the continuous discharge of pore gas. In addition, the rainwater infiltrates into the completely weathered layer, and the clay content of the completely weathered layer is less, The infiltration peak develops faster, so the proportion of final surface runoff increases little.

According to the water content time history curve (Fig. 7), the distribution regularity of the initial volume water content of the slope is poor in the slope body; The backward sequence of the initial response of each position sensor is SP3, SP1, SP4 and SP2. Under the heavy rain condition of Day1 (rainfall 1.5h), there is no obvious change in the water content of the surface layer and deep layer; Before the beginning of Day2 rainfall, the water content of shallow water address 1 and 3 increased to about 20%, and after 1

hour of rainfall, the water content increased to 26% – 27%. After the end of rainfall, the shallow volume water content decreased slowly and uniformly. After 3.2 hours of rainfall, the value of water address 4 began to increase; The growth trend of water content in day3 and day4 is similar to that in Day2, but the increase rate of water content slows down slightly, and the response speed of water content increases after rainfall.

Generally speaking, the change of slope water content has the following characteristics: compared with different depths at the same site, the change trend of soil volume water content is that the water content in the upper part increases first than that in the lower part. On the surface of soil, the change of water content has obvious correlation with rainfall, with a slight lag. After the rainfall stops, the water content has a downward trend. After the end of day4 rainfall, The decrease of water content is obvious. On the one hand, it is caused by the destruction of the shallow soil structure, the increase of the water content of the slope and the increase of the permeability coefficient of the soil. On the other hand, the existence of the free surface makes the soil saturated, and the rest of the water can be quickly discharged through the free surface; According to the spatial distribution characteristics of water content, in the later stage of rainfall, the surface runoff at the foot of the slope will be greater than that at the top of the slope, increasing the water head at the infiltration interface, resulting in the infiltration at the foot of the slope greater than that at the top of the slope. The area with high water content is larger at the foot of the slope, which will increase the pore water pressure at the foot of the slope and cause potential erosion damage under the condition of free surface.

Figure 8 shows the specific distribution of water content in profile L2 inside the slope. It can be seen that the high water content area is concentrated in the middle and lower part of the slope, which is more consistent with the water content monitoring. After excavation, the water content in 30cm on the surface of the slope is reduced to less than 25%, while the high water content area is concentrated in the deep part of the slope, because after rainfall and during excavation, The continuous infiltration of rainwater in the slope leads to the gradual downward movement of the distribution area of high water content, which indicates that even if the slope cannot be unstable and damaged during rainfall, after the rain stops, the rainwater continues to infiltrate under the action of gravity field, and the slope may also be unstable due to the strength attenuation caused by the increase of moisture.

4.2 Distribution characteristics of pore water pressure

The time history curve of slope pore water pressure is shown in Fig. 9. It can be seen from the figure that before rainfall, all sensors monitor negative pore water pressure, and the closer to the slope surface, the greater the negative value, that is, the greater the suction of soil matrix. Generally speaking, the increase and decrease trend of pore water pressure is highly consistent with the increase and decrease trend of water content; The rainfall infiltration response of eluvium and completely weathered layer is obvious. In the process of rainfall, once the pore water pressure begins to respond, it will rise from negative value to positive value in a short time; The initial response sequence of the sensor is Wp3, Wp1, wp4 and Wp2. It can be seen that the response speed of the slope toe is greater than that of the slope top. In the process

of rainfall, the shallow soil of the slope is saturated first, and then the water in the slope moves to the slope toe under the action of gravity, resulting in a large-area transient saturation zone at the slope toe first; Under the condition of short-time heavy rainfall, rainfall mainly increases the pore water pressure within 0.5m of the slope surface and 1m of the slope toe, which reduces the matrix suction, degrades the shear strength of the soil and reduces the stability of the slope.

4.3 Variation characteristics of soil pressure

The time history curve of vertical soil pressure at each monitoring point is shown in Fig. 10. Generally speaking, the vertical soil pressure rises in fluctuation during rainfall, and the response of soil pressure to rainwater infiltration has a certain lag, which is most obvious at the two sensor positions at the foot of the slope; Consistent with the distribution of water content, the spatial distribution of soil pressure shows the law that the slope toe is greater than the slope top. Therefore, under the condition of free surface, the spatial distribution of soil pressure shows the law that the slope toe is greater than the slope top. Therefore, under the condition of free surface, the slope toe is easy to be damaged first; The increase or decrease of vertical soil pressure in the slope is caused by the change of soil self weight, the stress change caused by slope deformation and the action of seepage force. There is no abnormal increase or decrease of soil pressure in the process of rainfall, indicating that there is no overall deformation trend of the slope.

