THE IMPACT OF ANTECEDENT MOISTURE CONTENT ON SLOPE EROSION IN DISPERSIVE SOILS IN THE WESTERN JILIN REGION, CHINA

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Abstract. Dispersive soils are highly sensitive to moisture content, and its particles are prone to hydraulic erosion and scouring. The objective of this study is to determine the impact of antecedent moisture content on the erosion of dispersive soils in the Zhenlai area and establish erosion characteristics. The soil samples were collected from the Zhenlai area in the western part of Jilin Province, China. The erodibility was assessed at five different antecedent moisture content levels (with a 2% increment) by simulating rainfall in a laboratory setting on small-scale slopes. The results indicate that there are significant differences in erosion characteristics among slopes with different antecedent moisture content levels. The sediment yield from slopes with antecedent moisture content above the optimum moisture content is 60% lower compared to slopes with moisture content below the optimum moisture content. The optimum moisture content was served as a clear erosion threshold. When introducing the soil parameter of matric suction, it was found that it effectively characterizes the sensitivity of dispersive soils in this area to variations in antecedent moisture content and their impact on slope erosion.
Keywords: *rainfall simulation, optimum moisture content, sediment yield, matric suction*

Introduction

Soil erosion during rainfall is a complex phenomenon involving the separation of soil particles and the transport and output of sediment (Ellison, 1945; Pieri et al., 2009; Warrington et al., 2009). The process of soil erosion is influenced by numerous factors, including rainfall characteristics, soil properties (such as soil moisture, roughness, slope, and crop residue), and surface conditions (Angulo-Martínez et al., 2012; Bradford and Foster, 1996; Chaplot and Le Bissonnais, 2003; Kinnell, 1993; Mahmoodabadi and Sajjadi, 2016; Qiu et al., 2022; Ramos et al., 2000). In addition to the aforementioned factors, the physical parameters of the soil also play a crucial role in water erosion. Wischmeier and Smith (1978) noted that particle size distribution and organic matter content are the primary indicators of soil erosivity. Norton et al. (1998) summarized previous research and concluded that clay mineral content, soluble salt content, and antecedent moisture content ϑ_a have a significant impact on soil erosion.

In soil erosion studies, there has been extensive research on the impact of rainfall and soil properties, and the conclusions have been relatively consistent (Mitchell and Soga, 2005; Singer and Le Bissonnais, 1998; Wischmeier and Smith, 1978; Zambon et al.,

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2021). However, the antecedent moisture content has conflicting effects on runoff generation and soil erosion and scouring (Augeard et al., 2008; Norton et al., 1998; Sachs and Sarah, 2017). Indeed, a considerable amount of research has put forward different conclusions on this matter. Govers and Loch (1993) conducted erosion experiments on clay soils in eastern Queensland and found that higher antecedent moisture content resulted in greater erosion resistance in clay soils. In a study conducted by Yi and Fan (2016) on loess slopes in Shaanxi, China, rainfall erosion experiments were carried out. The results indicated that higher antecedent moisture content in loess led to greater erosion. Different erosion characteristics were exhibited by antecedent moisture content in various soil types.

Dispersive soils exhibit a notable susceptibility to erosion, characterized by the autonomous detachment and suspension of soil particles upon contact with water. (Mitchell and Soga, 2005; Yong and Sethi, 1977). As a result, this unstable structure makes the soil highly susceptible to erosion, leading to numerous incidents worldwide caused. Dams constructed with dispersive soils are highly susceptible to hydraulic erosion, often resulting in catastrophic accidents (Fan and Kong, 2013; Parameswaran and Sivapullaiah, 2017). The presence of dispersive soils also affects soil-cement dams, roads, and geological and environmental structures (Goodarzi and Salimi, 2015; Gutiérrez et al., 2003; Nevels Jr, 1993; Ouhadi and Goodarzi, 2006). However, there is limited research specifically focused on the rainfall erosion aspects of dispersive soils. When dispersive soils are exposed and subjected to raindrop impact, the rapid wetting of soil particles and the lack of cohesion in aggregates can exacerbate soil disintegration (Qadir and Schubert, 2002). This disintegration can affect soil permeability, runoff, and erosion development (Moore and Singer, 1990; Singer and Le Bissonnais, 1998; So and Aylmore, 1993). However, these conclusions are often derived from experiments conducted under multifactorial conditions. There is limited research on the net effect of soil slope dispersion characteristics on runoff and erosion under different antecedent moisture content conditions. The soil samples used in this study were obtained from the Zhenlai area in Jilin, which is characterized by high soil dispersivity (Kong, 2017). Consequently, the region has been experiencing persistent erosion and soil degradation, resulting in severe ecological damage (Han et al., 2018).

Considering that both rainfall intensity and duration are crucial factors controlling soil erosion rates (Mahmoodabadi and Sajjadi, 2016; Mermut et al., 1997; Park et al., 1983). Therefore, this study conducted indoor rainfall experiments on dispersive soils in the western region of Jilin Province, employing a controlled variable approach to investigate the impact of different initial moisture content on the erosion of dispersive soils. This study places special emphasis on (i) determining the net effect of soil dispersion characteristics on erosion development, (ii) assessing the influence of changes in antecedent moisture content on the erosion of dispersive soils, and (iii) if there is an impact, analyzing the underlying reasons and mechanisms behind it.

Materials and methods

Site description and soil sampling

The study area is located in Zhenlai County, western Jilin Province, China. Zhenlai County is situated on the western edge of the Songnen Plain. To the north, it connects with the periphery of the Da Hinggan Mountains Plateau. In the central part, the terrain is characterized by rolling hills and ridges, while the eastern and southern parts consist

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of extensive alluvial plains. The elevation ranges from 129 m to 149 m above sea level. The study area enjoys abundant solar radiation resources, with an average annual sunshine duration of approximately 2898.5 h. The annual precipitation is around 402 mm, and Zhenlai County experiences a continental monsoon climate with significant evaporation and relatively low rainfall. The region has a forested area of 713,800 acres, with a forest coverage rate of 10.1% (Chen et al., 2019; Zhang et al., 2021). More information about local soil characteristics and the characteristics of natural disasters can be obtained from Han et al. (2018) as well as data published by the local government. Soil samples for this study were collected from a representative saline-alkali area in the northern part of Zhenlai County, with coordinates at N45°59’41.61”, E123°13’46.81”. To investigate the consistency of soil physicochemical characteristics at the sampling location, three soil pits were excavated at 10-m intervals. Each soil pit had a cross-sectional area of approximately 0.3 m^3 and a depth of about 1.5 m. Soil was excavated vertically from the surface using a spade, and samples were collected in 10 cm increments along the profile. Due to the severe erosion and washing of the land surface in the soil collection area, the particle composition of the soil surface has been significantly damaged. Additionally, it was found that within a certain range the near-surface, the physico-chemical properties and particle composition of the soil are similar (Kong, 2017; Zhang et al., 2021). Therefore, under comprehensive consideration, soil samples were collected from a depth of 20 cm to 40 cm for this experiment.

