

Article

Water Transport Characteristics and Their Impact on Stability of Unsaturated Xiashu Loess Slopes During the Entire Process of Rainfall Infiltration

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Abstract

The Xiashu loess in the middle and lower reaches of the Yangtze River with typical aeolian characteristics is widely distributed in the hilly areas and is the main kind of landslides in this area. The paper reveals the infiltration process of the Xiashu loess slope under different rainfall intensity conditions on the basis of on-site artificial rainfall simulation tests and laboratory experiments. The distribution of pore water pressure inside the Xiashu loess slope under different rainfall intensity conditions were compared and analyzed. The relationship between rainfall intensity and water content at different depths was clarified, and the relation function among rainfall intensity conditions, slopes, and the ultimate depth and critical rainfall intensity of the Xiashu soil slope landslide is proposed. The research results indicate that: (1) the infiltration rate and depth of the soil at the foot of the slope are greater than those at the top and middle of the slope; (2) an increase in the rainfall duration is found to cause an increase in slope infiltration depth; (3) an increase in the rainfall duration can lead to a more significant influence of the infiltration depth under the slope angle; (4) the infiltration depth of rainfall with low intensities and long durations is larger than that of high intensities and short durations. Finally, the ultimate rainfall infiltration depth under different slope angles and rainfall conditions was determined. The research results can be used to forecast the Xiashu loess soil landslide scale, providing theoretical basis for early warning of instability of Xiashu loess slope under different unfavorable conditions.

Keywords: Xiashu loess landslides; infiltration hydrodynamics; artificial rainfall simulation tests; critical rainfall intensity; ultimate infiltration depth

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1. Introduction

Xiashu soil is generally referred to as the “Xiashu loess soil”, formed in the late Pleistocene of the Quaternary period. It is formed by wind accumulation under arid climate conditions during the late Pleistocene of the Quaternary period. Xiashu soil is mainly distributed in different landforms of plains, hills, and mountains. It has ex-

tremely strong water sensitivity characteristics. The physical properties, hydraulic properties, and shear strength of Xiashu soil vary significantly under different dry and wet conditions. Existing studies have shown that nearly 70% of landslide hazards in Jiangsu Province are concentrated in the distribution area of Xiashu soil. Although the scale of Xiashu landslide disaster is small, it is dangerous and can cause severe damage to people's lives and property in the low mountainous and hilly areas. Therefore, conducting a hydrodynamic analysis of the typical rainfall infiltration process of Xiashu soil can help to explore the sliding mechanism of Xiashu soil landslides and is of great significance.

Over the past few decades, many researchers have studied the structure, infiltration characteristics, deformation behavior, and mechanical strength properties of Xiashu soil, and they have made certain progress [1,2]. Xiashu loess consists of two parts: a loess layer and a laterite layer, which differ in composition and structure, and its properties are significantly influenced by water content [3,4]. Some scholars have experimentally obtained the permeability and compression characteristics of Xiashu soil under specific compaction efforts and different water contents, and they established strength and landslide prediction models for Xiashu soil under varying water content conditions [5–7]. Ding et al. [8] analyzed the relationship between the compression coefficient of Xiashu soil and various microstructural parameters through experiments. Other researchers conducted analyses from the aspects of particle size distribution, mineral composition, and chemical composition of Xiashu soil, and they identified factors affecting differences in its physical and mechanical properties [9,10]. Some investigators have found significant differences in the physical, mechanical, and strength characteristics of Xiashu soil under different water content conditions [11–14]. For example, Liu et al. [15] selected Xiashu soil samples subjected to different wetting–drying cycles and employed unsaturated direct shear tests to study the influence of wetting–drying cycles on the mechanical properties of Xiashu soil.

Rainfall alters the seepage field within slope soils. To describe its variation patterns, many researchers have proposed rainfall infiltration formulas and models to quantify the influence of rainfall on the seepage field of slope soils. The current mainstream infiltration models include the Richards equation, the Srivastava-Yeh model, the Green-Ampt model, and the Phillips model. Under gravity-driven infiltration and constant rainfall intensity, Wang [16] and Baiamonte [17] derived accurate and simple analytical solutions to the Richards equation. Wang et al. [18] investigated the characteristics of soil moisture profile changes during water infiltration in loess and developed a water infiltration model suitable for loess areas. This model not only calculates cumulative infiltration and wetting front depth but also estimates soil moisture profile distribution based on the Green-Ampt infiltration model. To establish the hydraulic conductivity for different slope angles, Guo Xianghong et al. [19] analyzed the mechanism by which infiltration head affects water infiltration and attributed this effect to its influence on the hydraulic conductivity of a generalized saturated zone. They developed an improved Green-Ampt model capable of simulating the effect of different infiltration heads on water infiltration. Meanwhile, Chen et al. [20] extended the Green-Ampt equation to sloping surfaces and compared the extended solution using the same hyetograph with the original formulation. They calculated infiltration and runoff for different slope angles while keeping the horizontal projection length constant. Their theoretical and numerical results indicate that the infiltration amount increases with an increasing slope angle. J. Almedeij et al. [21] redefined the ponding time from a different perspective and established a modified Green-Ampt model with a wider range of applicability.

In previous studies, many researchers have investigated the influence of rainfall on slope infiltration and stability through physical modeling experiments [22]. Zhong et al.

[23] conducted a physical model study of a gently inclined accumulation landslide induced by intermittent rainfall. Their results show that failure of such a slope first occurs at the toe of the slope. Bai et al. [24] carried out field rainfall tests on a natural double-layer loess slope and found that during the rainfall process, the infiltration rate was fastest at the top platform of the slope, followed by the upper part of the slope, and slowest at the lower part of the slope. Guo et al. [25] analyzed the spatiotemporal variation of rainfall infiltration using monitoring data from an in situ landslide test site and developed a rainfall infiltration model that comprehensively considers the non-uniform distribution of initial soil moisture content and the slope environment. Tu et al. [26] conducted artificial rainfall tests on a low-cut slope of a highway in the Northwestern Loess Plateau and investigated the effect of rainfall intensity on the infiltration depth of the loess slope. Huang et al. [27] used simulated rainfall events to study the effects of vegetation cover, rainfall intensity, and slope gradient on post-rainfall soil moisture increase and the infiltration recharge coefficient, and they obtained the infiltration laws of soil under different slope gradients and rainfall intensities.

To summarize, the existing research on Xiashu soil has mainly focused on its material composition and sources, sedimentary age, and physical and mechanical characteristics. The main physical and mechanical aspects studied include the structure, infiltration characteristics, deformation behavior, and the influence of water content on the structure and strength of Xiashu soil. However, there is a lack of research on the non-uniform evolution of rainfall infiltration and failure at different slope positions under full-process field artificial rainfall tests, as well as a lack of empirical formulas for infiltration depth under different rainfall intensities, rainfall durations, and slope angles, and critical thresholds for landslides [28,29].

This study investigates the evolution of rainfall infiltration and failure of Xiashu soil slopes. Taking the Xiashu soil slope as the research object, field rainfall model tests and laboratory experiments were conducted to analyze the relationships among the volumetric water content, displacement deformation, and mechanical indicators of the landslide body during rainfall infiltration. Combined with the experimental results and numerical simulations, the coupling relationships among rainfall, displacement deformation, and mechanical indicators of the landslide body were examined. The infiltration and failure mechanism of the Xiashu loess slope under different rainfall conditions was revealed. Based on the mechanical indicators of a typical landslide body obtained from field tests, a comprehensive multi-indicator monitoring and early warning method for a typical landslide body was established. This study can provide a reference for the stability assessment and risk prevention and control of Xiashu loess slopes under rainfall conditions.

2. Methodology

2.1. On-Site Rainfall Model Test

2.1.1. Test Site Profile

The artificial rainfall test site was located on the southwest slope of Xiashu Town, Jurong City, Jiangsu Province. The slope surface was tea plantation land, and the northeast side of the slope foot was near the natural pond, so the water was convenient. The surrounding threats were farmland and crops.

The surface lithology of the slope body was mainly composed of silty clay in the lower Shu Formation, and the slope vegetation was sparse with tea trees. According to the field investigation, the overall height difference of the slope body was about ~8–10 m: the front was slow, the middle platform was gentle, and the back edge was steep. The first set of steps was about ~5–6 m, the slope was ~35–40°, the middle and rear might

have been the back wall of the early local collapse, about 50° , the height difference was about $\sim 3\text{--}4$ m, and the rear edge wall was bare and dry. There were gullies and soil cracks on the slope surface, and the primary pond was about $\sim 5\text{--}6$ m outside the north-east side of the slope foot. Topographic profile is shown in Figure 1.

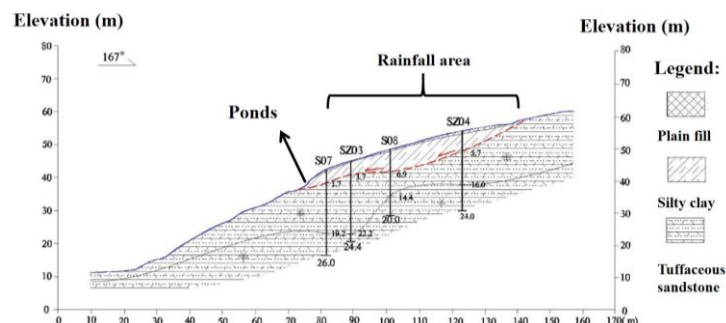


Figure 1. Topographic profile.

2.1.2. Test Device and Working Method

(1) Artificial rainfall simulation device

The artificial rainfall simulation system of JLC-RY1 was adopted (Figure 2a and Table 1). The artificial simulated rainfall system mainly included a water supply system, a bracket, a sprinkler, and a control and monitoring system. According to the actual situation of the site, the rainfall area of this work was set at 6.4×4.6 m (Figure 2b), six sprinkler heads were uniformly set, the rainfall height was $\sim 1\text{--}2.5$ m, the rainfall intensity was 6 mm/h, and the rainfall duration was $\sim 1\text{--}23$ h.

Table 1. Rainfall performance parameters of jlc-ry1 artificial rainfall simulation system.

Rainfall Performance Parameters of jlc-ry1 Artificial Rainfall Simulation System	
Effective rainfall area	10–30 m ²
Effective rainfall height	1–3 m
Continuous variation range of rainfall intensity	20–200 mm/h
Rainfall uniformity coefficient	>0.8
Rainfall measurement error	$\leq 2\%$
Rainfall duration	arbitrarily
Rain gauge resolution	0.1 mm

(2) Monitoring device and working method

Surface displacement, deep displacement monitoring points, and high-density resistivity monitoring were set up synchronously on the slope during the process of rainfall. Meanwhile, soil samples were collected by trough and shallow well to test water content, gravity, strength, and other indicators. At the same time, the high-density resistivity monitoring was carried out under different rainfall conditions and different times.



Figure 2. Artificial rainfall simulation device ((a) JLC-RY1 device; (b) site of on-site rainfall model).

