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Physical simulation experiment for raindrop splash erosion characteristics of shallow loess in hilly and gully region of Yan'an

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Abstract: Rainfall is an important factor that induces erosion and deformation damage on the slope surface in loess gully area. Taking the primary loess in Yan'an area as the research object, using the self-designed physical simulation test platform of normal-head single-droplet soil spallation, we systematically study the evolution of spallation of primary loess under different rainfall characteristics, soil water content and surface slope conditions. The experimental results show that the spattering depth increases exponentially with the rainfall duration, and the maximum spattering depth, spattering volume and raindrop frequency show linear and exponential growth, respectively. The influence of raindrop diameter and drop height on soil spallation deformation is more significant, and the soil is more prone to spallation damage under small rainfall intensity and large rainfall intensity. The soil is more susceptible to spallation damage in the case of small rainfall with high moisture content and large rainfall with low moisture content. The maximum spallation depth decreased linearly with the surface slope, while the spallation volume decreased and then increased with the surface slope. Based on the experimental results, an empirical expression for predicting the characteristic indexes of raindrop spallation of in-situ loess was proposed.

Key words: loess hilly and gully region; rainfall; undisturbed loess; splash erosion characteristics; evolvement rules; influence factor

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1 Introduction

The geological environment of loess hills and gullies is complex and fragile, and its rainfall-induced loess geohazards are frequent (Dou et al., 2023; Jin et al., 2023; Li et al., 2020), especially in recent years, the frequency of extreme rainfall climates in the Yan'an area has increased significantly, resulting in many environmental geotechnical problems such as shallow landslides, soil erosion, and ecological damage to loess slopes (Peng et al., 2019; Sun et al., 2019) (Fig. 1(c)), which is highly unfavorable to the development of urban and rural construction and regional ecological environmental protection in Yan'an hilly and gully area (Nan et al., 2021; Li et al., 2019; Xie et al., 2016). The Yan'an loess is a typical strongly water-sensitive unsaturated soil, and the rainfall hydraulic erosion effect is an important influencing factor that causes the deterioration of loess mechanical properties and slope catastrophe. Therefore, it is necessary to carry out an in-depth study on the rainfall erosion of loess in the Yan'an hilly and gully area to reveal the characteristics and influence law of loess hydraulic splash erosion damage under rainfall.

In recent years, many scholars have conducted a series of studies on the splash erosion characteristics of different regions and types of soils using artificial rainfall simulation methods, and more valuable results have been achieved. Soil type, rainfall characteristics (raindrop diameter, rainfall height, rainfall intensity, rainfall duration, raindrop temperature, etc.), soil moisture status, and surface slope are the key factors affecting soil splash erosion，which are also the influencing factors of key research in the rainfall erosion test. For different types of loess, the experiment indicated that loess in different regions show significant microstructural differences, the wetting deformation of loess is mainly caused by the destruction of large and medium pore structures, and the microtopography formed by the collapse of loess is favorable for the concentration and infiltration of surface runoff (Wang et al., 2020). Furthermore, soil erosion processes are directly influenced by soil properties due to the solid structural and highly water-sensitive of loess (Cheng et al., 2008), in which splash erosion is mainly affected by soil particle size (Sun et al., 2021).In addition, through study of the contribution of soil internal forces and raindrop striking forces (external forces) to splash erosion, it was found that soil internal forces play a key role in the splash