Identification of soil dispersion

The soil samples used in this experiment were collected from the Zhenlai area in Jilin, with a depth of 20-40 cm underground. The soil samples gathered from the field were transported to the laboratory and uniformly mixed. Subsequently, the mixed soil samples were divided into three groups, designated as Soil Sample 1, Soil Sample 2, and Soil Sample 3. These three groups were then subjected to dispersive soil identification using methods such as the pinhole test and the hydrometer method, as recommended by the American Society for Testing and Materials (ASTM).

The pinhole test is the most direct and relatively reliable method in the identification of dispersive soils. Its principle involves simulating the soil’s resistance to erosion under the influence of a certain percolating water flow. Under the influence of a 50 mm water head, the three groups of soil samples were subjected to a 5-min duration of the pinhole test. The water flow passing through the pinhole ranged from 300 ml to 420 ml, resulting in final soil sample erosion hole diameters falling between 2 mm and 4 mm (as shown in *Fig. 1*). Based on the turbidity of the water solution and the size of the erosion holes after the pinhole test, a comprehensive assessment was made to determine the dispersive characteristics, and the results are summarized in *Table 1*.

To conduct a double hydrometer test on the three groups of soil samples, the following process was followed: 30 g of each sample was taken from different groups and placed into a filter bottle containing distilled water. The bottle was ventilated for 10 min, and the solution was then drained into a volumetric flask, which was filled to 1000 ml without adding a dispersant (static water sedimentation test). Secondly, 30 g of each sample was taken from the same groups and placed into a flask containing 100 ml of distilled water. The flask was mixed well and left to stand for 18 h before being boiled for 1 h. The solution was then drained into a volumetric flask, filled to 1000 ml with distilled water, and mixed well. 10 ml of dispersant, Sodium hexametaphosphate,

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was added to the resulting solution, which was then subjected to static water sedimentation testing. The particle size distribution curves for the final soil samples are shown in *Figure 2*. In the figure, the curves labeled with a plus sign (+) represent the particle size distribution curves after adding a dispersant. Based on the particle size distribution curves, the dispersivity of each group of soil samples was calculated. As indicated in *Table 2,* the dispersivity of all the soil samples in each group is greater than 50%. Therefore, it can be concluded that all the tested soil samples are dispersive soils.

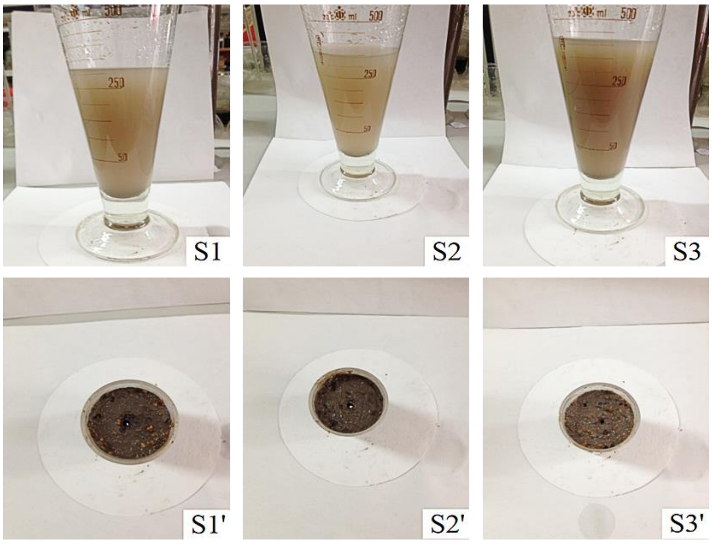

Figure 1. *Turbidity of water flow and pinhole size after pinhole test; S1-S3 are turbidity degrees of different soil samples; S1'-S3' are the pinhole sizes of different soil samples*

Table 1. *Results of the integrated determination of soil sample dispersion*

Sample	Turbidity of aqueous solution	Pore size after erosion (mm)	Results
1	Very cloudy	3～4	Dispersive soil
2	More cloudy	2～3	Dispersive soil
3	More cloudy	2～3	Dispersive soil

Table 2. *Comprehensive judgment results*

Sample	Clay particle content without dispersant	Clay particle content added dispersant	Dispersion	Soil sample dispersion
1	40.35	45.59	88.51	Dispersive soil
2	39.31	42.45	92.60	Dispersive soil
3	42.45	47.69	89.01	Dispersive soil

Physicochemical properties of soil

Norton et al. (1998) conducted a comprehensive review of factors influencing soil erosion and summarized them, which can be attributed to properties such as clay mineral nature, exchangeable cations, soil pH, moisture content, and organic matter

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content. The collected samples were air-dried, crushed, sieved and evenly mixed. The particle size distribution of the soil samples and other fundamental geotechnical tests were conducted using sieving and hydrometer methods. The results are presented in *Tables 3* and *4*. According to the World Reference Base for Soil Resources (WRB) system as of 2015, soils can be classified into Sodic Solonca.