(3) Test condition design

The rain intensity was designed as a constant value of 60 mm/h (simulated rain-storm condition). The rainfall duration time was designed as 1 h, 2 h, 4.5 h, and 23 h (simulated slope deformation and failure at different rainfall times). Values of surface displacement, deep displacement, soil moisture content, weight, internal friction angle, cohesion force, and slope resistivity were monitored. The observation duration was designed as 3 days before, during, and after rainfall. The method of equal rainfall intensity and change of rainfall duration was adopted to carry out synchronous slope displacement deformation monitoring. The soil tests were taken before rainfall, and after rainfall 24 h, 48 h, and 72 h in different artificial rainfall simulation conditions. The equipment information and frequency monitored on site are shown in Table 2 and Table 3, respectively.

Table 2. On-site monitoring contents and equipment.

Monitoring Content	Test Device	Remarks
Surface displacement monitoring	TOPCON gm101 total station (horizontal displacement monitoring), accuracy ($\pm (1.5 \text{ mm} + 2 \text{ ppm} \times d)$)	The polar coordinate method is used for horizontal displacement monitoring. When polar coordinate observation is used, the total station is erected at the reference point, and the prism is erected at the back viewpoint and the monitoring point. The mean square error of the height difference of the station is less than 1.5 mm.
	Leica dna03 digital level (vertical displacement monitoring), accuracy (0.3 mm/km)	Leica dna03 electronic level and indium watt leveling rod are used for second-order leveling observation, and CODAPS is used for calculation after observation. The mean square error of the coordinates of the displacement monitoring points is less than 1.0 mm.
Deep displacement monitoring	Portable pulley inclinometer, accuracy (0.2 mm)	The portable pulley inclinometer shall be used to monitor the depth of 0–2 m. The system accuracy of the inclinometer shall not be less than 0.25 mm/m, and the resolution shall not be less than 0.02 mm/500 mm.
High density resistivity test	GD-10 high density electrical measurement system, accuracy (± 24)	The GD-10 high-density electrical method measurement system is adopted. The electrode is buried to the main section of the slope. The slope resistivity is continuously observed during and within 48 h after rainfall to obtain the change of slope resistivity. The measurement range is 0.10%.

Table 3. Monitoring frequency of rainfall model test.

Test Process	Monitoring Items	Monitoring Frequency	Remarks
Before test	Initial value	Once/d	Take the mean value
Before rainfall starts	Vertical displacement, horizontal displacement and inclinometer	Observation once	/
Rainfall range	Vertical displacement	Once/h	/
Three days after rainfall	Vertical displacement, horizontal displacement and inclinometer	Once/d	/
Non test time	Vertical displacement	Once/5 d	/

Before the start of the test, weeds on the slope surface were manually removed to eliminate the influence of vegetation cover. A high-density resistivity survey line was arranged along the main sliding direction of the slope, extending to cover the entire slope area. Surface displacement monitoring points and deep displacement monitoring points were established along the central axis of the main sliding direction, on both sides, and within the test area, as well as its periphery. An artificial sampling trench was set up in the middle of the test area, and sampling points were arranged at the toe, middle, and top of the slope at depths of 0 m, 0.2 m, 0.5 m, 0.8 m, 1.0 m, 1.5 m, and 2.0 m. During the test, undisturbed soil samples were collected using a cutting ring, as shown in Figure 3. A trough drilling sampling method was adopted, and the moisture content values obtained from groove sampling were cross-checked and compared. The comparison results showed that the moisture content values from groove sampling were basically consistent with those from trough drilling, with a difference within the allowable error range of 1%, indicating that the accuracy of the groove sampling meets the evaluation requirements. During the test, verification analyses using Luoyang shovel sampling and moisture content testing were also carried out at other points in the test area. The test results were generally consistent with those from trench sampling, indicating that the collected samples were minimally disturbed.

**Figure 3.** Undisturbed sample of ring cutter during test.

The test slope shall be manually excavated and the test trench shall be set, and the soil sample shall be taken from the side wall. The soil test shall be carried out in strict accordance with the soil test specification, in which the direct shear and quick shear method shall be used for the shear strength index test. At the same time, in order to minimize the impact of rainfall infiltration on the side wall, the width of the side wall of the test trench is widened after each rainfall. The four rainfall events were conducted in

the same area. The slope of the test section was monitored during the rainfall and for 72 h after the rainfall ceased. To reflect the individual impact of each rainfall scheme on slope infiltration and to ensure that the rainfall schemes were independent of each other without mutual interference, after each rainfall scenario, the slope was left to rest for 14 to 21 days depending on weather conditions before the next rainfall. This allowed for independent observation of the effects of rainfall events with different durations on slope infiltration, facilitating comparative analysis.

From March to late July 2023, the natural rainfall data in the test area were continuously observed and recorded. Values of the surface displacement, deep displacement, soil moisture content, gravity, internal friction angle, cohesion force, and slope resistivity were observed during two heavy rainfall processes from June 17 to July 20.

From March to mid-July 2023, four artificial rainfall conditions and two natural rainfall conditions were observed. Three hundred and twenty-two groups of physical and mechanical index testing, 18 groups of high-density resistivity detection, and slope deformation observation before and during rainfall (every 1 h), and 3 consecutive days after rain, were completed. The basic information about artificial rainfall and natural rainfall conditions was listed in Table 4.

Table 4. Scheme of artificial rainfall test conditions.

Rainfall Conditions		Rainfall Intensity	Rainfall Time	Monitoring Cycle and Content
Artificial rainfall test conditions	The first round of rainfall	60 mm/h	for 1 h	Displacement deformation, electrical resistivity, and sampling testing: before and after rainfall, as well as 24 h, 48 h, and 72 h after rainfall
	The second round of rainfall	60 mm/h	for 2 h	Displacement deformation (1 h/time in rain), electrical resistivity and sampling tests: before and after rainfall, and 24 h, 48 h, 72 h after rainfall
	The third round of rainfall	60 mm/h	for 4.5 h	Displacement deformation (1 h/time in rain), electrical resistivity and sampling tests: before and after rainfall, and 24 h, 48 h, 72 h after rainfall
	The fourth round of rainfall	60 mm/h	First continued rainfall 10 h; 24 h later, continued rainfall 9 h; 24 h later, continued rainfall 4 h.	Displacement deformation (1 h/time in rain), sampling and testing: before and after rainfall, and 24 h, 48 h, 72 h after rainfall; Electrical resistivity test: Conduct one test before rain and one test at the end of the third day of rainfall
Natural rainfall monitoring conditions	The first natural rainfall	282 mm/3 d	Natural rainfall	On 20 June, on-site sampling testing and displacement deformation monitoring were carried out
	The second	64.9 mm/3 d	Natural rainfall	On 18–19 July, sampling tests and slope deformation monitoring were conducted on site

2.2. Numerical Simulation

In order to further analyze the influence of rainfall infiltration on the Xiashu soil slope, a two-dimensional numerical model was established according to the actual slope size of 1:1 with five geotechnical layers, including hard plastic silty clay, plain filled soil, plastic silty clay, fully weathered quartz monzonite, and strong weathered quartz mon-

zonite. Numerical settings of the size information of the slope model established were consistent with the field test slope, and the location of the monitoring point was the same as that of the field test. The slope top elevation of the model slope was 9.80 m, the slope bottom elevation was 4.00 m, the slope platform length was 7.50 m, the entire slope length was 20 m, the groundwater level was set at the height of 2.5 m, and the side slope angle was 35°.

2.2.1. Numerical Model

The mesh of slope models is shown in Figure 4, taking the slope with 35° slope angle as an example. In the model analysis, the soil layer mesh size is set to 0.1 m. Totally, 2394 nodes and 1668 units exist in the form of mixed quadrilateral and triangular mesh.

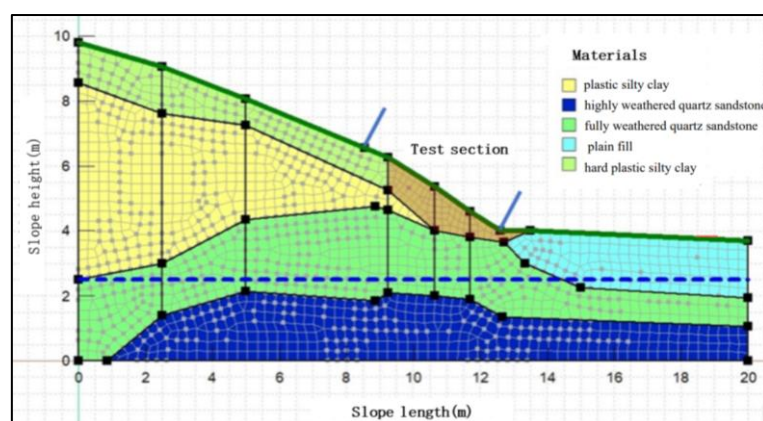


Figure 4. Numerical model (Brown section is landslide area).

In this paper, the SEEP/W module in Geo-studio is used to establish a two-dimensional seepage model of unsaturated soil. The VanGenuchten model is used to simulate the soil–water characteristic curve of each rock layer, and the permeability coefficient of each soil layer is measured by variable head permeability test. The relevant parameters of the soil–water characteristic curve and permeability curve of each rock and soil layer are shown in Table 5.

Table 5. Related parameters of soil water characteristic curve and permeability curve of each rock and soil layer.

Rock and Soil Layer	Saturation Permeability Coefficient	Saturated Moisture Content	Residual Moisture Content	Dry Density	Initial Moisture Content
	ks/(m/h)	$\theta_s/(m^3/m^3)$	$\theta_r/(m^3/m^3)$		$\theta_i/(m^3/m^3)$
Hard plastic silty clay	5.00×10^{-3}	0.32	0.032	1.48	0.18
Plain fill	5.00×10^{-3}	0.31	0.03	1.45	0.15
Plastic silty clay	2.50×10^{-3}	0.26	0.026	1.52	0.20
Fully weathered quartz monzonite	1.00×10^{-3}	0.2	0.02	1.60	0.12
Strong wind fossil quartzite	8.60×10^{-4}	0.18	0.018	1.65	0.10

The slope surface is set based on the field test. Only the rainfall flow boundary with different rainfall intensity is applied in the test section. The rainfall flow boundary set on the surface of the slope model is the same as the field test, i.e., the rainfall intensity and rainfall duration set are consistent with the field test conditions.

Based on the study of soil–water characteristic curve by VanGenuchten function, the expression in the form of power function of unsaturated soil volume water content and matric suction can be obtained as follows:

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\frac{s}{a})^n]^m} \quad (1)$$

where: θ_w is the soil volume water content during the calculation period; θ_s is the saturated water content; θ_r is the residual water content; a is the soil parameters of the intake air value function; s is the pressure head; n and m are fit parameters.