4.4 Deformation and failure characteristics

The rainfall simulation caused three damages to the test model, which generally showed the characteristics of "step-by-step retreat and sequential damage". The first is slope surface erosion damage. The erosion effect of rainfall on the slope is mainly slope surface erosion and slope internal erosion. The slope surface erosion is mainly rain splash erosion, surface erosion and rill erosion (Liu et al 2021; Huang et al 2020; Deng et al 2020). Rain splash erosion will directly destroy the cementation between soil particles, break up sand and silty clay particles, and then produce transition and displacement. This effect continues in the process of rainfall; Surface erosion refers to the dispersion and migration of soil particles by thin-layer water flow on the slope, which mainly occurs in the early stage of Day1 rainfall. See Fig. 11a for splash erosion and surface erosion; Under the differential erosion of slope flow, rill erosion is generated (Fig. 11b). In the process of rill erosion, small streams of rill disperse and transport the soil at the head, wall and bottom of rill. Rill erosion accelerates the erosion process of slope, so that the soil particles on slope are continuously dispersed and transported, and finally, In the middle and lower part of the slope, the shallow surface of the slope is damaged due to slope surface erosion (Fig. 11c). This damage weakens soil cementation, changes the surface soil structure, and increases the rate of rainwater infiltration and soil component loss.

Second, the free face of the model is damaged by collapse. Two hours after day4 rainfall, collapse occurs in the middle of the free face. The shape of the collapse area is narrow at the top, wide at the bottom and irregular at the edge. The collapse area is about 1500cm^2 and the volume is about 4500cm^3 . The area of

the collapse area gradually expands during rainfall. After rainfall, the area expands to about 2500 cm², and the top of the collapse area obviously widens, The trailing edge gradually extends to the top of the slope. Figure 12 shows the failure development process of the free face.

The third is slope internal erosion, which is mainly latent erosion. Latent erosion is observed on the left side of the leading edge free surface in the later stage of Day2 rainfall. Latent erosion refers to the process of water flow moving along the pores and cracks in the soil, continuously infiltrating, scouring and dissolving the soil and bringing out fine particles in the soil. It is observed that sand particles are brought out in the latent erosion channel, It shows that the formation of latent erosion channel accelerates the loss rate of soil particles in the slope (Fig. 13).

5 Analysis Of Landslide Formation Mechanism

5.1 Analysis of influencing factors

From the physical simulation test results, high-intensity rainfall will cause rapid changes in the internal water content of the slope in a short time, resulting in changes in pore pressure and soil pressure. However, rainfall does not cause abnormal increases or decreases in the internal soil pressure and pore water pressure of the slope. During the rainfall process, the slope has no overall damage trend, but causes local damage on the slope surface, showing "step-by-step retreat The characteristics of "sequential failure" can evolve into overall instability. Comprehensive analysis shows that the causes of slope instability can be mainly divided into internal and external causes, the internal cause is the physical and mechanical properties of rock and soil mass and slope structure, and the external cause is mainly rainfall intensity.

(1) Rainfall intensity: rainfall causes slope surface erosion on the slope surface and latent erosion in the slope body, resulting in the collapse of soil particles on the slope surface and the formation of dominant seepage channels in the slope (Deng et al 2020; Zhang et al 2019). When the rainfall intensity is small, most of the rainwater can infiltrate into the shallow surface of the slope. At this time, the increment of water content in the slope is small, and the attenuation of shear strength of eluvium is also small. When the rainfall intensity reaches the rainstorm intensity or above, on the one hand, the water content of soil in the slope increases, resulting in the attenuation of soil strength; on the other hand, the increase of rain intensity leads to the increase of rainwater kinetic energy and runoff on the slope surface, The soil particles on the slope surface are dispersed and taken away, and a large number of scouring rills are formed on the slope surface. The comprehensive effect of the two aspects reduces the overall stability of the slope. At the same time, the continuous increase of water content in the slope may also produce latent erosion and form internal erosion;

(2) Physical and mechanical properties of rock and soil mass: when granite residual soil contacts with water, the free oxide that provides cementation force for the interior of the soil mass will dissolve with water, resulting in reduced strength, greater compressibility and softening characteristics of the soil mass

(Sun et al 2018;Chen et al 2016) .At the same time, due to poor grading, the soil components are partially taken away under slope surface erosion and potential erosion, A large number of gullies and potential erosion channels on the slope surface are formed, which reduces the strength of soil mass;

(3) Slope structure: most of the slopes in the study area are eluvium + granite completely weathered layer, and the topographic slope is generally large ($35^{\circ} \sim 55^{\circ}$). The existence of free surface at the front edge reduces its anti sliding force and reduces the stability of the slope.

5.2 Analysis of deformation and failure mechanism

According to the field investigation and test results, the formation and evolution of this kind of rainfall landslide is divided into the following four stages: original slope evolution stage, soil particle migration stage, local failure stage on the slope surface and overall instability stage.

(1) Original slope evolution stage

Under the joint influence of climate, structure and rock mass properties, residual soil with special physical and mechanical properties such as good permeability, poor grading, large void ratio and rapid decline of strength with the increase of water content in the study area and slope body with large slope and unified binary structure are formed (Fig. 14).