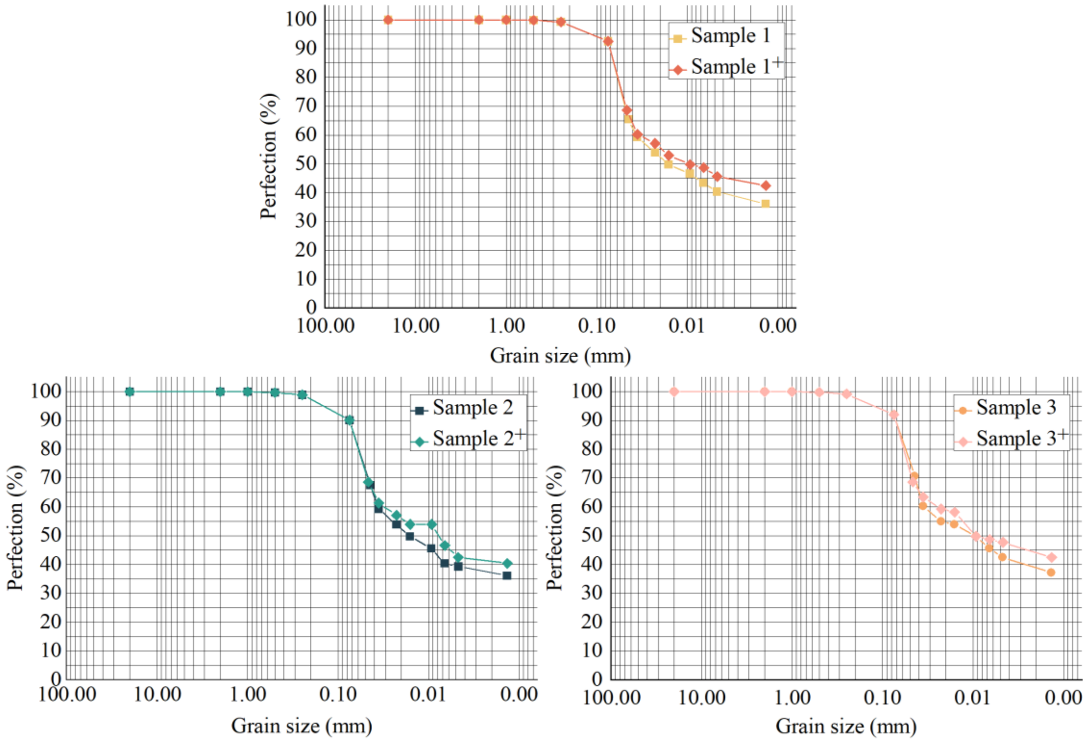

Figure 2. *Particle size distribution curve of soil samples*

Table 3. *Particle size distribution of soil sample*

Granular group (mm)	Percent (%)
> 2	0
2-0.75	8.48
0.075-0.005	50.82
0.005-0.002	4.19
< 0.002	36.51

In the Zhenlai area, the soil typically contains a relatively low proportion of coarse particles. The soil particles are primarily composed of silt particles in the range of 0.075 to 0.005 mm and clay particles smaller than 0.002 mm. Both silt and clay particles have poor permeability and possess a high specific surface area, making the soil properties susceptible to changes in moisture content. In *Table 4*, the total soluble salt content accounts for 0.417%, with Na^+ comprising 0.10% of the chemical composition of the soil samples. The Na^+ ion content indeed plays a crucial role in the dispersivity of the soil. Na^+ ions adsorb on the surface of clay particles. Since water molecules are polar molecules and easily polarized, the adsorption of Na^+ ions results in the binding of a

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significant number of water molecules. This leads to an increase in the thickness of the diffuse layer in the double electric layer, causing repulsion forces to exceed attraction forces. Ultimately, this results in soil particles being suspended in the solution, giving rise to the highly dispersive characteristics of the soil (McElroy, 1987).

The $Ca2^+$ ion content and the content of other iron and aluminum oxides in the soil samples are relatively low compared to the Na^+ ion content. Based on previous research in the Zhenlai area, it has been observed that the organic matter content in the soil is also relatively low. However, the presence of these substances can have a significant impact on inhibiting the dispersion of soil particles and the aggregation of colloidal particles (Churchman et al., 1993).

These physicochemical characteristics of the soil samples make the soil in this region highly dispersive. Thus, the land in this region is continually subjected to erosion throughout the year, resulting in severe damage to the ecosystem and significant soil degradation (Kong, 2017).

Table 4. *Physicochemical properties of soil*

Item			Content	Tast/calculation method
Physical	Natural density		1.64 g/cm^3	Pycnometer
	Natural water content		16.3%	Drying method
	Optimum water content		20%	Compaction test
	Liquid limit		31.5%	Liquid-plastic combine tester
	Plastic limit		23.5%	
	Plastic limit index		7.9	$\omega_L - \omega_p$
	Liquid limit index		-1.21	$(\omega - \omega_p)/(\omega_L - \omega_p)$
Chemical	CEC		6.5 mmol/100 g	EDTA-NH_4OAc method
	PH		8.7	Potentiometry
	Organic content		0.23%	Potassium dichromate titration
	Total soluble salts		0.445%	Water-bath evaporation
	Ion components	Na^+	0.121%	Flame photometer
		K^+	0.002%	
		Ca^{2+}	0.008%	EDTA complexometric titration
		Mg^{2+}	0.008%	
		$SO4^{2-}$	0.015%	
		Cl^-	0.015%	$AgNO_3$ titration
		HCO^{3-}	0.199%	Neutralisation titration

Rainfall test design

To investigate the impact of antecedent moisture content on slope soil erosion, the mixed soil samples with natural moisture content were dried in an oven at 105°C and then crushed through a 2-mm sieve. Subsequently, the air-dried soil was mixed with deionized water to prepare soil samples with moisture contents of 16%, 18%, 20%, 22%, and 24%. Small-scale slopes were constructed with a height of 40 cm, a width of 48 cm, and a slope angle of 40°.

Artificial rainfall simulation experiments were conducted with five different moisture content groups: 16%, 18%, 20%, 22%, and 24%. It was determined that the optimum

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moisture content for the soil was 20% based on Proctor compaction test. The decision to conduct the slope soil moisture content experiments with a 2% incremental increase was based on the following assumptions: dispersive soils have a tendency to disperse when they come into contact with water, and they exhibit poor stability and erosion resistance. Additionally, they are more sensitive to changes in electrolyte concentration than typical soils. Therefore, the small incremental moisture content changes were selected for the experiments to better observe the impact of moisture content variations on the erosion of dispersive slope soils.

To simulate the impact of antecedent water content on a slope with dispersion, indoor simulation rainfall experiments were conducted. The experimental equipment included: (1) a storage pond, (2) a siphon pump, (3) a pressure gauge, (4) a rainfall nozzle, (5) a slope, (6) a model box (with a length of 107 cm, a width of 48 cm, and a height of 46 cm), (7) a sediment pond, and 8) a high-definition camera. In order to simulate actual conditions, many holes were opened on the bottom of the model box to prevent the saturation of the slope soil and to avoid affecting the experiment.