Four parameters (θ_s , θ_r , a , and m) in the VanGenuchten model have a great influence on the position, slope, and line of soil–water characteristic curve. The parameters of van Genuchten are determined by parameter inversion method, and similar initial parameters are obtained by engineering analogy method. Then, the built-in parameter optimization module in geo–studio is adopted, and the time series curve of 0.2 m depth moisture content monitored on site is used as the objective function, and the trial-and-error method is used for calibration. In the present numerical simulation, rainfall infiltration mainly occurs in the layer of hard plastic silty clay. Take hard plastic silty clay as an example, where $a = 16$ kPa and $n = 1.5$, then $m = 0.33$.

2.2.2. Calculation Parameters and Boundary Conditions

Based on the site drilling data of the slope, laboratory test results, a review and comparison of engineering codes, and drawing on experience from previous engineering cases, the final geotechnical material parameters adopted are presented in Table 6. In the rainfall seepage analysis of the slope, a two-dimensional unsaturated seepage model was established using the SEEP/W module in Geo-studio. The Van Genuchten model was employed to simulate the soil–water characteristic curves of each geotechnical layer, and the permeability coefficients of each soil layer were measured using variable-head permeability tests. The relevant parameters of the soil–water characteristic curves and permeability curves for each geotechnical layer are listed in Table 6.

Table 6. Selection of geotechnical material parameters for slope model.

Rock Soil Layer	Unit Weight/(kN·m ⁻³)	Cohesion/kPa	Friction Angle/(°)	Compressibility Factor/mPa ⁻¹	Poisson's Ratio
Hard plastic silty clay	19	6	10	0.19	0.39
Plain fill	15	5	9	0.2	0.43
Plastic silty clay	20	10	14	0.16	0.35
Fully veathered quartz	30	15	18	0.1	0.28
Strong vind quartz	32	16	19	0.1	0.27

Boundary conditions were applied to the model based on the actual field test conditions. The rainfall infiltration analysis is a transient analysis, with rainfall intensity varying over time. The slope surface is configured correspondingly to the field test: a rainfall flux boundary with different rainfall intensities is applied only to the test section. The two sides of the slope model are set as infinite space conditions, and the bottom boundary is set as a zero-pressure headline. The rainfall flux boundary on the slope surface is consistent with the field test, i.e., the rainfall intensity and duration are set to match the corresponding field test conditions. The boundary condition setup is shown in Figure 5.

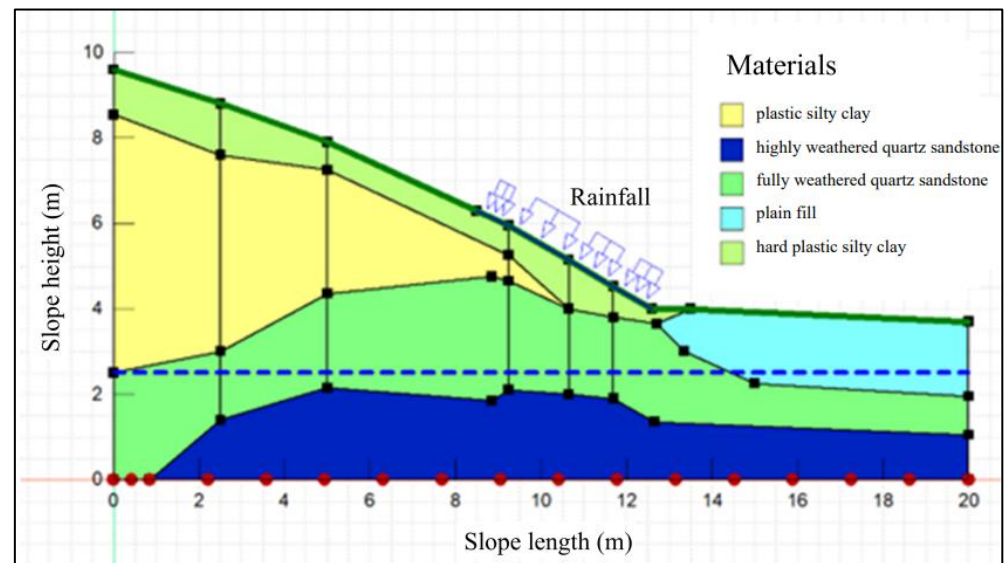


Figure 5. Setting of boundary conditions.

3. Results

3.1. Characteristics of Slope Water Content During Different Rainfall Processes

In the on-site rainfall experiments, soil samples were taken at different depths of 0 m, 0.2 m, 0.5 m, 0.8 m, and 1.0 m at the foot, middle, and top of the slope at different time periods after the rainfall ended. The moisture content of the soil was tested on site to obtain the variation law of soil moisture content with time at different depths.

When the rainfall intensity was 60 mm/h and the rainfall duration was 1 h, the time series of the volume water content at different depths of the slope top, slope, and slope foot was shown in Figure 6. It could be seen that the volume moisture content at 0 m of the slope surface increased rapidly from 17% to 32% during the rainfall period of 1 h. After reaching saturation, the moisture content decreased rapidly due to evaporation and decreased to slightly higher than the initial moisture content 72 h after the rainfall. The volume moisture content of the soil at the depth of 0.2 m in the slope increased during the rainfall period, and the increase amplitude was lower than that of the soil at 0 m. After the rainfall, the moisture content did not decrease immediately, but it increased for a period of time and then decreased. The decreasing amplitude of the volume moisture content was also lower than that of the soil at 0 m, and the soil at the depth of 0.2 m did not reach saturation. The volume moisture content of soil at depths of 0.5 m, 0.8 m, and 1 m did not change significantly; that is, the infiltration did not reach those depths. When the rainfall intensity was 60 mm/h and the rainfall was 1 h, the maximum infiltration depth of Xiashu soil slope was within the range of 0.2 m to 0.5 m. By comparing the changes of soil volumetric moisture content at different locations of 0.2 m, it was found that the increase amplitude and growth rate at the foot of the slope were higher than those at the top and middle of the slope. It was inferred that the infiltration rate and depth of the soil at the foot of the slope were greater than those at the top and middle of the slope.

The observed phenomenon was similar to the findings of Guan et al. [30] and Chen et al. [31], which reported that during rainfall infiltration on slopes, the infiltration rate was fastest at the crest, relatively fast at the toe, and slowest at the middle, while the infiltration depth is greatest at the toe, greater at the crest, and shallowest at the middle. However, there were also differences: the variation trend of infiltration depth with slope position was consistent, but the infiltration rates at different slope positions follow the order crest > toe > middle. The reason for this discrepancy may be the time lag between

collecting field soil samples for moisture content measurement after rainfall and obtaining soil moisture content data from moisture sensors in the present rainfall model test. It was inferred that the infiltration depth of the soil at the foot of the slope is greater than those at the top and middle of the slope.

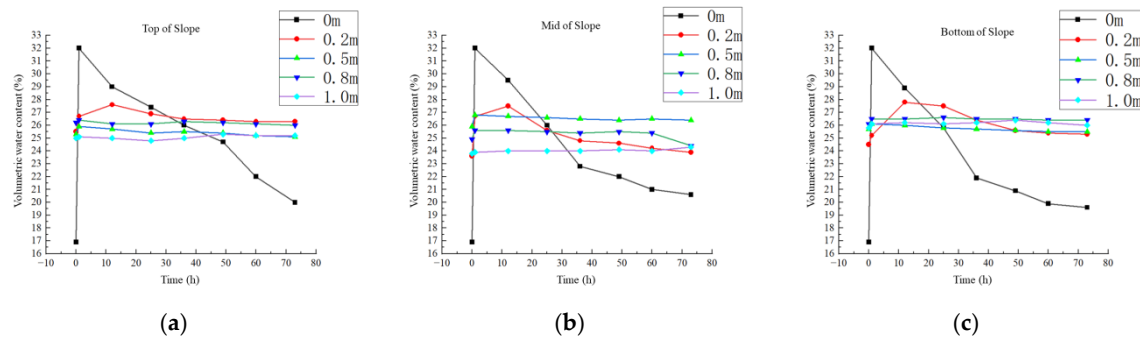


Figure 6. Time series of moisture content at different locations for 1 h rainfall. (a) slope top; (b) middle slope; (c) slope foot.

The third round of artificial rainfall had the condition of rainfall intensity 60 mm/h and continuous rainfall total of 4.5 h. Figure 7 showed that with the increase of rainfall duration and the total rainfall, the moisture content at the depth of slope, about 0.20 m, increased continuously with the increase of rainfall, and the peak value was reached within 24 h after rainfall. At the depth of 0.50 m at the top and foot of the slope, the moisture content reached the peak value after the rain after about 24 h, and at the depth of the middle slope after about 48 h. At the slope depth of 0.8 m, the change was small within 24 h; the foot and top of the slope had a slight change about 24–48 h after the rain, and the change was small in the slope middle. At the slope depth of 1.0 m and below, the moisture content was basically unchanged during rainfall, which indicated that rainfall infiltration did not affect the moisture content of the Xiashu soil below the depth of 1 m.

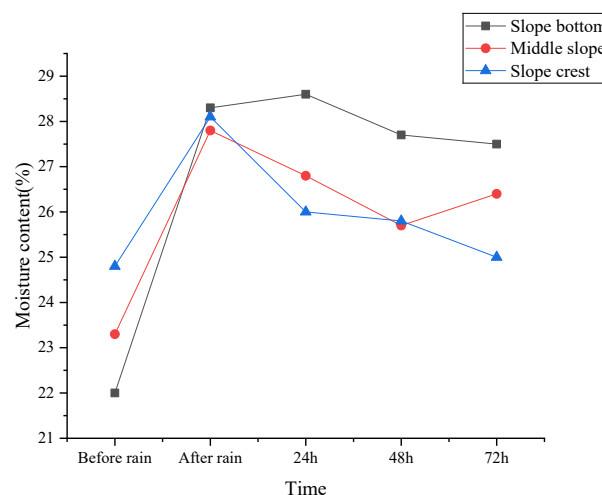


Figure 7. Curve of moisture content with time (the third rainfall condition).

Taking the monitoring results of 0.5 m depth moisture content as an example, the moisture content of the test slope at the top, middle, and foot of the slope increased to different degrees within 24 h after the rain, and the average moisture content was 23.4%

before the rain, reaching 28.0% after the rain. After the moisture content reached the maximum moisture content of 28.3%, the moisture content gradually decreased.

Based on the relationship between moisture content and time, the maximum moisture content after rainfall occurred within 24 h after rain. The maximum moisture content change curves before and after rainfall at different depths were shown in Figure 8.