erosion process (Hu et al., 2018). For different rainfall conditions, it was found that raindrops at low rainfall intensities play a crucial role in runoff and soil loss, and tiny raindrops are prone to cause soil splash erosion (Qin et al., 2014), while soil loss at high rainfall intensities mainly depend on runoff generation such as excess infiltration rate or overflow (Vaezi et al., 2017). Moreover, there is a power function relationship between soil splash erosion rate and rainfall kinetic energy (Xiao et al., 2018). Splash erosion pit depth is linearly related to raindrop diameter, raindrop kinetic energy and compaction, and raindrop kinetic energy have a higher effect on splash erosion pit depth than compaction (Lv et al., 2023). The amount of splash erosion increases with rainfall rainfall duration in a power function trend, the amount depends on the content of loose particles on the soil surface and the homogeneity of soil particles at the beginning of the rainfall period, and the amount of increase splash erosion decrease in the later stages of the rainfall due to the increased soil surface densification and the decreased water infiltration rate (Liu et al., 2016). Therefore, the mechanical striking effect of raindrops is more significant, and the dissipation effect of soil is weaker in low-temperature condition (Li et al., 2022). For soils with different water contents, changes in soil physical and mechanical properties due to changes in water content, thus affecting the erosion characteristics of the soil. For instance, the splash erosion rate decrease with increase water content, and the increased water content diminished splash erosion (Qin et al., 2014; Li et al., 2024). For soils with different slopes, studies had shown that changes in slope have a significant effect on soil splash erosion characteristics (Li et al., 2019; Bao et al., 2001). For example, the up-slope splash erosion decrease with increasing slope and down-slope splash erosion increase and then decrease with increasing slope (Liu et al., 2011; Wang et al., 2021). The damage patterns of slopes under short-term extreme rainfall conditions is mainly splashing and scouring damage, and the erosion effect is more significant than that of slopes with smaller gradients (Zhen et al., 2023).

In conclusion, raindrop splash erosion causes soil structure destruction, soil particle dispersion, and migration, which is the initial process of rainfall erosion occurrence, so the raindrop striking action is the critical factor in the evolution of soil splash erosion deformation and damage. Existing literature has achieved more valuable results in soil rainfall erosion tests, which provide a good reference for further quantitative research on soil erosion under simulated rainfall conditions. However, the experimental results from the different test conditions, such as soil type and rainfall characteristics selected in the previous studies, had some variability and lack of systematicity. Given this, the Upper Pleistocene (Q_3) undisturbed loess in Yan'an hilly and gully was researched to meet the following objectives, which utilized the self-designed physical simulation test platform of constant head single-raindrop soil splash erosion, three diameters of raindrops were selected for raindrop splash tests at five raindrop frequencies and three raindrop drop heights on soils with three initial moisture contents and four surface slopes, respectively. The study was carried out to systematically investigate the splash erosion characteristics of undisturbed loess under different conditions of raindrop frequency, raindrop diameter, raindrop drop height, soil humidity, and surface slope to expose the evolution of splash erosion deformation and damage of undisturbed loess under different test conditions, to analyze the influence laws of rainfall characteristics, soil humidity, and surface slope on the splash erosion depth, splash erosion range and splash erosion volume of undisturbed loess, and to establish a statistical prediction model of raindrop splash erosion characteristics of undisturbed loess, and provide scientific bases for the study and disaster prevention and control of rainfall erosion of sloping soils in loess hilly-gullies areas.

2 Materials and methods

2.1 Test material

The test soil was selected from the high loess slope at a work site in Yan'an New Area (Fig. 1(a-c)). The sampling depth was about 0.50 m below the surface, the natural density of the soil body was 1.45 g/cm^3 ~1.55 g/cm^3, the water content was 12.50%~16.40%. It belonged to the Upper Pleistocene (Q_3) loess, was yellowish-brown in color, with good uprightness, and it was pressed into a powdery form. The basic physical properties indexes are shown in Table 1. The undisturbed loess column sampling steps are: i) Select the sampling area on the slope, cut off

the top layer of soil in the sampling area to ensure that the lower soil is uniform and free of organic impurities, etc.; ii) Adopt the plexiglass tube with a diameter of 160 mm and a height of 200 mm (wall thickness of 2.5 mm) as the sampling mold, press the tube while cut the soil sample from top to bottom until the soil column is filled with the tube and then separate from the lower soil, and the height of the soil column beyond the sample tube ends 10 ~ 20 mm(Fig.1(d); iii) Take the soil column specimen as a whole into a plastic bag sealed and stored, the upper and lower surfaces of the soil column bulk soil cover to prevent the loss of water content of the soil body, and in the soil column specimen on the upper surface of the marking; iv) Before the splash erosion test to refine the soil column specimen, cut off the excess soil at both ends of the soil column, so that the surface of the soil column is flush with the mouth of the specimen tube, that is, the preparation of the soil column specimen is complete.