This study imposed the following limitations: (1) To mitigate the influence of varying rainfall intensities in model experiments, six beakers were evenly placed in the model box before each slope experiment. Ten 10-min rainfall tests were conducted to achieve a rainfall uniformity of 80% or higher before proceeding with the actual experiment. The uniformity of one of the slope rainfall experiments is presented in *Figure 3*. (2) Each rainfall event had a duration of 60 min with an intensity of 20 mm/h, which was based on local moderate rainfall conditions determined by the local government meteorological department. (3) The salt content in the test soil samples was maintained at their natural levels, and degree of compaction of the soil was set to 90%. (4) A high-definition camera was positioned in front of the rainfall simulation model box to capture the entire process of artificial rainfall erosion for each experimental group.

To distinguish between the moisture content test groups, this study used the 20% moisture content (optimum moisture content) as the dividing line. Moisture contents of 16% and 18% were referred to as lower ϑ_a, while moisture contents of 22% and 24% were referred to as higher ϑ_a.

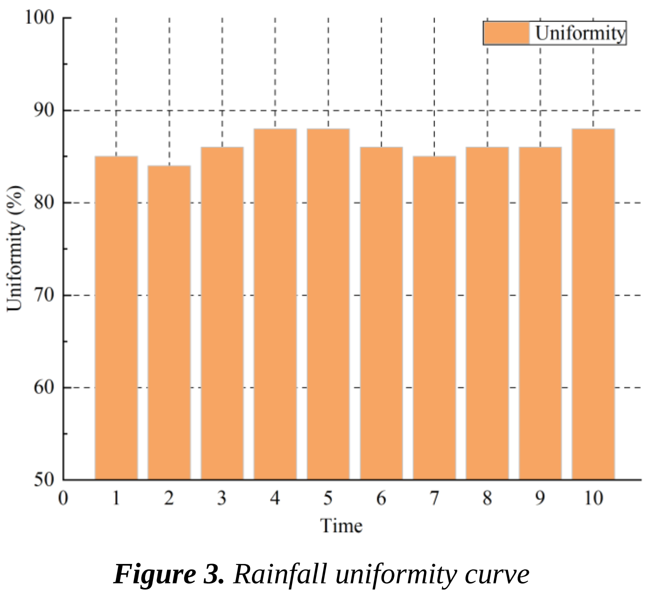

Figure 3. *Rainfall uniformity curve*

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Soil-water characteristic curve

Dispersive soils are highly sensitive to water, and this study was conducted in five groups, with moisture content incrementing by 2% in each experiment. To better analyze the impact of subtle changes in moisture content on soil erosion, the soil-water characteristic curve was employed to analyze slope erosion under different antecedent moisture content conditions. To measure matric suction, the contact filter paper method was used, and the calibration equation for this method is as follows (Wang et al., 2003):

$$\begin{aligned} log(u_a - u_\omega) &= 5.493 - 0.0767\omega_f(\omega_f \leq 47\%) \\ log(u_a - u_\omega) &= 2.470 - 0.0120\omega_f(\omega_f > 47\%) \end{aligned} \quad \text{(Eq.1)}$$

where: $(u_a - u_\omega)$ represents matric suction (kPa); ω_f represents the filter paper moisture content (%).

Statistical analysis

In avoiding the effects of different rainfall intensities in the modeling tests, the rainfall uniformity at each location of the model box was ensured to be above 80% before each rainfall test. The Christiansen uniformity coefficient was introduced to describe the sum of the absolute values of the deviations of the rainfall from the mean rainfall at each measurement point. The Christiansen uniformity coefficient is a statistic based on the mean deviation, which can visualize the degree of deviation of the measured parameter from the mean. Its formula is given below (Christiansen, 1942):

$$CU = (1 - \frac{\sum_{i=1}^{n} S_i |h_i - \bar{h}|}{\sum_{i=1}^{n} S_i h_i}) \times 100 \quad \text{(Eq.2)}$$

where: CU is Christiansen uniformity coefficient (%); h_i is depth of precipitation at a given point (mm); $\bar{h}$ is average depth of precipitation at each measurement point on the sprayed area (mm); S_i is sprayed area represented by a given point (m^2); n is number of points of rain barrels subjected to rainfall.

Linear regression analysis was employed to investigate the relationship between matric suction and sediment yield or water flow. The goodness of fit of the data was assessed using the coefficient of determination, R-squared (R^2), indicating the degree of fit. Additionally, Pearson correlation coefficient ($|\rho|$) was utilized to determine the linear relationship between parameters. And, a linear expression was derived to represent the fitted relationship.

Results

Early stage of rainfall erosion (0-5 min)

As shown in *Figure 4*, during the “raindrop splash” stage (5 min), all five groups of slope soil were dispersed into primary particles under the impact of raindrops and carried away by the water flow. When ϑ_a is relatively small, small streams form on the slope surface, and the slope surface is uneven with some small erosion pits left by the impact of raindrops; When ϑ_a is relatively large, the slope soil surface appears to be

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muddy and viscous. Many small streams can be observed flowing along the slope surface, and the slope surface is relatively regular, with fewer small erosion pits forming. In general, with the increase in antecedent moisture content, the slope surface gradually transitions from a wet state to a muddy state, and the mechanical impact of raindrops also weakens. It is worth noting that the higher the antecedent moisture content of the slope, the more slurry dispersed by soil particles is generated on slope surface due to rainfall.

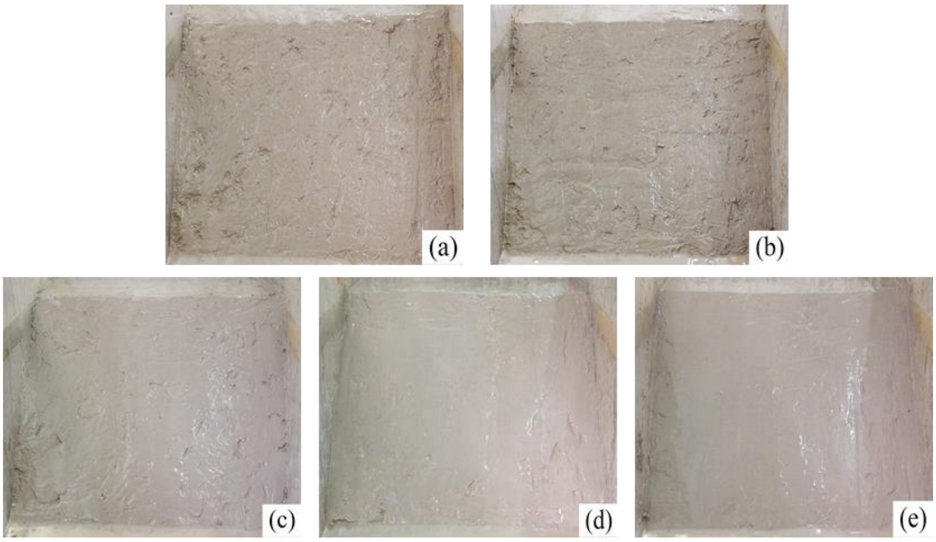

Figure 4. *Late stages of raindrop splash erosion on dispersive soil slopes with different antecedent water contents (5 min); (a) 16% moisture content; (b) 18% moisture content; (c) 20% moisture content; (d) 22% moisture content; (e) 24% moisture content*