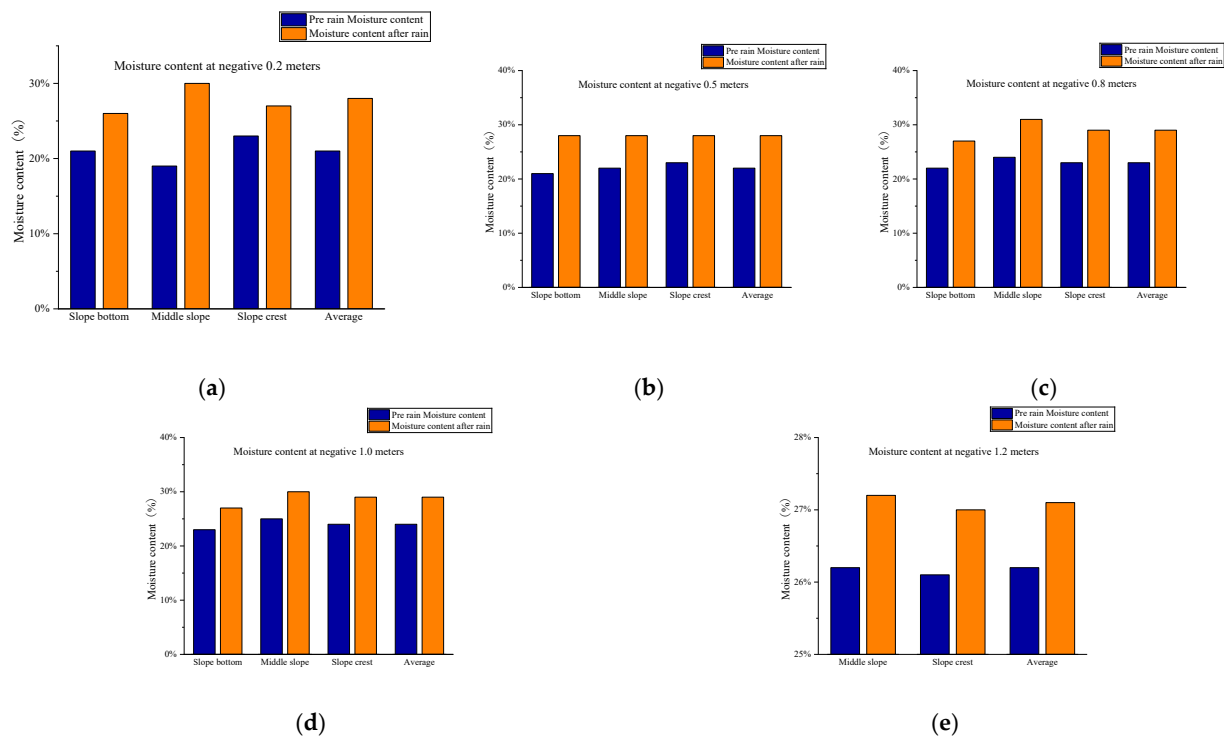
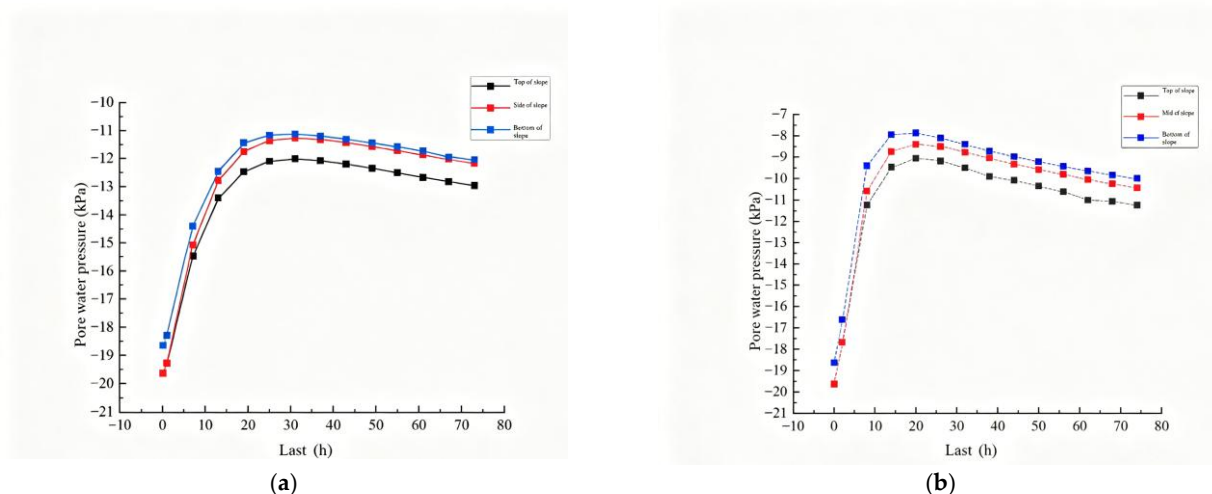


Figure 8. Characteristics of water content at different positions of slope with depth under the third round of artificial rainfall. (a) moisture content at depth 0.2 m; (b) moisture content at depth 0.5 m; (c) moisture content at depth 0.8 m; (d) moisture content at depth 1.0 m; (e) moisture content at depth 1.2 m.

3.2. Pore Water Pressure Distribution Characteristics

Rainfall infiltration changed the pore water pressure in the soil mass of the slope, which changed the soil stress and affected the stability of the slope. During the rainfall test, the conditions with rainfall intensity of 60 mm/h and duration of rainfall of 1 h, 2 h, 4.5 h, and 8 h were analyzed. The changes of pore water pressure at 0.2 m buried depths at different positions of the slope were compared (Figure 9).



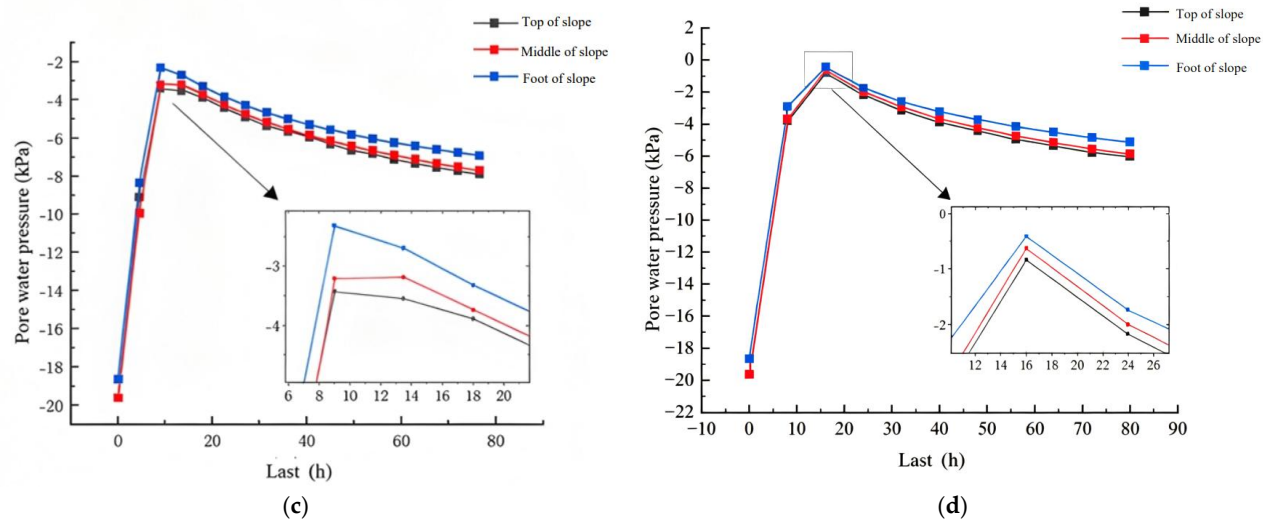


Figure 9. Pore water pressure change curve ((a) Rainfall 1 h; (b) Rainfall 2 h; (c) Rainfall 4.5 h; (d) Rainfall 8 h).

Under the initial condition, the pore water pressure was basically the same due to the similar water content at the three slope locations. During the process of rainfall, pore water pressure increased rapidly. The increase of the pore water pressure did not stop at the end of rainfall owing to the fact that the rainwater continued to penetrate downward in the slope. After the end of rainfall, the pore water pressure reached a stable state and then decreased owing to the fact that the soil inside the slope entered the drainage stage. Limited by the permeability of the Xiashu soil, the rainwater inside the slope drained slowly, resulting in a slow decrease in the pore water pressure.

The peak value of pore water pressure was found to increase with an increasing rainfall duration. The peak value of pore water pressure was nearly 0 when the rainfall was 8 h. The distribution of the pore water pressure of the slope showed a certain regularity under different rainfall durations: the foot of slope > the middle of slope > the top of slope, which could be explained by the rainfall process: the rainfall collected at the foot of the slope with a relatively fast infiltration rate, making the maximum infiltration depth. Because the pore water pressure at the slope foot was greater than that at the other parts, the slope of Xiashu soil was easily damaged at the slope foot, which might lead to the tensile failure of the slope from the bottom to the top.

The peak pore water pressure increases with increasing rainfall duration. When the rainfall duration reached 8 h, the peak pore water pressure approached zero. Under different rainfall durations, the dissipation rates of pore water pressure at different depths after rainfall vary; the pore water pressure dissipates gradually from the top to the middle and then to the toe of the slope [32]. The distribution of pore water pressure along the slope exhibits a certain regularity: toe > middle > crest. This can be explained by the rainfall process: rainfall runoff and internal water accumulate at the toe, where pore water pressure dissipates slowly and the infiltration depth is therefore greatest. Because the dissipation rate of pore water pressure at the toe is slower than that at other locations, the pore water pressure at the toe of the Xiashu soil slope becomes the highest, making the slope toe susceptible to local failure [33,34], which may eventually lead to tensile failure of the slope from the bottom upward.

At the same time, the stability coefficients of the slope under the four working conditions of continuous rainfall of 1 h+duration of 72 h, continuous rainfall of 2 h+duration of 72 h, continuous rainfall of 4.5 h+duration of 72 h, and continuous rainfall of 8

h+duration of 72 h are calculated. The stability coefficients of the slope under different rainfall conditions are shown in Table 7.

Table 7. Variation of slope stability coefficient under different rainfall conditions.

Rainfall Conditions	Initial State	1 h After Rainfall	24 h After Rainfall	48 h After Rainfall	72 h After Rainfall
Rainfall of 1 h+duration of 72 h	1.627	1.554	1.532	1.526	1.526
Rainfall of 2 h+duration of 72 h	1.634	1.543	1.515	1.506	1.506
Rainfall of 4.5 h+duration of 72 h	1.573	1.460	1.401	1.392	1.393
Rainfall of 8 h+duration of 72 h	1.573	1.460	1.401	1.392	1.393

As shown in Figure 5, from the beginning of rainfall to 1 hour after rainfall, the pore water pressure of the slope rises sharply. Correspondingly, as seen in Table 7, the slope stability coefficient is in a state of rapid decline during this period, indicating that the rapid increase in pore water pressure directly affects the stability of the slope. After a rainfall duration of 24 h to 72 h, the pore water pressure within the slope shows a decreasing trend at different rates, while the slope stability coefficient gradually declines until it stabilizes.