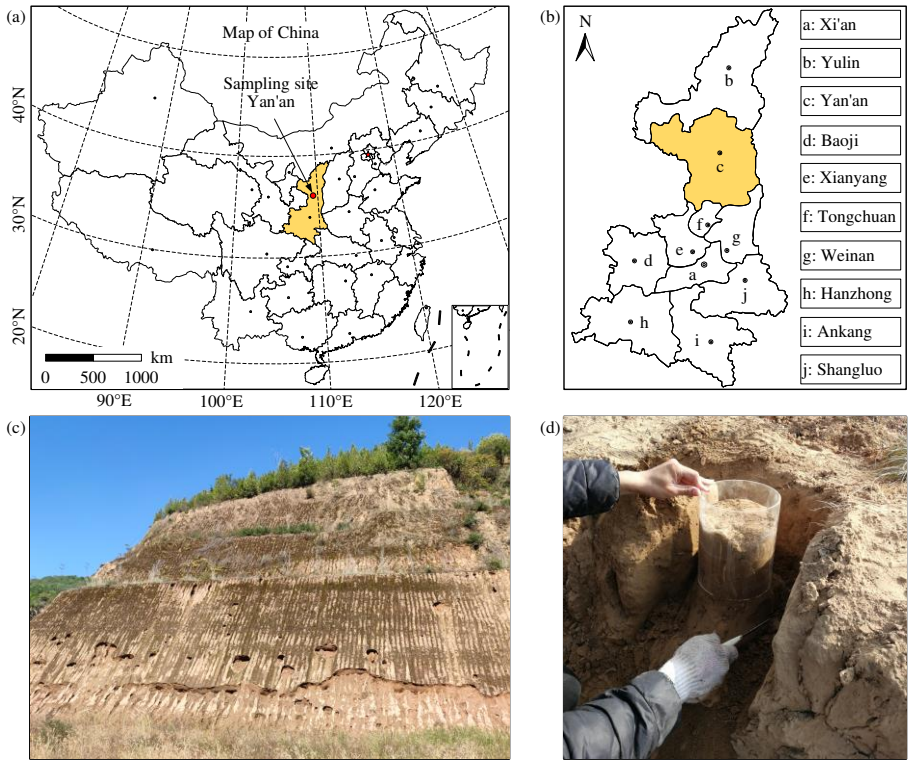


Fig. 1. Location of the sampling site (Nan et al., 2021; Li et al., 2019): (a) Geographical location; (b) Sampling site of Yan'an on the Loess Plateau of China; (c) Rainfall erosion failure of loess slope; (d) Undisturbed loess sampling

Table 1 Physical parameters of tested Q_3 loess on the shallow slope

Type	Color	Natural Density (g/cm^3)	Natural Water Content (%)	Optimum Water Content (%)	Maximum Dry Density (g/cm^3)	Porosity (%)	Particle Proportion	Plastic Limit (%)	Liquid Limit (%)
Q_3	yellowish brown	1.45	14.50	15.45	1.75	50.50	2.71	17.1	30.3

2.2 Test apparatus

The experiment was carried out on a self-developed and designed physical simulation test platform for soil splash erosion by raindrops on undisturbed loess, which mainly includes a continuous water supply system, a raindrop simulation system, a specimen fixation system, and a data acquisition system, as shown in Figure 2. The continuous water supply system consists of a water storage tank, a constant head water supply cylinder, a water supply pump, a plastic connecting water pipe, etc.; the water supply pump provides circulating water for the water storage tank, and the water storage tank and the constant head water supply cylinder are connected in series to provide a continuous and stable water head for the rainfall simulation system. The rainfall simulation system consists of glass dripping tube, adjustable bracket, precision water regulator valve, acrylic sectional transparent windshield, etc., glass dripping tube nozzle for conical, and the selection of the diameter of *d* for 3, 4, 5 mm nozzle to simulate