Development stage of rainfall erosion

As shown in *Figure 5a* and *b*, when ϑ_a is lower, the slope surface forms more erosion pits under the impact of raindrops, and raindrops gather into small runoff, gradually eroding the surface particles of the slope. When the rainfall continues for 30 min, the slope surface is left with uneven erosion pits and the gullys formed by runoff erosion. The slope with 18% moisture content exhibits a tendency of reduced erosion compared to the slope with 16% moisture content.

As shown in *Figure 5c*, *d*, and *e*, when ϑ_a is at its optimum moisture content and higher, a significant amount of slurry is formed on the slope surface during the early stage of rainfall (0-5 min). This slurry is continuously eroded by raindrops and water flow, gradually being washed away. Eventually, the surface of the slope becomes smoother with no noticeable erosion pits. With the increase in ϑ_a, the surface of the slope becomes even smoother.

Slope erosion under different antecedent moisture content (Rainfall termination phase- 60th min)

As shown in *Figure 6*, with the increase in ϑ_a, the erosion on the slope surface gradually weakens. When ϑ_a is relatively low, the slope surface is noticeably uneven, with many irregular erosion pits. There are many small, narrow grooves on the slope surface that branch, merge, and connect, eventually converging into small gullies at the

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foot of the slope. Many erosion pits can also be seen to disperse into primary small particles. Compared to the 16% moisture content slope, the 18% moisture content slope exhibits many irregular, small, narrow grooves, but these grooves are shallower and narrower. There are no significant deep gullies at the base of the slope.

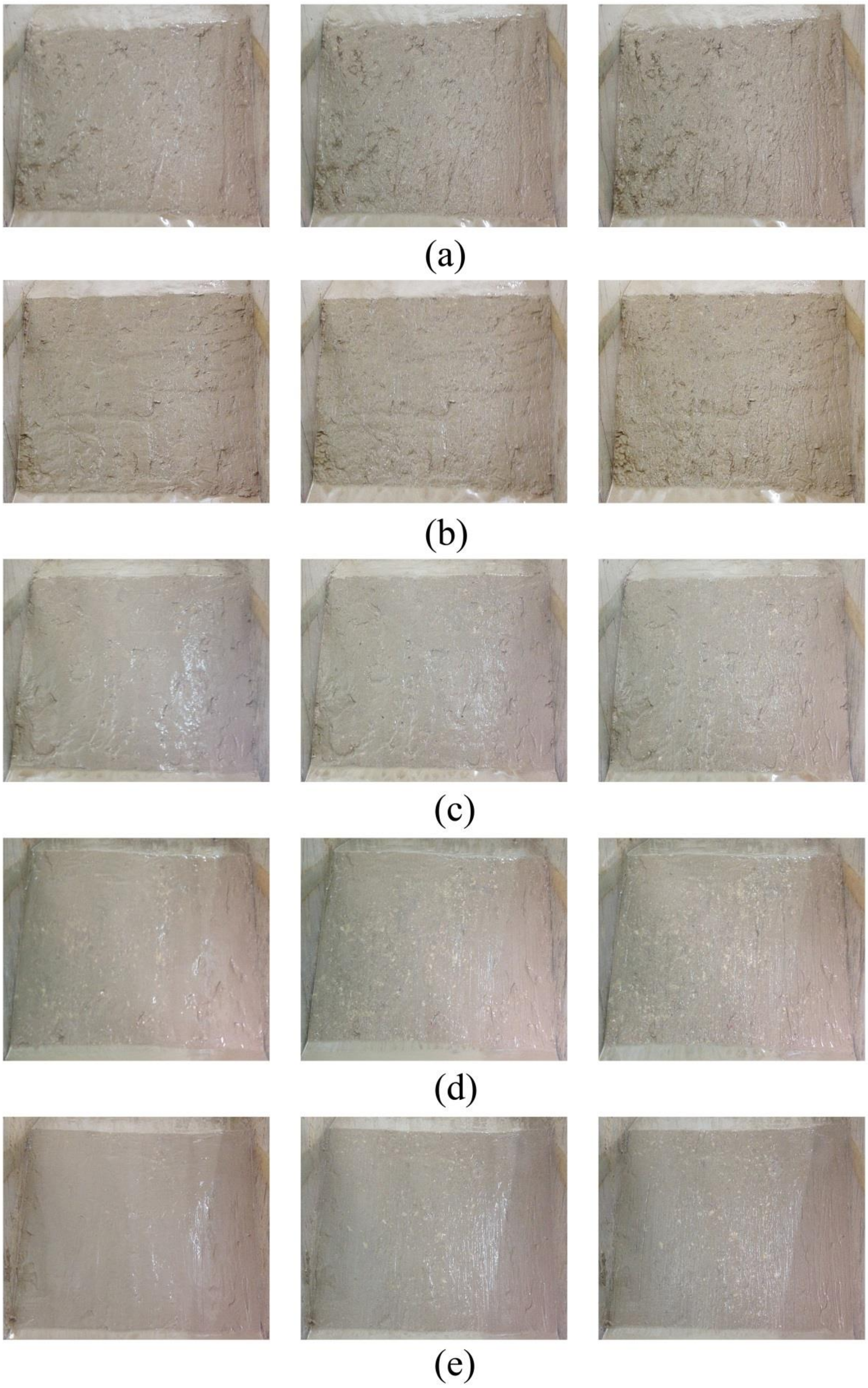

Figure 5. *Erosion development stages under different antecedent moisture content. (a) 16% moisture content; (b) 18% moisture content; (c) 20% moisture content; (d) 22% moisture content; (e) 24% moisture content*

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At the optimum moisture content (20%), the slope surface is smooth and relatively even, with only slight, isolated small grooves. But there are no branching, merging, or continuous grooves on the slope, and there are no small gullies forming at the base of the slope. The erosion resistance is better in this condition. When ϑ_a is relatively high, the slope surface is relatively smooth and structurally intact, with no apparent small erosion pits, and the base of the slope remains unaffected by erosion. There are only traces of vertical water flow on the slope surface. Overall, using the optimum moisture content as the erosion boundary, the five groups of samples exhibit distinct erosion characteristics.