3.3. Wetting Front Characteristics

In order to reveal the relationship between infiltration depth and slope angle under different rainfall conditions, four rainfall conditions were set up in the paper. The study observed the infiltration situation under the conditions of slope angles at 30°, 35°, and 40°, and rainfall durations of 1 h, 2 h, 4.5 h, and 8 h. The infiltration depth was recorded after 72 h since the end of rainfall duration. Under different rainfall conditions, the relationship between infiltration depth and slope was shown in Figure 10. Results suggested that slope infiltration depth decreased with an increasing slope angle with a slightly reduced range: with a larger range of 30–35° than that of 35–40°. Under the same slope angle, an increasing rainfall duration led to a greater slope infiltration depth and a more significant influence of the infiltration depth on the side slope angle. Under the same slope angle, a longer rainfall duration leads to a greater infiltration depth on the slope surface, and the influence of the slope angle on infiltration depth becomes more significant. The relationship between rainfall duration and slope surface infiltration depth is consistent with the results of the loess slope rainfall model tests conducted by Cui et al. [35].

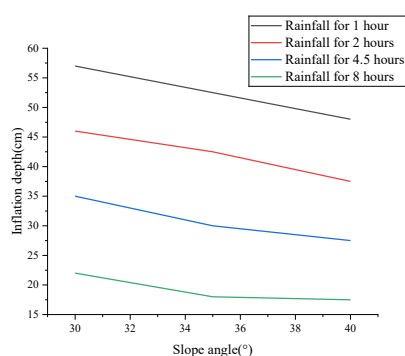


Figure 10. Infiltration depth versus slope under different rainfall conditions.

3.4. Macroscopic Characteristics of Rainfall Intensity and Damage Area

3.4.1. Deformation and Failure Characteristics

In the first three artificial rainfall and natural rainfall before slope cutting, no obvious deformation and failure occurred. Thus, the slope body was in a stable state. During the process of the fourth artificial rainfall, the slope foot collapsed locally after cutting off the slope foot. Later, the test area entered the plum rain season, and the slope area was gradually damaged under several natural rains.

Before the fourth round of artificial rainfall, the slope of the test area was cut, and the height of the slope was about 1 m. After 10 h of continuous heavy rainfall on 24 May and 5 h of heavy rainfall on 25 May, the slope foot collapsed and was damaged. Figure 11a shows a local slide failure of slope foot during the rainfall process of the fourth round (25 May 2023) artificial rainfall condition.

During the natural rainfall from 17–19 June 2023, local collapse occurred at the foot of the slope area. The collapse area was about 0.5 m long and 1.2 m wide, and a high steep ridge of about 0.2 m was formed at the rear edge (Figure 11b).



Figure 11. Local slide failure of slope foot during the rainfall process ((a) 10 h of continuous heavy rainfall; (b) after heavy natural rainfall).

During the natural rainfall from 15–17 July 2023, the slope of the test area was destabilized as a whole. Field investigation showed that the middle and lower parts of the test area slid downward as a whole. The main sliding direction is N37° E, resulting in the overall destruction of the leading-edge observation point. In the middle and lower part of the slope, curved tension cracks were formed, which are basically consistent with the slope body strike in the slope cutting range. Between the slope cutting surface and the central monitoring points DBA2, DBA4, DBA5, and CX02 front, the whole soil slides downward to form a platform, and the slumping bodies accumulate at the cut slope of the original slope foot. The vertical settlement and horizontal slip distance of the formed steep slope are about ~20–55 cm and ~10–35 cm, and the displacement and deformation are greatest near the main section in the middle of the landslide.

The tensile crack at the back edge of the test area and the lateral crack extending along the back edge of the cut slope boundary from the foot of the slope have been basically through. The width of the crack is about ~5–20 cm, and the vertical settlement and dislocation form a steep ridge of about ~10–45 cm. The soil displacement and deformation are obvious at the lower part of the central monitoring point DBA4 on the south side of the slope and the upper part of the monitoring point DBA1 and CX01 on the rear edge of the slope. On both sides of the slope body, many small feathery shear cracks are formed along the upper part.

According to the results of field investigation, it is preliminarily judged that the whole test section has entered the stage of accelerated deformation and failure.

3.4.2. Slope Displacement Analysis

Cumulative vertical displacement is the most intuitive index to judge the instability of the Xiashu soil landslide. When the vertical displacement reaches a certain threshold, the slope gradually begins to instability. The amount of vertical displacement at different locations is observed to be different in the displacement monitoring of the field test. Therefore, the vertical displacement monitoring at the top, middle, and foot of the slope is considered. Figure 12 shows the cumulative vertical displacement time history curve at the top, middle, and foot of slope when the rainfall intensity is 60 mm/h and the rainfall duration is 1 h, 2 h, 4.5 h, and 8 h. It can be seen that an increasing rainfall duration causes an increasing cumulative vertical displacement of slope. The time–history curve of cumulative vertical displacement of different rainfall duration is found to be very similar.

With the beginning of rainfall, the vertical displacement began to increase gradually. It can be seen that the three locations all showed an increasing vertical displacement at the final stability with an increasing rainfall duration. The increased amplitude was different, and it was not a simple linear relationship. During the rainfall period, the soil moisture on the surface of the slope increases rapidly, and the saturation rate is fast. Due to the influence of the soil infiltration rate, the rainfall has not penetrated into the deep side of the slope, and the vertical displacement increases slowly. After the rainfall stopped, the rainfall did not dissipate in the slope, and it continued to infiltrate the soil deeper into the slope. With an increase in the wetting front, more soil body weight was increased, the shear strength decreased, and an increasing vertical displacement deformation rate. At this time, little cracks were appeared at the surface of the soil slope, and the slope deformation gradually stabilized after a period of time. A time lag was observed between the increase of vertical displacement and the stop of rainfall. This time lag was found to be increasing with an increase in the rainfall duration. It is found that under the same rainfall duration, the cumulative vertical displacement is the largest at the foot of the slope, the second in the middle of the slope, and the smallest at the top of the slope, indicating that the failure of Xiashu soil slope often starts at the foot of the slope and gradually extends to the upper part of the slope. In the deformation monitoring of Xiashu soil slope, the slope foot should be the key monitoring place.

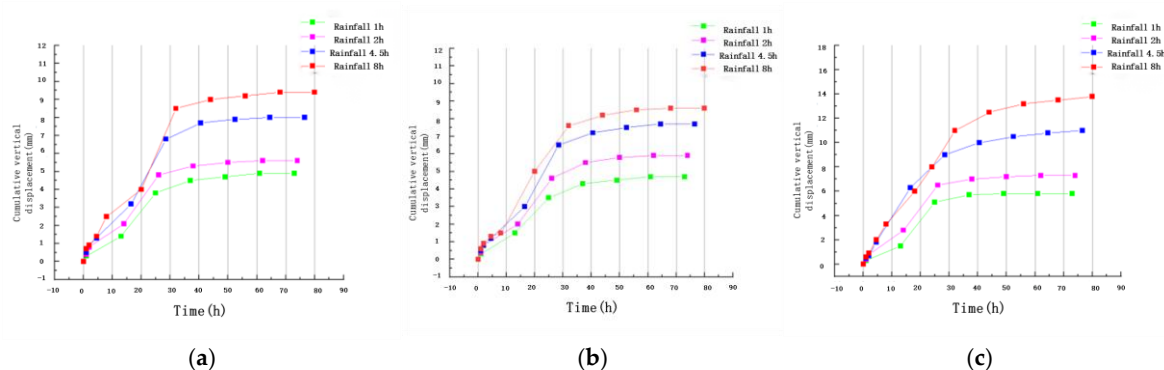


Figure 12. Cumulative vertical displacement of slope at different positions. (a) Top of slope; (b) Middle of slope; (c) Foot of slope.

3.5. Classification of Deformation and Failure Stages of Xiashu Loses Soil Slope

According to the surface displacement monitoring curve of the test area, the test slope gradually evolved from a natural slope to a potential instability slope under the disturbance of artificial rainfall, natural rainfall, and slope-cutting activities. The surface monitoring data show that the first three artificial rainfall of the test slope are in the sta-

ble stage, and the surface deformation is very small. After the influence of the fourth artificial rainfall combined with slope cutting factors, the slope foot appeared local slump failure, and the cumulative horizontal displacement of the observation point at the slope foot exceeded 4 mm. The slope enters the creep deformation stage, and the slippery surface begins to form gradually. Later, under the influence of several natural rains, the creep deformation of the slope gradually increased. The creep deformation showed a gradual characteristic, indicating that the sliding surface continued to develop and tended to run through. After the heavy rainfall from June 17 to 19, the slope deformation gradually increased, and the tangent angle $\alpha_i \approx 45^\circ$ was obtained according to the cumulative displacement time curve. The whole slope entered the iso-velocity deformation stage, and subtle deformation cracks began to appear inside the slope. The slope foot collapsed, which further accelerated the deformation and failure process. After the test area experienced several small rainfalls, the slope deformation continued to develop slowly. From 15–17 July, natural heavy rainfall occurred on the test slope. The sliding surface of the test slope gradually penetrated and evolved into landslide. The whole test slope entered the accelerated deformation stage. The tangent angle of the cumulative displacement–time curve α_i varies between 70° and 85° . The slope is in the transition stage from uniform acceleration to acceleration (pre-slip) in the acceleration deformation stage. This indicates that the overall instability failure of the landslide is about to occur.

The characteristics of the cumulative curve of the slope deformation–moisture content–time during the rainfall of the Xiashu loess slope under the test section show that the cumulative deformation curve type of the rainfall landslide is consistent with the step curve type. The occurrence and development of the landslide are affected by heavy rainfall and other factors. Such repeated adverse external factors lead to the continuous reduction of the strength index of rock and soil mass on the slope. Eventually, external factors such as heavy rainfall will increase sharply, resulting in the rapid evolution of slope deformation and sudden landslide disaster. This will change from the step evolution type to the sudden cumulative deformation and failure type of instability (Figure 13).