the different raindrop diameters. The adjustable bracket to adjust the glass dripping tube from the upper surface of the specimen distance to simulate the different raindrop drop heights of h for 1000, 1500, and 2000 mm. The precision water valve controls the water flow rate in the glass drip irrigation to simulate the intensity of rainfall (raindrop frequency q). The sectional transparent windshield is made of Plexiglas tubes with a diameter of 360 mm and a wall thickness of 5 mm, which is assembled and placed directly under the glass drip tube to prevent the interference of the surrounding wind and ensure the raindrops fall vertically into the center of the sample surface of the soil column. The specimen fixation system consists of a tray support, specimen tray, and soil column specimen. Place the undisturbed loess column on the specimen tray and adjust the fine-tuning bolts on the tray support so that the specimen tray is lifted upwards and tilted, which can simulate the different inclination conditions of the slope. The data acquisition system consists of a rotatable tripod, laser rangefinder, high-definition camera, and electronic digital calipers; when collecting data, first remove the transparent windshield of the first section on the top, adjust the crossbar of the rotatable tripod so that the infrared point of the laser rangefinder (precision 1.0 mm) is projected in the center of the spatter pit, and then record the rangefinder readings at the initial and t moments of the test, h_0 and h_t, which means that the cumulative splash erosion depth of the corresponding moment is $\Delta h_t=h_t-h_0$; the splash erosion damage process is recorded in real-time by a remote-controlled high-definition camera, and the lateral splash erosion range of the test specimen is measured by electronic digital calipers (accuracy 0.01 mm).

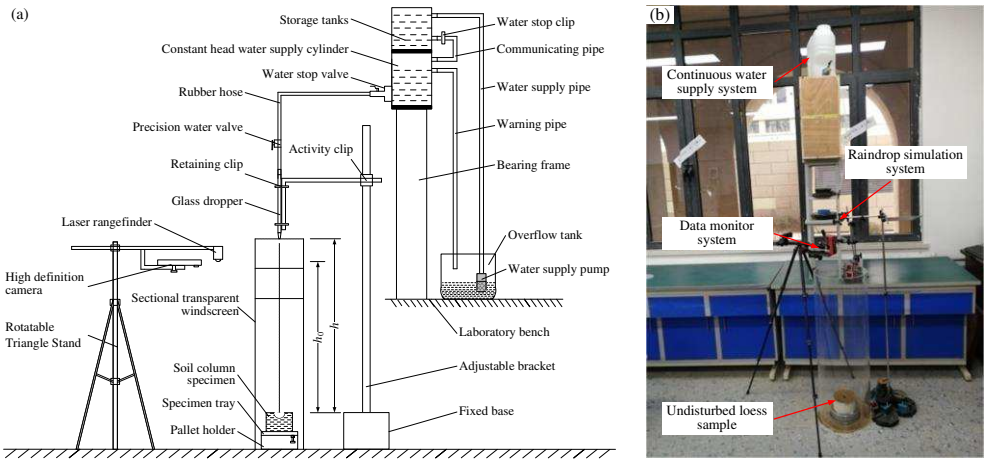


Fig. 2. Physical simulation test platform for raindrop splash erosion of undisturbed loess: (a) Structural Composition, (b)Physical Appearance

2.3 Test scheme and procedure

According to the size of rainfall can be divided into light rain (<10mm/d), moderate rain (10~25mm/d), heavy rain (25~50mm/d), torrential rain (50~100mm/d), downpour (100~250mm/d), heavy downpour (>250mm/d). Rainfall in northern Shaanxi is concentrated in summer and fall (June-October), especially in July-September when heavy rainfall occurs, with daily rainfall of 100-150 mm/d. Based on the statistics of rainfall-induced geological disasters in the loess plateau area of northern Shaanxi, it was found that the frequency of geological disasters triggered by three types of weather, namely, long-holding slight rainfall (10 mm/d), medium-long-holding moderate rainfall (50-60 mm/d), and short-holding heavy rainfall (70~100 mm/d), was the highest (Sun et al., 2019; Li et al., 2009) (Fig. 3). Given this, the simulated rainfall intensity of this test took the critical value of each rainfall level as the control index, which the rainfall intensity was taken as 10, 25, 50, 100, 200mm/d. Taking the raindrop diameter of 3 mm as the standard test group, the test raindrop frequency q (the simulated rainfall intensity) can be approximated as 10, 25, 50, 100, and 150 drops/min by calculating. The test mainly considered five types of influencing factors: raindrop frequency q (10, 25, 50, 100, 150 drops/min), raindrop diameter d (3, 4, 5 mm), raindrop drop height h (1000, 1500, 2000 mm), soil moisture w (natural moisture content, dry sample, humidified sample), and surface slope α (0°, 30°, 45°, 60°), to explore the characteristics of raindrop splash erosion of undisturbed loess under different test conditions, the specific design of the test program is shown in Table 2.