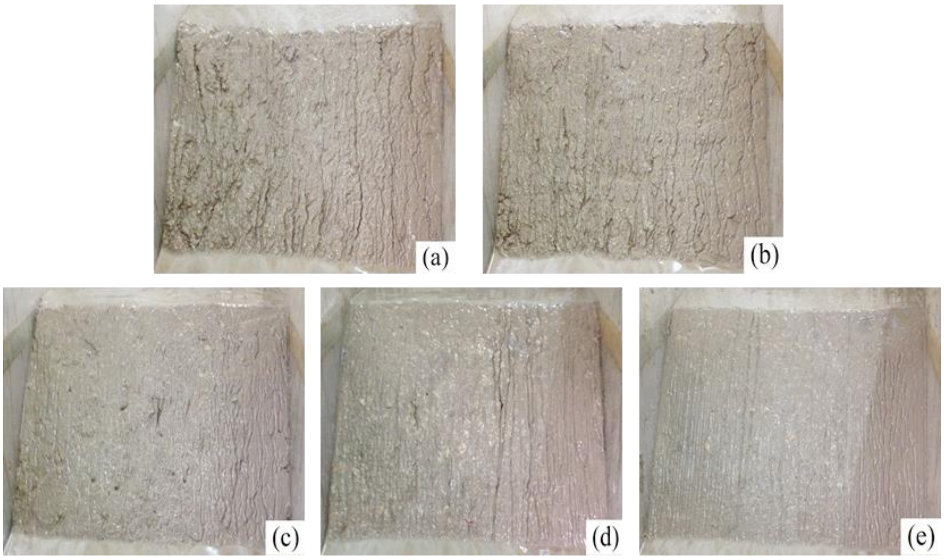

Figure 6. *Erosion of slopes with 16%, 18%, 20%, 22% and 24% in the antecedent moisture content; (a) 16% moisture content; (b) 18% moisture content; (c) 20% moisture content; (d) 22% moisture content; (e) 24% moisture content*

Sediment yield and flow

Under rainfall conditions, the sediment yield of the slope soil is an important indicator of soil erosion (Pandey et al., 2016; Walling and Webb, 1996). To quantitatively analyze the erosion of slope soil under rainfall, the sediment yield and flow rate of the slope soil with different initial moisture contents were measured and are shown in *Figure 7*; As the antecedent moisture content increases, the sediment yield of the slope soil decreases. The sediment yield for the 16% moisture content slope is 6.18 dkg, and for the 18% moisture content slope, it is 5.08 kg, representing a decrease of 17.8%. When the antecedent moisture content is at the optimum moisture content (20%), the sediment yield sharply decreases, with a sediment yield of 3.21 kg. This represents a nearly 50% reduction in sediment yield compared to the 16% moisture content slope. When the antecedent moisture content is highest (24%), the sediment yield continues to decrease, but the reduction is less pronounced, with a 4.20 kg decrease in sediment yield compared to the 16% moisture content slope, which represents a 67% reduction. The total water flow generally decreases with an increase in the antecedent moisture content. There is an overall increasing trend in water flow from ϑ_a values between 16% and 22%, but when the slope soil's antecedent moisture content goes from 22% to 24%, the increase in flow is minimal. In summary, the variation in ϑ_a significantly affects the sediment yield and flow rate of the slope samples. When A is at its optimum moisture content, there is a

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significant change in sediment yield and flow rate. A clear erosion threshold boundary is represented by the optimum moisture content.

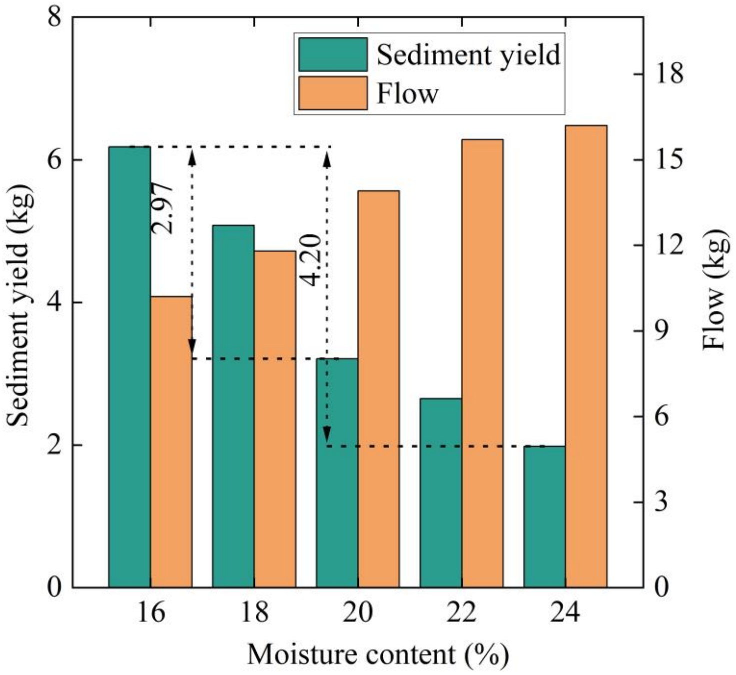

Figure 7. *Sediment yield and flow at different antecedent moisture content*

Mineral composition

The mineral composition of soil particles has a significant impact on soil erosion. Particle composition analysis before and after desalination of the soil samples, as well as X-ray diffraction (XRD) experiments, were conducted. As shown in *Figure 8*, clay mineral composition primarily consists of illite-smectite (I-S) mixed layers, accounting for more than half of the composition, while the content of illite and chlorite is relatively low. There are some minor primary minerals in the composition, which may be due to unavoidable errors during the Stokes extraction process. But clay minerals still dominate the composition.