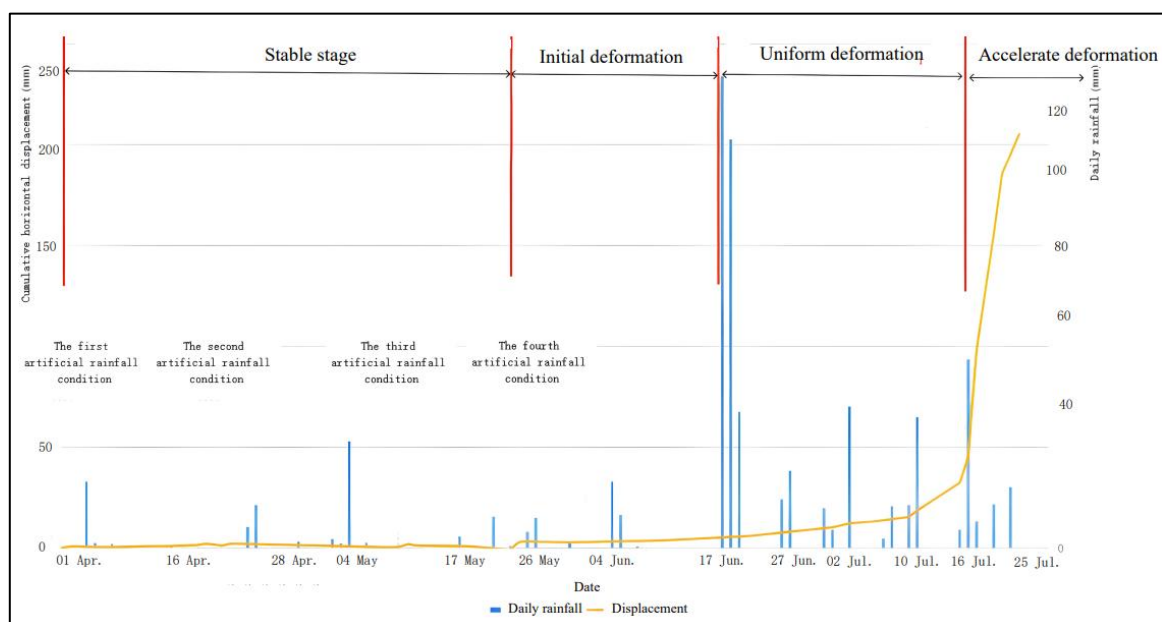


Figure 13. Classification of deformation evolution stages of test slope.

4. Discussion

4.1. Relationship Between Rainfall Intensity, Slope Angle, and Soil Strength at Different Depths

4.1.1. Influence of Rainfall Duration on Infiltration Depth

The field test results show that each index of Xiashu soil changes greatly with the change of water content. The change rate of water content exceeds 3% as the limit in this paper, which is used as the criterion for determining the influence of rainfall infiltration. In order to study the influence of different rainfall durations on the infiltration depth of Xiashu soil slope, the paper analyzed the slope infiltration test data of slope with a 35° slope angle and rainfall intensity of 60 mm/h (Figure 14). It can be seen that an increasing rainfall duration will induce an increasing infiltration depth of the Xiashu soil slope. The growth curves at different positions of slope are similar, but the increasing process is not a simple linear relationship. A turning point occurs at the 2 h rainfall duration. The infiltration depth increases rapidly under the rainfall duration is less than 2 h. The growth rate of infiltration depth gradually slows down after the rainfall duration exceeds 2 h. This is because in the early stage of rainfall, the soil surface of the slope is in an unsaturated state, and the infiltration rate is fast.

As rainfall proceeds, the soil moisture content in the shallow slope layer gradually increases and reaches saturation, while the infiltration rate gradually decreases. In addition, the infiltration rate of the deeper soil on the slope becomes slower. Under different rainfall durations, the infiltration depth varies with position on the slope, showing that the infiltration depth is greatest at the toe of the slope, followed by the crest, and shallowest at the middle of the slope. As depth increases, the rainwater infiltration capacity gradually weakens [36]. The average infiltration depths from three different positions were used for fitting, and the resulting fitting curve is approximately described by Equation (2).

$$y = 34 \times x^{0.33} \quad (2)$$

where y is the infiltration depth; x is rainfall duration.

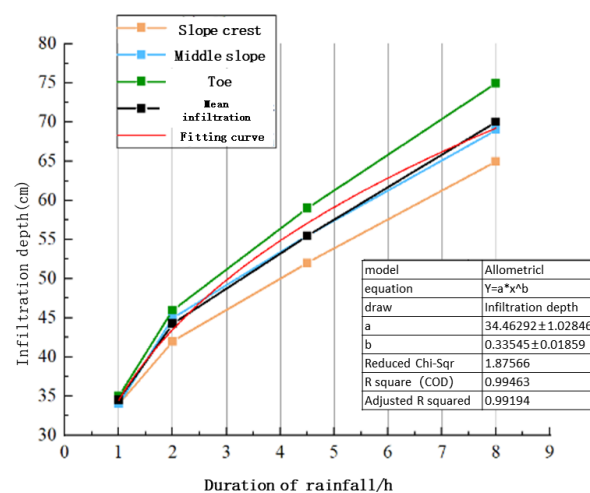


Figure 14. Infiltration depth curves of different rainfall durations.

4.1.2. Influence of Rainfall Intensity on Infiltration Depth

In order to study the influence of rainfall intensity on the infiltration depth of Xiashu soil slope, the paper analyzed the rainfall test data of the slope with 35° slope angle undergoing 2 h different rainfall intensity (Figure 15). When the rainfall intensity is excessive, the slope infiltration depth does not increase significantly with the increase of rainfall intensity with the slow increasing speed, which is because the slope infiltration

is mainly controlled by the rainfall intensity when the rainfall intensity is less than the slope infiltration intensity. At this time, with the increase of rainfall intensity, the overall slope infiltration increases significantly. However, when the rainfall intensity exceeds the slope soil infiltration intensity, the slope soil infiltration intensity turns to be controlled by the slope soil infiltration intensity. In this case, the increased rainfall intensity has no obvious effect on the slope infiltration depth, i.e., the increase of infiltration depth is not obvious. Under different rainfall intensities, the infiltration depth of slope at different positions is different: the infiltration depth at the foot of slope is the largest, and the infiltration depth at the top of slope is the smallest. The average values of infiltration depth with rainfall duration can be described as Formula (3).

$$y = 27 \times x^{0.14} \quad (3)$$

where y is the infiltration depth; x is rainfall duration.

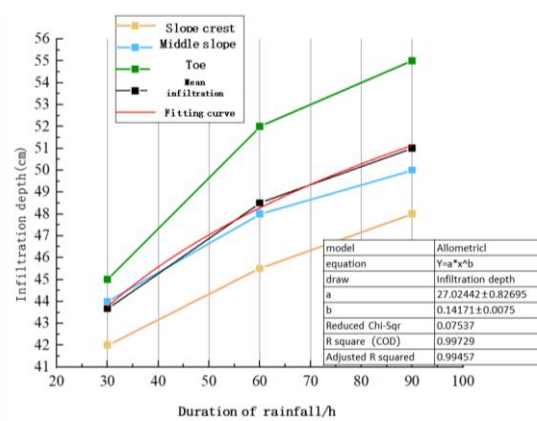


Figure 15. Infiltration depth curves of different rainfall intensities.

4.1.3. Influence of Slope Angle on Infiltration Depth

In order to study the influence of different slope angles on the infiltration depth of the Xiashu soil slope, the infiltration depth of slope angles with rainfall intensity of 60 mm/h and rainfall of 2 h was compared and analyzed (Figure 16). The increase of slope angle, the infiltration depth at different positions of the slope decreases gradually. This is because the larger of the slope angle, the more rainfall will be lost in the form of runoff. This is more of a scouring effect, and the rainfall infiltration effect is weakened. When the infiltration amount generated by rainfall decreases, the infiltration depth decreases with the increase of slope angle. The infiltration depth is different at different positions of slope, which is the largest at the foot of slope and the smallest at the top of slope. The average values of infiltration depths at three different locations were used for fitting, and the fitting curve was approximated as: $y = 72 - 0.65 \times x$.

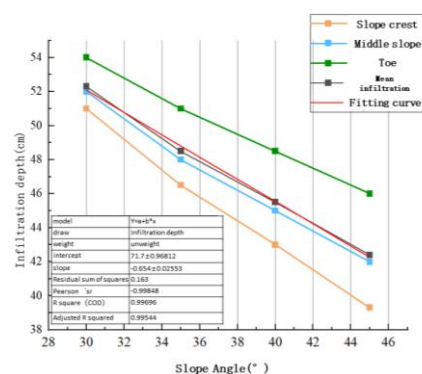


Figure 16. Infiltration depth curves at different slope angles.

As shown in Figure 16, the R^2 value for the fitting of slope angle against infiltration depth is 0.997, indicating that the correlation between the data points is reasonable and highly reliable. The Pearson correlation coefficient is -0.998 , which is close to -1 , indicating that the data points for slope angle and infiltration depth all lie close to a straight line, and that slope angle and infiltration depth exhibit a strong negative correlation. The residual sum of squares (RSS) is the sum of the squared differences between the observed values and the model-predicted values. Generally, the smaller the RSS, the better the predictive ability of the regression model. Here, the RSS for the fitting of slope angle against infiltration depth is 0.163, which is very close to zero, indicating that the regression model has good predictive performance and can be effectively applied to estimate the infiltration depth of Xiashu soil slopes under different slope angles during rainfall conditions.

4.1.4. Statistical Evaluation and Uncertainty Analysis of Infiltration Depth Models

To quantitatively assess the reliability of the empirical relationships established in Sections 4.1.1–4.1.3, we evaluated the goodness-of-fit, parameter uncertainty, and residual behavior of each model. The statistical results are summarized in Table 8.

Table 8. Goodness-of-fit statistics for infiltration depth models.

Relationship	Fitting Equation	Reduced Chi-Sqr	R^2	Adjusted R^2
Rainfall duration.	$y = 34 \times x^{0.33}$	1.875	0.995	0.992
Rainfall intensity	$y = 27 \times x^{0.14}$	0.075	0.997	0.994
Slope angle	$y = 72 - 0.65 \times x$	/	0.996	0.995

As shown in Table 3, the R^2 values for the fitting of infiltration depth against rainfall duration, rainfall intensity, and slope angle are all greater than 0.95, indicating that the proposed models can explain most of the variation in infiltration depth. When adjusted for the relatively small sample size, the adjusted R^2 values remain above 0.95, suggesting that these models are not overfitted. The reduced chi-square value for the infiltration depth versus rainfall duration fitting is 1.875, which is greater than 1, indicating some degree of variability in the model data. In contrast, the reduced chi-square value for the infiltration depth versus rainfall intensity fitting is 0.075, which is less than 1, suggesting that the sample size may be insufficient or that there is a cancellation effect of random errors in the data.

4.1.5. Influence of Different Rainfall Patterns on Infiltration Depth

In order to clarify the influence of different rainfall patterns on the infiltration results of Xiashu soil slope, different combinations of rainfall duration and intensities were made to simulate different rainfall patterns and observe the infiltration of slope under different rainfall patterns while maintaining the same rainfall. The effective rainfall is defined as rainfall intensity times rainfall duration, applying four combinations of rainfall to the slope of Xiashu soil: (1) 1 h of rainfall duration and 90 mm/h of rainfall intensity; (2) 2 h of rainfall duration and 45 mm/h of rainfall intensity; (3) 3 h of rainfall duration and 30 mm/h of rainfall intensity; (4) 4.5 h of rainfall duration and 20 mm/h of rainfall intensity. After 72 h of the end of the rainfall, different rainfall processes can reach the infiltration depth. Figure 17 shows the infiltration results under different rainfall processes.