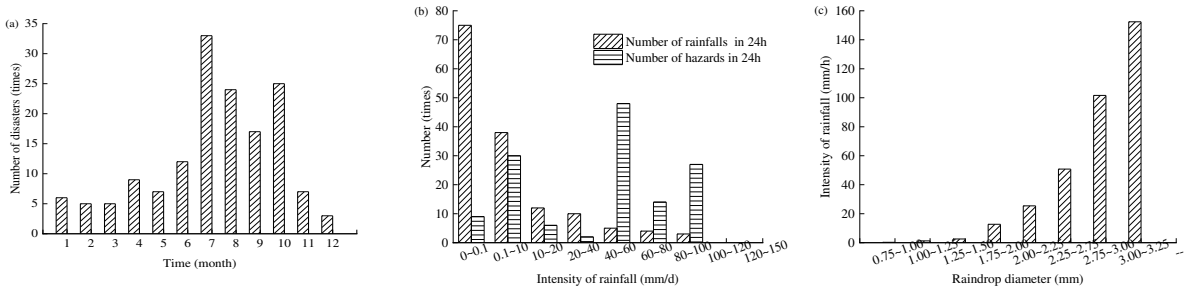


Fig. 3. Statistical relationships between rainfall characteristics and geologic hazards in northern Shaanxi: (a) number of hazards versus month, (b) number of hazards versus rainfall intensity, (c) rainfall intensity versus raindrop diameter

Table 2 Test scheme

Test group	q (drops/min)	d (mm)	h (mm)	w (%)	α (°)	t (min)
R1	10、25、50、100、150	3	1000	natural water content	0	60
D2	10、25、50、100、150	4	1000	natural water content	0	
D3	10、25、50、100、150	5	1000	natural water content	0	
H4	10、25、50、100、150	5	1500	natural water content	0	
H5	10、25、50、100、150	5	2000	natural water content	0	
M6	10、50、100	5	1000	drying specimen, w<5%	0	
M7	10、50、100	5	1000	wetting specimen, w>30%	0	
S8	100	5	1000	natural water content	30	
S9	100	5	1000	natural water content	45	
S10	100	5	1000	natural water content	60	

Note: q raindrop frequency; d raindrop diameter; h raindrop drop heights; w soil moisture; α surface slope.

Specific implementation steps of the raindrop splash erosion test for undisturbed loess are as follows:

(1) Placed the prepared specimen on the specimen tray (Fig. 4 (a)). In the specimen surface, pre-lay a plastic film and raindrop test drops, adjusted the specimen tray so that the raindrops fall to the center of the specimen surface position after removing the plastic film, the installation of the sectional transparent windshield (Fig. 4 (b)).

(2) A measuring cylinder was pre-positioned below the glass burette, adjusted the rubber hose on the precision water regulator valve to be raindrops falling speed stabilization (error of not more than ± 3 drops/min) and to achieve the target value of raindrop rate after the removal of the measuring cylinder, and then formally carry out the splash erosion test. In the test process, after the stabilization of the raindrop rate adjustment will not repeat the water regulator valve is on or off operation, the test pause (open) phase can be realized by placing (removing) the measuring cylinder under the glass drip irrigation.

(3) After the splash erosion test formally started, the stopwatch was turned on at the same time for timing, and the total duration of the simulated rainfall was 60 min. The depth of the splash pit (Δh_t) was observed at intervals of 2, 2, 3, 3, 5, 5, 5, 5, 10, 10, 10 min in turn (Fig. 4(c)). At the end of the test, the splash erosion diameter of the specimen is measured by using the electronic digital calipers (the diameter of the splash pit, denoted as D) and splash erosion diffusion diameter (The splash erosion accumulation range of soil particles to the surrounding, noted as K) (Fig. 4(d)), and recorded the test data and test phenomena; assuming that the splash erosion volume of the soil (V_{loss}) is approximately equal to the volume of the splash pit, whose size can be calculated according to the depth of the splash erosion pit and splash erosion diameter to determine.