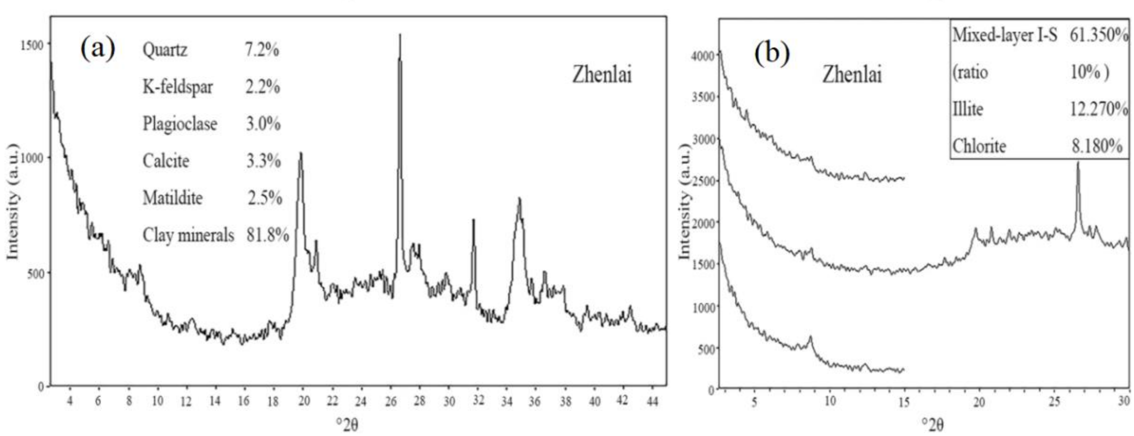

Figure 8. *XRD diffraction pattern of clay in dispersive soil in Zhenlai area*

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As shown in *Figure 9*, the test soil samples contain a significant amount of fine particles and colloids. Before desalination, the content of silt-sized particles exceeds 50%, and the colloid content is 36%. However, after desalination, the content of silt-sized particles decreases to 16%, while the colloid content increases to 44%.

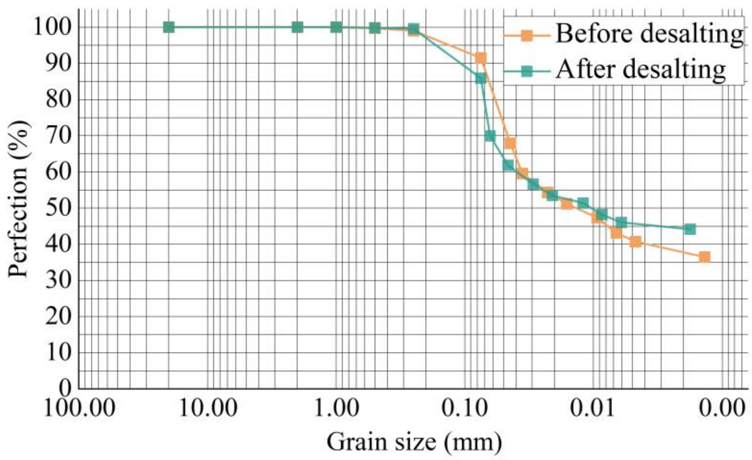

Figure 9. *Particle size composition of dispersive soils before and after desalting*

Discussion

Slope erosion characteristics

When ϑ_a is lower, the slope of the sample is heavily eroded. Although, in the early stages, there are mud-like soil particles on the slope and the soil particles have also undergone dispersion due to moisture. this type of moisture-induced dispersion is localized, and the thickness of the dispersed soil layer is relatively thin. It is insufficient to cover the pores in that layer as it flows down the slope. Therefore, when the surface mud is washed away by raindrops and water flow, the new surface layer of the slope undergoes further wetting, erosion, and dispersion. In this process of erosion, the surface of the slope gradually becomes uneven. This uneven structure leads to the formation of small streams on the slope during the middle stage of rainfall erosion, and small erosion pits gradually develop. As the rainfall continues, the flow on the slope increases, and the slope gradually transitions to the stage of developing rill erosion. So, when ϑ_a is lower, it is observed that at the foot of the slope, gullies are formed, along with intersecting small rills and uneven erosion pits.

When the slope's moisture content is at the optimal or higher levels, the slope surface is smooth and even, with no noticeable uneven erosion pits. The slope samples exhibit stronger erosion resistance. This is the slope tends to accumulate water earlier, resulting in a larger area of moistness and pooling on the slope. This leads to a rapid dispersion of the soil samples into their original particles over a large area. Subsequently, the stirring effect of water flow and raindrops turns the slope into mud. Under this effect, the dispersed slurry-like soil moves down the slope as a whole, obstructing the pores in that layer of soil (Gal et al., 1984; McIntyre, 1958). This restricts the infiltration of water and the detachment and transport of surface soil particles, ultimately leaving longitudinal water flow traces on the surface of the slope. Therefore, it is observed that when ϑ_a is higher than the optimal moisture content, the slope exhibits stronger erosion resistance.

The different moisture content levels result in varying erosion resistance characteristics in the slope of the samples. This primarily depends on whether the soil particles are significantly wet and dispersed before the onset of rainfall erosion, leading to the formation of a muddy soil surface. This muddy surface has a significant impact on the development of erosion in the slope samples and the formation of gullies. Liu et al. (2011) and Singer and Le Bissonnais (1998) have observed the formation of a sealing layer on certain soils. This sealing layer can reduce the soil's porosity and infiltration coefficient, significantly affecting the infiltration of rainfall into the soil. Unfortunately, this study did not monitor the presence of such sealing layers.

Relationship between matric suction and amount of erosion

As shown in *Figure 7*, there are significant differences in sediment yield and runoff on the soil slope with respect to the optimal moisture content, and the optimal moisture content can serve as a clear erosion threshold. Seguel and Horn (2006) found a strong linear relationship between matric suction and the erosion threshold. Deng et al. (2018) analyzed the relationship between matric suction and erosion and collapse in red soils. Assouline and Mualem (1997) developed a dynamic erosion model that mathematically expresses matric suction ψ through the initial soil shear strength $\tau(\rho, \psi)$, thus establishing an erosion threshold model for soil. In this section, we will explore the mechanism of the optimal moisture content as the erosion threshold for soil samples and analyze the relationship between matrix suction and erosion.