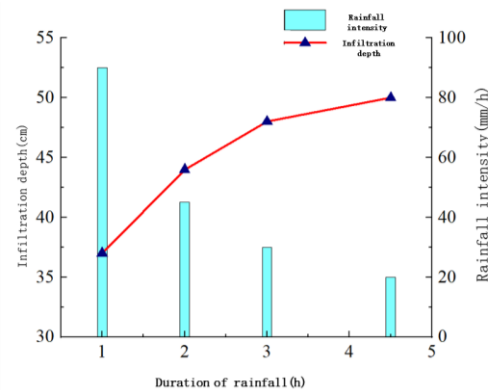


Figure 17. Infiltration results of different rainfall modes.

It can be seen that when the rainfall keeps the same, the infiltration effect of the rainfall with the characteristic of low-intensity and long-duration is better than the high-intensity and short-duration rainfall, while the infiltration depth in real is greater. This phenomenon can be explained by two main reasons. On the one hand, when the rainfall intensity exceeds the soil infiltration intensity, the increased rainfall intensity will be limited by the soil infiltration intensity, resulting in the reduced impact of the increased rainfall intensity on the rainwater infiltration. On the other hand, the rainfall duration is short, affected by evaporation and infiltration rate, rain does not have enough time to penetrate, and the actual infiltration amount is less than that of low-intensity and long-duration rainfall, resulting in a smaller infiltration depth. To summarize, it can be seen that there is not a simple relationship between slope infiltration depth and rainfall. With the same rainfall, the final infiltration results will also be different due to the difference in rainfall intensity and duration.

4.2. Landslide Depth Analysis

During the field test, when the slope angle is 45° and the rainfall intensity is 90 mm/h, the soil slope of Xiashu soil is damaged after the rainfall duration of 8 h, which has a sliding depth of 0.55 m, and an infiltration depth of 0.7 m. It can be seen that the sliding depth is approximately 0.8 times the infiltration depth, inferring that the depth of landslide failure has a certain relationship with the depth of infiltration.

The shear strength of Xiashu soil is greatly affected by water content, and the internal friction angle and cohesion decrease rapidly with the increase of water content. During rainfall, as the position of the wet front in the slope moves forward, the thickness of the softened soil in the slope increases, and the shear strength of the soil in the depth range of the wet front decreases sharply. Therefore, the probability of landslides from the soil in the depth range of infiltration increases significantly. When the shear strength decreases to a certain critical value, the force provided by the shear strength is not enough to support the sliding force of the slope. The failure of Xiashu soil slope is also the reason for the failure depth of most landslides lying in the range of slope infiltration depth.

Since only one landslide occurred during the field test, it can only be inferred that the landslide damage range is within the infiltration depth of the Xiashu soil slope. However, the relationship between the landslide damage depth and the slope infiltration depth cannot be further defined. Thus, additional tests can be performed to explore the relationship between the two parameters in future studies.

4.3. Analysis of Rainfall Infiltration Results

In order to verify the accuracy of the numerical results, the numerical set of the simulated slope was the same as that of the field rainfall test. Changes of the volume water content of the two were compared to analyze the infiltration conditions of the two. In the slope of numerical simulation, the location and depth of moisture content monitoring points set are also the same as that of the on-site rainfall test. The depth of volumetric moisture content monitoring is set as 0 m, 0.2 m, 0.5 m, 0.8 m, and 1.0 m. The rainfall intensity is also 60 mm/h, the slope angle is 35°, and the rainfall duration is 1 h, 2 h, 4.5 h, and 8 h. The infiltration difference between the two was compared under this condition.

The moisture content of the soil at the depth of 0 m and 0.2 m increases significantly, while the moisture content of the soil at the deeper depths does not change significantly. This suggests that the maximum infiltration depth under this working condition is within the range of 0.2 m to 0.5 m. By comparing it with the change of volume water content in field rainfall test, it is found that the change of time history curve of volume water content is basically the same. In order to verify the reliability of the numerical simulation results, the setting conditions of the simulated slope were the same as that of the field rainfall test. Changes of the volume water content of the two were compared to analyze the infiltration conditions of the two. In the slope of numerical simulation, the location and depth of moisture content monitoring points set are also the same as that of the on-site rainfall test. The volumetric moisture content monitoring points set in the numerical model are also at depths of 0 m, 0.2 m, 0.5 m, 0.8 m, and 1.0 m. The rainfall intensity is also 60 mm/h, the slope angle is 35°, and the rainfall duration is 1 h, 2 h, 4.5 h, and 8 h. The infiltration difference between the two was compared under this condition. The measured and simulated results of infiltration depth under different working conditions are shown in Figure 18.

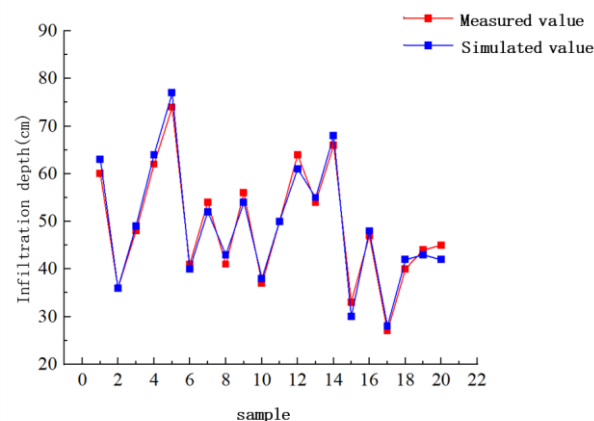


Figure 18. Comparison between measured and simulated infiltration depth.

According to the comparison result of Figure 15, it can be seen that the difference between the measured value and the simulated value of the infiltration depth under different working conditions is small. The average relative error between the measured value and the simulated value of the slope infiltration depth is 3.5%, indicating that the simulation effect of the slope model is good, the simulation results are acceptable, and the simulation accuracy is high.

The discrepancy between the measured value of infiltration depth and the simulated value of slope model can be explained by many reasons. First of all, the slope model established assumes that all soil layers are isotropic and homogeneous in the numerical

simulation process, while the real slope soil layer is mostly heterogeneous soil and rarely has homogeneous soil layer. The anisotropy of the soil layer in the field slope leads to a variety of uncertainties and mutability, resulting in different results. Secondly, in the setting of parameters and boundary conditions of the simulation, although the parameters and boundary conditions are adjusted many times to make them as consistent as possible with the field conditions, there are always differences in such debugging, and it is difficult to maintain a high degree of consistency. Finally, grid division, time step, test error, and other conditions will also affect the results. In summary, there are some errors that are small and within the acceptable range between the measured values and the simulated values.

4.4. Early Warning Threshold of Infiltration Depth of Xiashu Soil Slope

From the aforementioned analysis, it can be seen that when the moisture content of the soil increases, its shear strength decreases greatly, which has a great influence on the stability of the slope. Infiltration depth can directly represent the infiltration range of the slope soil, and its size also determines the stability of the slope. Therefore, the infiltration depth of the slope can be considered as an index to judge the stability of the slope.

According to the safety code of slope engineering, when the stability coefficient of slope is less than 1.05, the slope can be judged to be unstable and prone to landslide disaster. Previous analysis indicated that the required infiltration depth for slope landslides is different under different slope angles. Slopes with larger slope angles can also slide under smaller infiltration depths. Therefore, slopes with different slope angles are considered separately.

Based on the linear fitting results of infiltration depth and stability coefficient under different slope angles, the infiltration depth can be calculated when the stability coefficient of slope with different slope angles is the critical value of 1.05. The infiltration depth required for landslides is larger with smaller slope angle, but the opposite is true for steep slope, which is largely related to slope morphology. The infiltration depth required for slope landslide with different slope angles is illustrated in Figure 19.

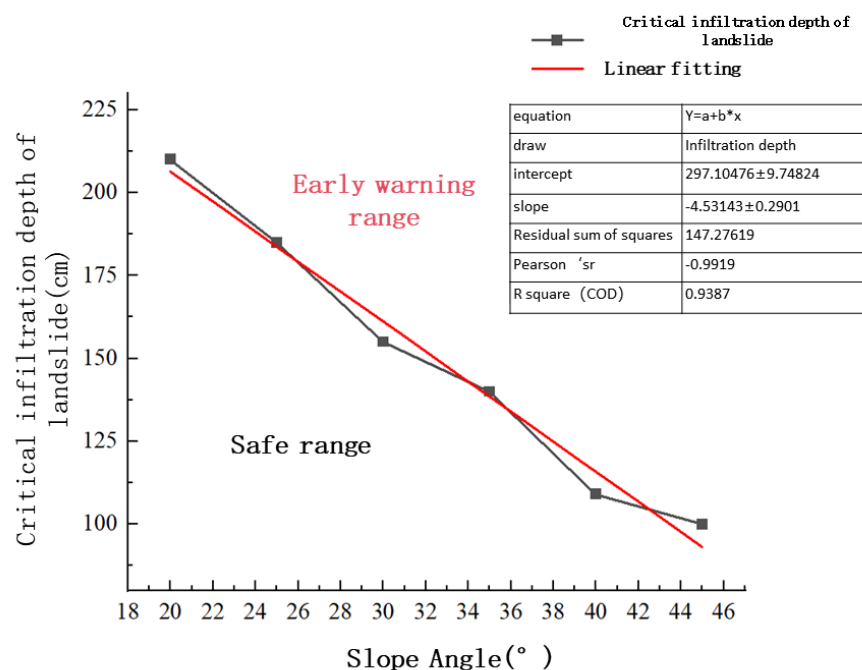


Figure 19. Critical value of infiltration depth when landslide occurs.

A linear relationship between the infiltration depth and the slope angle is found from Figure 16. In order to verify the validity of the method, one landslide occurred during the test was analyzed. Results suggest that the slope infiltration depth was within the warning range. This indicates that the method mentioned above was effective. The deeper the slope is, the more difficult the infiltration is, and the influence of the soil moisture content change on slope stability is different between surface and deep area. Considering the perspective of safety, the critical infiltration depth of landslide occurrence can be appropriately reduced to increase its warning range.

4.5. Limitations of This Study and Future Work

This study employed field rainfall tests and laboratory experiments on a Xiashu soil slope to investigate the infiltration process of Xiashu loess slopes under different rainfall intensities. The distribution of pore water pressure within the Xiashu soil slope under different rainfall intensities was analyzed, and the relationship between rainfall intensity and water content at different depths was clarified. A functional relationship among rainfall intensity conditions, slope angle, ultimate landslide depth, and critical rainfall intensity was proposed. Nevertheless, certain limitations remain.

The relationship reported between infiltration depth and landslide depth is based on only one observed failure event. Subsequent studies will conduct rainfall tests with multiple intensities to observe and verify previous findings.

The rainfall model tests on Xiashu loess adopted a single rainfall intensity of 60 mm/h, which makes it difficult to generalize the findings to real-world situations with wide variations in rainfall intensity. In the future, we will conduct rainfall model tests using a range of rainfall intensities to facilitate broader application of the research outcomes.

Moreover, some of the predictive models in this study may exhibit data variability. Future work will integrate the results of multiple tests to optimize the fitting of the predictive models.