(4) To study the influence of rainfall conditions (raindrop frequency, raindrop diameter, raindrop drop height) on the splash erosion characteristics of undisturbed loess, the intensity of the test rainfall is controlled by adjusting the precision water-regulating valve to control the raindrop rate to be 10, 25, 50, 100, 150 drops/min in order. The different nozzle diameters of the glass droppers is replaced to realize raindrop diameter of 3, 4, and 5 mm. The height of the glass dropper from the surface of the specimen is adjusted to simulate drop heights of 1000, 1500, and 2000 mm, respectively.

(5) Preparation of specimens with different humidity (natural moisture content specimen, drying specimen, humidification specimen), with the natural moisture content of 14.50% of the soil samples as a benchmark, the

undisturbed soil column specimens was placed in the oven, drying at a constant temperature of 40 degrees Celsius 72h after taking out, test its moisture content of 4.50%, and then in the constant temperature and humidity containers more than 24h of static, which can prepare drying specimens; humidification specimen can be calculated through the target value of saturated water content of loess required to add water, the use of spray cans at intervals of 1h in the undisturbed soil column on the upper surface of equal amount of water spraying humidification, until the soil was close to saturation, each time after the humidification is placed in a plastic bag sealed and preserved, after the completion of the humidification of the specimen into the constant temperature and humidity containers in the static 72h, the test of its water content of 33.58%, which can prepare humidification specimen.

(6) To analyze the influence of surface slope (0°, 30°, 45°, 60°) on the splash erosion characteristics of undisturbed loess by adjusting the tilting angle of the specimen tray to make the surface of the soil column specimen is 0°, 30°, 45°, 60° in turn, and then the raindrop splash erosion test is carried out; the splash erosion failure diameter in the horizontal direction is taken to be D_h, the splash erosion failure diameter in the slope direction is taken to be Ds, the splash erosion spreading diameter in the horizontal direction is taken to be K_h and the splash erosion spreading diameter in the slope direction is taken to be Ks (Fig. 4(d)).

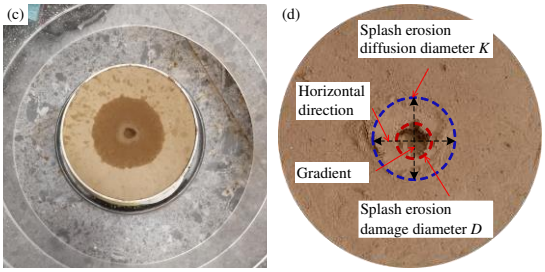


Fig. 4. Test process of raindrop splash erosion for undisturbed loess: (a) Soil Column Specimen, (b) Raindrop Simulation, (c) Soil Splash, (d) Splash Extent