(2) Soil particle transport stage

This stage is mainly characterized by slope surface erosion and potential erosion in the slope caused by rainfall, and the power source is mainly the kinetic energy and potential energy of rainwater. In granite residual soil, sand particles are skeleton particles, clay particles and free oxides are attached to skeleton particles as cement to form aggregate structure (Liu et al 2021), and its microstructure is simplified as shown in Fig. 15. Combined with physical simulation analysis, in slope surface erosion, splash erosion, surface erosion and rill erosion have a process from weak to strong, resulting in the dispersion and migration of soil particles on the slope surface; At the initial stage of erosion, rainfall infiltration only causes the change of water content in the shallow surface layer of the slope, resulting in a small increase in the earth pressure in the slope. With the intensification of erosion, rill erosion begins to appear, the runoff at the foot of the slope increases, and the rainfall infiltration at the foot of the slope also gradually increases. Finally, the transient saturation zone is first formed at the foot of the slope, and latent erosion damage occurs under the action of continuous rainfall, The soil particles in the slope are also gradually lost; In the late stage of erosion, there is a high water content concentration area in the middle and lower part of the slope, which also leads to the rapid growth of soil pressure and pore water pressure at the foot of the slope.

(3) Local failure stage of slope surface

This stage is mainly characterized by local collapse of rill head, ditch wall and free surface at the front edge. The main power source is the potential energy of soil itself, followed by hydrodynamic action

(Fig. 16). After the formation of the rill, the loss of fine particles in the soil at the wall and bottom of the rill accelerates, the rill continues to deepen and widen, the self-weight of the soil increases due to the increase of water content, and the local collapse occurs under the action of gravity due to the softening of the microstructure of the soil. Then, the slope surface erosion and collapse continue and become more and more intense, The surface runoff continuously transports the collapsed materials on the ditch wall, and the ditch wall and ditch wall will continue to collapse under the action of gravity, so that the ditch will gradually develop and expand, and the ditch head will continue to retreat. However, at this time, there is no abnormal change in earth pressure and pore water pressure, indicating that there is no overall deformation trend of the slope, and the damage of the slope is still limited to the slope surface, and there is no overall instability.

(4) Overall instability stage

After the local failure stage, the slope soil is eroded and softened, the microstructure of the slope surface is destroyed due to slope surface erosion, the bonding force between particles is reduced, the strength is greatly reduced, and local collapse occurs on the slope; A latent erosion channel is formed in the slope, which reduces the stability of the slope. At this time, under the action of gravity and seepage, it is very easy to produce tensile cracks at the rear of the slope, and then the overall instability of the slope will produce sliding (Fig. 17).

6 Conclusion

Based on the physical simulation of on-site rainfall and the background of mass landslide disaster, this paper deeply explores the disaster mechanism of typical landslide, and draws the following conclusions:

- (1) After continuous high-intensity rainfall, the proportion of surface runoff of this kind of high prone slope in the study area is finally stable at about 55%. After rainfall, the high water content area is concentrated in the middle and lower part of the slope, and the response speed of soil pressure and pore water pressure at the foot of the slope is greater than that at the top of the slope;
- (2) The physical simulation results show that rainfall does not cause abnormal increase or decrease in the values of soil pressure and pore water pressure in the slope, indicating that the failure of the slope is limited to the local failure of the slope surface and toe, and there is no overall deformation and failure trend;
- (3) The deformation and failure of slope shows the slope surface erosion caused by rainfall on the slope surface, and the collapse and potential erosion of free surface at the slope toe, which generally shows the failure characteristics of "step-by-step retreat and sequential failure";
- (4) The causes of slope instability can be divided into internal and external causes, the internal cause is the physical and mechanical properties of rock and soil mass and slope structure, and the external cause is mainly rainfall intensity. On this basis, the formation and evolution of this kind of rainfall landslide can

be divided into four stages: original slope evolution stage, soil particle migration stage, local failure stage on slope surface and overall instability stage, The deformation and failure mechanism of landslide is deeply explored from the macro and micro perspectives.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

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Figures

Figure 1

Slope engineering geological profile

Figure 2

Panorama of the test site

Figure 3

(a) Layout plan of rainfall simulation test; (b) Some monitoring instruments(the unit is cm in the figure)

Figure 4

(a) Sensor layout plan; (b) Section I-I' (the unit is cm in the figure)

Figure 5

Layout of test site

Figure 6

Rainfall intensity and proportion of runoff

Figure 7

Time history curve of water content

Figure 8

Water cut isopleth map of L2 profile

Figure 9

Time history curve of pore water pressure

Figure 10

Time history curve of earth pressure

Figure 11

Evolution process of slope surface erosion

Figure 13

Sub-erosive channel of free surface

Figure 14

Evolution stage of original slope

Figure 15

Stage of soil particle transport

Figure 16

Local failure stage of slope surface

Figure 17

Overall instability stage