5. Conclusions

This study provides new insight into the instability process of unsaturated Xiashu loess slope under different rainfall conditions. The main conclusions in the study are as follows:

1. The direct influence of rainfall infiltration on the unsaturated Xiashu loess slope is that the reduces of effective stress caused by the decrease of suction or the increase-ment of the pore water pressure in unsaturated Xiashu loess (especially the shallow soil) leads to the decrease of the shear strength, which is one of the main reasons for the instability of the Xiashu soil slope induced by rainfall.
2. The main composition of Xiashu soil is clay minerals, especially the existence of montmorillonite. The montmorillonite has some special properties such as swelling and shrinkage, hydrophilicity, easy cracking, and great change in strength, which can cause the changes in water content of Xiashu loess. The influence of water content on the properties of unsaturated Xiashu loess is one of the main factors that leads to the instability of slope after rain.
3. The result of monitoring data analysis and deformation characteristics of the on-site rainfall model shows that the infiltration of Xiashu loess soil depth is influenced by the rainfall duration, rainfall intensity, rainfall patterns, and the slope angle. The relationship between infiltration depth and each influencing factors is analyzed through different fitting models, which effectively reveals the instability scale of the Xiashu loess slope is not large, and the depth of the sliding surface is shallow.

4. Due to the influence of climate, cracks and fissures are often developed on the surface of Xiashu loess slope. As the convenient channels for rainfall infiltration, cracks are one of the controlling factors of the stability of the Xiashu loess slope. The cracks can reduce the overall strength of unsaturated soil by about 60–70% and mainly occur in the surface layer of the soil about 4.0 m deep, which is consistent with the actual situation that the saturation softening of the soil after rainfall is also mainly in the surface layer. It accords with the rule that the sliding of Xiashu soil slope is usually shallow, tractive, and lagging.

The findings of this study provide several practical guidelines for the stability assessment and risk prevention of Xiashu loess slopes under rainfall conditions. During rainfall, the infiltration rate, infiltration depth, and cumulative displacement at the toe of a Xiashu loess slope are greater than those at the top and middle of the slope. Therefore, field monitoring should be prioritized at the slope toe, where moisture content sensors and displacement gauges should be installed. This enables earlier detection of instability precursors compared to monitoring at the crest or mid-slope. The empirical equations relating infiltration depth to rainfall duration, rainfall intensity, and slope angle (Equations (1)–(3)) offer a simple tool for rapidly estimating the wetting front depth. Furthermore, the critical infiltration depth for landslide initiation proposed in this study can be directly used as a warning threshold for rainfall-induced landslides in Xiashu soil. When the monitored or predicted infiltration depth approaches the critical value corresponding to a given slope angle, preventive measures such as surface sealing, drainage enhancement, or temporary evacuation can be triggered.

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References

1. Hong, J.B.; Cao, Q.L. Q3 Study on overconsolidation characteristics of viscous soil in Xiashu Formation. *J. Jiangsu Agric. Coll.* **1996**, 95–97. (In Chinese)
2. Liu, J.G.; Lv, M.K. Engineering geological characteristics of Xiashu soil in Nanjing. *Surv. Sci. Technol.* **1996**, 36–38.
3. Xia, J.; Liu, Z.T.; Chen, X.M. Study on heterogeneity of Xiashu loess in Nanjing. *J. Eng. Geol.* **2001**, 253–257.
4. Hu, Y. Feasibility study on Xiashu loess as landfill liner. *West. Explor. Eng.* **2005**, 220–222.

5. Li, J. Research on Regional Prediction and Prediction of Xiashu soil Landslide in Ningzhen Area. Doctoral Dissertation, Hohai University, Nanjing, China, 2007. (In Chinese)
6. Miao, Y.H.; Zhang, L.X. Discussion on the bearing capacity of Xiashu loess in Zhenjiang area. *Eng. Surv. Investig.* **2007**, *16*, 16–19.
7. Han, A.; Qiao, C.; Ding, C. Study on structural strength of Xiashu soil in Nanjing. *J. Eng. Geol.* **2009**, *17*, 371–376.
8. Ding, C.Y.; Han, A.M.; Wu, N.; Qiao, C. Study on microstructure and deformation characteristics of Xiashu soil in Nanjing. *West. Prospect. Eng.* **2009**, *21*, 1–3+7. (In Chinese)
9. Zeng, F.W. Study on the difference of physical and mechanical properties of Xiashu soil in Nanjing area. *Highw. Eng.* **2010**, *35*, 104–106.
10. Sun, S.; Wang, W.; Wei, J.; Song, J.; Yu, Y.; He, W.; Zhang, J. The physical–mechanical properties degradation mechanism and microstructure response of acid–alkali-contaminated Xiashu loess. *Nat. Hazards* **2021**, *106*, 2845–2861.
11. Han, A.M.; Li, T.; Zhang, L.; Xu, H. Experimental study on soil water sensitivity in Xiashu, Nanjing. *J. Nanjing Univ. Technol. (Nat. Sci. Ed.)* **2015**, *37*, 81–86.
12. Shi, W.; Wei, J.H.; Song, J.L.; Le, H.L.; Gao, X.B. Effect of water content on shear strength of Xiashu soil. *J. Southeast. Univ. Nat. Sci. Ed.* **2016**, *35*, 97–101.
13. Wang, Y.L.; Liu, S.Q.; Jiang, P.M. Experimental study on the influence of water content and suction on the strength characteristics of unsaturated Xiashu soil. *J. China Three Gorges Univ. (Nat. Sci. Ed.)* **2020**, *42*, 48–52.
14. Hu, Y.; Sun, S.; Li, K. Study on influence of moisture content on strength and brittle-plastic failure characteristics of Xiashu loess. *Adv. Civ. Eng.* **2023**, *1*, 5919325.
15. Liu, S.Q.; Wang, Y.L.; Cai, G.J.; Jiang, P.M.; Wang, J.; Zhang, M. Experimental study on effects of dry and wet cycling and suction on mechanical properties of unsaturated Xiashu soil. *J. Southeast Univ. (Nat. Sci. Ed.)* **2019**, *51*, 473–479.
16. Wang, Q.; Lai, J.; Li, Y. Comparative analysis of Green-Ampt model and Philip infiltration model. *Trans. Chin. Soc. Agric. Eng.* **2002**, *2*, 13–16.
17. Baiamonte, G. Analytical Solution of the Richards Equation under Gravity Driven Infiltration and Constant Rainfall Intensity. *J. Hydrol. Eng.* **2020**, *25*, 04020031. [https://doi.org/10.1061/\(asce\)he.1943-5584.0001933](https://doi.org/10.1061/(asce)he.1943-5584.0001933).
18. Wang, W.; Wang, Z.; Wang, Q.; Zhang, J. Improvement and verification of Green-AMPT infiltration model in loess. *J. Hydraul. Eng.* **2003**, *34*, 30–34.
19. Guo, X.; Sun, X.; Ma, J.; Bi, Y. Green-Ampt model under different infiltration head conditions. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 64–68.
20. Chen, L.; Young, M.H. Green-Ampt infiltration model for sloping surfaces. *Water Resour. Res.* **2006**, *42*, 887–896.
21. Almedeij, J.; Esen, I.I. Modified Green-Ampt infiltration model for steady rainfall. *J. Hydrol. Eng.* **2014**, *19*, 04014011.
22. Zhang, T.; Zhang, Z.; Xu, C.; Hao, R.; Lv, Q.; Jia, J.; Liang, S.; Zhu, H. Destabilization Mechanism of Rainfall-Induced Loess Landslides in the Kara Haisu Gully, Xinyuan County, Ili River Valley, China: Physical Simulation. *Water* **2023**, *15*, 3775.
23. Zhong, W.; Zhu, Y.; He, N. Physical Model Study of an intermittent rainfall-induced gently dipping accumulation landslide. *Water* **2022**, *14*, 1770.
24. Bai, W.; Li, R.; Pan, J.; Li, R.; Wang, L.; Yang, Z. Measured Rainfall Infiltration and the Infiltration Interface Effect on Double-Layer Loess Slope. *Water* **2023**, *15*, 2505.
25. Guo, Z.; Jian, W.; Liu, Q.; Nie, W. Rainfall infiltration analysis and infiltration model of slope based on in-situ tests. *Rock Soil Mech.* **2021**, *42*, 8.
26. Tu, X.B.; Kwong, A.K.L.; Dai, F.C.; Tham, L.G.; Min, H. Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides. *Eng. Geol.* **2009**, *105*, 134–150.
27. Huang, J.; Wu, P.; Zhao, X. Effects of rainfall intensity, underlying surface and slope gradient on soil infiltration under simulated rainfall experiments. *Catena* **2013**, *104*, 93–102. <https://doi.org/10.1016/j.catena.2012.10.013>.
28. Guan, X.; Li, R.; Zhang, S.; Zeng, C.; Bai, W. Study on rainfall infiltration of loess slope under different rainfall intensity and slope ratio. *Yellow River* **2022**, *44*, 106–111.
29. Chen, L.; Bai, S. A test study on the comparably similar material ratio of rock blasting inclination of brittle rock body. *J. Petrol. Geophys.* **2006**, *27*, 1050–1054.
30. Guan, X.D.; Li, R.J.; Pan, J.Y.; Sun, P.; Yao, Y.F. Testing and comparison of heavy rainfall infiltration of loess slope at different slope ratios. *J. Xi'an Univ. Technol.* **2021**, *37*, 286–294.
31. Chen, L.W.; Zhang, X.C.; Pei, X.J.; Zhang, S.; Gong, W.X.; Zhong, Y.J. Model test of the linear loess fill slope instability induced by rainfall. *Hydrogeol. Eng. Geol.* **2021**, *48*, 151–160.

32. Yu, D.J.; Huang, Q.B.; Kang, X.S.; Chen, X.; Liu, Y. A model test study of the interface seepage and failure mechanism of loess-filled slope. *Hydrogeol. Eng. Geol.* **2022**, *49*, 119–128.
33. Jiang, Y.F.; Li, J.K. Study on the instability mechanism of loess slope under different rainfall intensities and slope angles. *Chin. J. Geol. Hazard. Control* **2025**, *36*, 48–63.
34. Zhong, P.W.; Zhang, H.L.; Tian, K.L.; Chen, H.; Nie, K.Y. Study on the Influence of Continuous Rainfall Infiltration on the Loess Slope Stability. *Yellow River* **2018**, *40*, 76–81.
35. Cui, X.C.; Luo, Y.S.; Qing, H.T.; Wei, Y.L.; Zhao, L.F.; Chen, W.; Wu, C.P. Erosion mechanism of loess slope failure induced by heavy rainfall. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2025**, *41*, 173–182.
36. Pan, J.Y.; Hou, D.Y.; Li, R.J.; Zhu, Q.C.; Wei, Y.Q.; Zhang, Z. Rainfall infiltration test and analysis of loess slope under different rainfall intensities. *J. Eng. Geol.* **2018**, *26*, 1170–1177.

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