As shown in *Figure 10a*, with the decrease in moisture content, matric suction gradually decreases. The logarithmic coordinates of matric suction are plotted against the final water flow and sediment yield to create a scatter plot, followed by fitting, as shown in *Figure 10b*. The four fitted curves are labeled as a, b, c, and d. The mathematical expressions, R^2 values, and correlation coefficients of the curves are listed in *Table 5*. It can be observed that R^2 for all three curves is very high, with correlation coefficients above 0.95, indicating a strong relationship between matric suction and the final water flow and sediment yield on the slope. It is noteworthy that both water flow and sediment yield exhibit a sudden change in slope at a matric suction of 1100 Kpa, corresponding to the optimal moisture content.

Table 5. *Linear parameters between substrate suction and erosion indicators*

Fitted curve	**Formula**	**R^2**	$\lvert\rho\rvert$
L_a	$y = -6.53x + 34.35$	0.99	0.99
L_b	$y = -2.21x + 21.35$	0.97	0.99
L_c	$y = 4.99x - 11.97$	0.99	0.99
L_d	$y = 0.98x + 0.28$	0.90	0.97

At lower ϑ_a values, the matric suction reaches several thousand Pascals, resulting in higher soil permeability and poor water retention capacity on the slope (Zhang et al., 2004). Only localized areas of the soil reach sufficient moisture for eventual dispersion. In contrast, at higher ϑ_a values, the matric suction is only in the hundreds of Pascals, resulting in lower water permeability and better water retention capacity. Consequently, the slope can become uniformly moistened and dispersed early on, forming a slurry, which affects the subsequent erosion of the slope.

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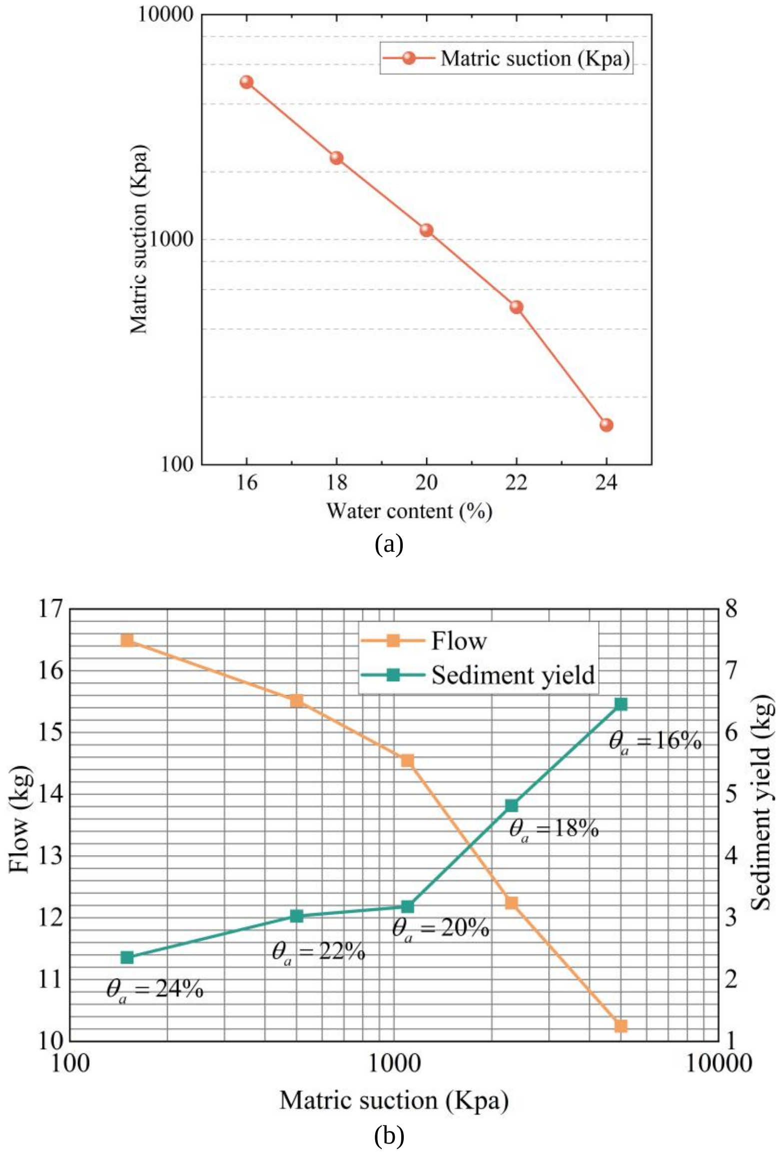

Figure 10. *Soil-water characteristic curve and relationship between matric suction and erosion quantity*

The effect of minerals on erosion

Mineral and particle composition have significant effects on soil erosion rates and erosion processes (Wakindiki and Ben-Hur, 2002; Wei et al., 2015; Zamani and Mahmoodabadi, 2013). Arjmand Sajjadi and Mahmoodabadi (2015), Ramos et al. (2000) and Zhang et al. (2020) found that soils with a higher content of fine particles exhibit greater erosion resistance compared to other soils. However, based on the sample tests conducted in this study, it can be observed that the differences in antecedent moisture content lead to significant variations in erosion for soils with higher content of fine particles and colloids (*Figs. 7* and *9*). Its erosion resistance fluctuates dynamically in accordance with the moisture content. The influence of minerals on erosion should needs to be considered in light of the impact of antecedent moisture content on erosion.

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Conclusions

Indoor simulated rainfall tests were conducted on dispersive soil slopes in Jilin with antecedent moisture content values of 16%, 18%, 20%, 22%, and 24%. High-definition cameras were used to observe, capture, and record the erosion process of the slope soil. It was found that the optimum moisture content serves as a clear threshold for erosion. Significant differences in erosion behavior were observed between higher moisture content values (ϑ_a = 22%, 24%) and lower moisture content values (ϑ_a = 16%, 18%) in dispersive soil slope erosion. Monitoring five groups of slopes with different antecedent moisture content values revealed that the abundant formation of muddy particles on the slope surface during the early stages of rainfall erosion determined the characteristics of later erosion development. Statistical analysis of the sediment yield and water flow generated during the erosion process revealed a significant change at the optimal moisture content. A strong correlation between matric suction and erosion was found based on measurements of matric suction in samples with different antecedent moisture content values. The matric suction can mechanistically explain why the optimal moisture content serves as the threshold for erosion. When establishing erosion models for the dispersive soils in the Jilin region, it is crucial to consider the variations in erosion characteristics caused by different antecedent moisture content values. Additionally, this study can offer relevant insights for environmental conservation efforts related to the local soils and geology.

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