3 Experimental results and analysis

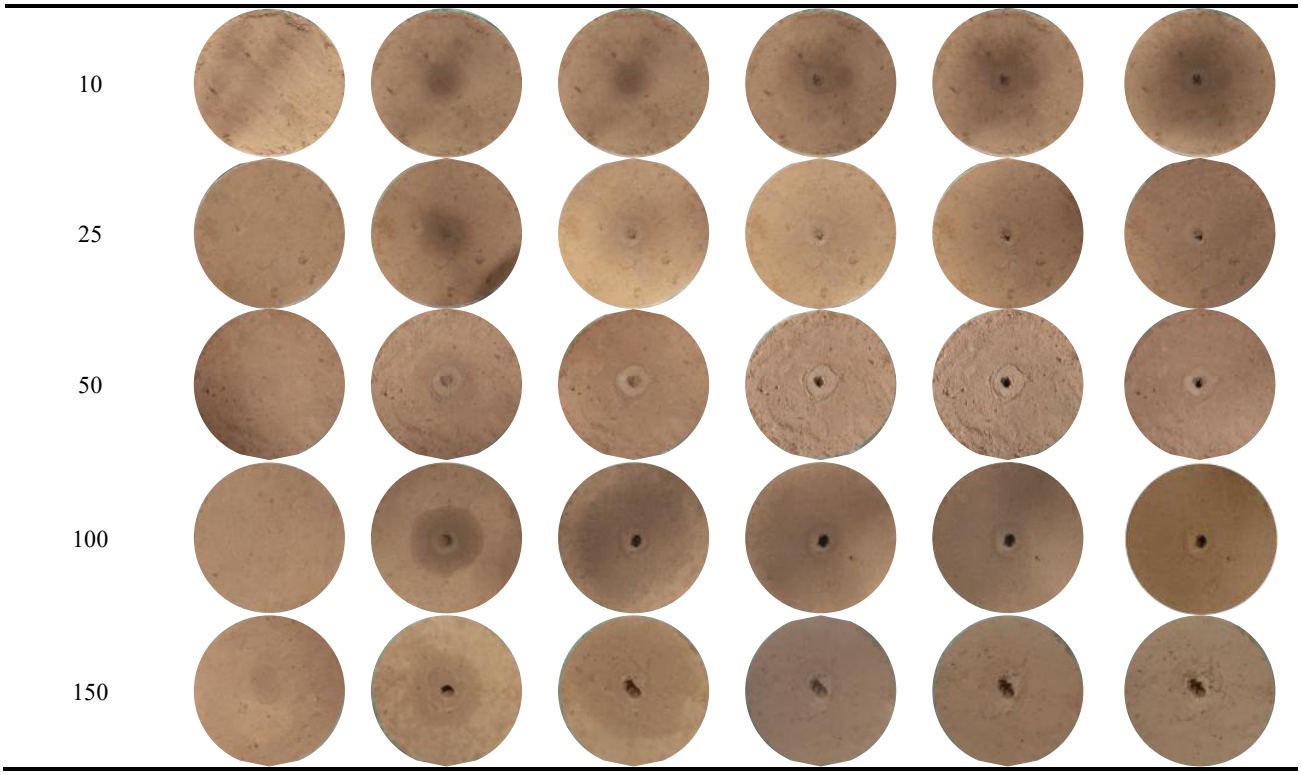
3.1 Experimental results of splash erosion

（1）The development process of deformation and failure of undisturbed loess under raindrop splash erosion

Taking standard group R1 as an example, the development process of splash erosion damage of undisturbed loess under different raindrop frequency conditions is shown in Table 3. Table 3 shows that raindrops drop to the surface of the specimen, the contact point is subjected to the action of the raindrop hydrodynamic striking and the occurrence of soil particles bursting in all directions, and the splash erosion loss of soil particles accumulates in the periphery of splash pits to form splash erosion diffusion circle; with the continuous striking action of the raindrops, the loss of the soil at the point of striking is aggravated continuously, which in turn forms a similar "Cylindrical" splash pit. With the increase in rainfall duration, the water continuously to the hit point of the soil body around the infiltration and diffusion, soil strength due to increased water content and deterioration, raindrop splash damage effect is more and more significant, resulting in splash erosion pits from small to large, shallow to deep. With the growth of rainfall intensity, the wetting range of the soil body rapid expansion, contacts enhanced by successive strikes from raindrops, and the depth and width of the splash pits increase significantly. The splash erosion deformation and damage process of the undisturbed loess presents the development law of raindrops hitting, water infiltration, soil body wetting and softening, soil particles loss by splashing, shallow and small splash pits,and deep and large splash pits.

Table 3 Splash damage development process of undisturbed loess under different raindrop frequency conditions (R1)

q /drops.min^{-1}	Splash pit morphology at different rainfall calendars					
	t=0min	t=2min	t=10min	t=20min	t=30min	t=60min



By testing the splash erosion characteristics of undisturbed loess under different raindrop frequencies, raindrop diameters, raindrop drop heights, soil moisture, and surface slopes, the splash erosion damage profiles of undisturbed loess under various test conditions are obtained, as shown in Table 4.

Table 4 Comparison of spatter damage morphology of in-situ loess under different test conditions

q (drops/min)	*d* (mm)			*h* (mm)		*w* (%)		*α* (°)		
	3.0	4.0	5.0	1500	2000	4.50	33.58	30	45	60
10										
25										
50										
100										
150										

（2）Test results of splash erosion characteristics of undisturbed loess under different test conditions

According to the test data, the time course curves of splash erosion depth and range of undisturbed loess under different test conditions are plotted as shown in Fig. 5(a-h) and 6. Statistical and computational analysis of Fig. 5(a-h) and 6 show that the test results of splash erosion characteristic indexes of undisturbed loess under different test conditions are shown in Fig. 7.

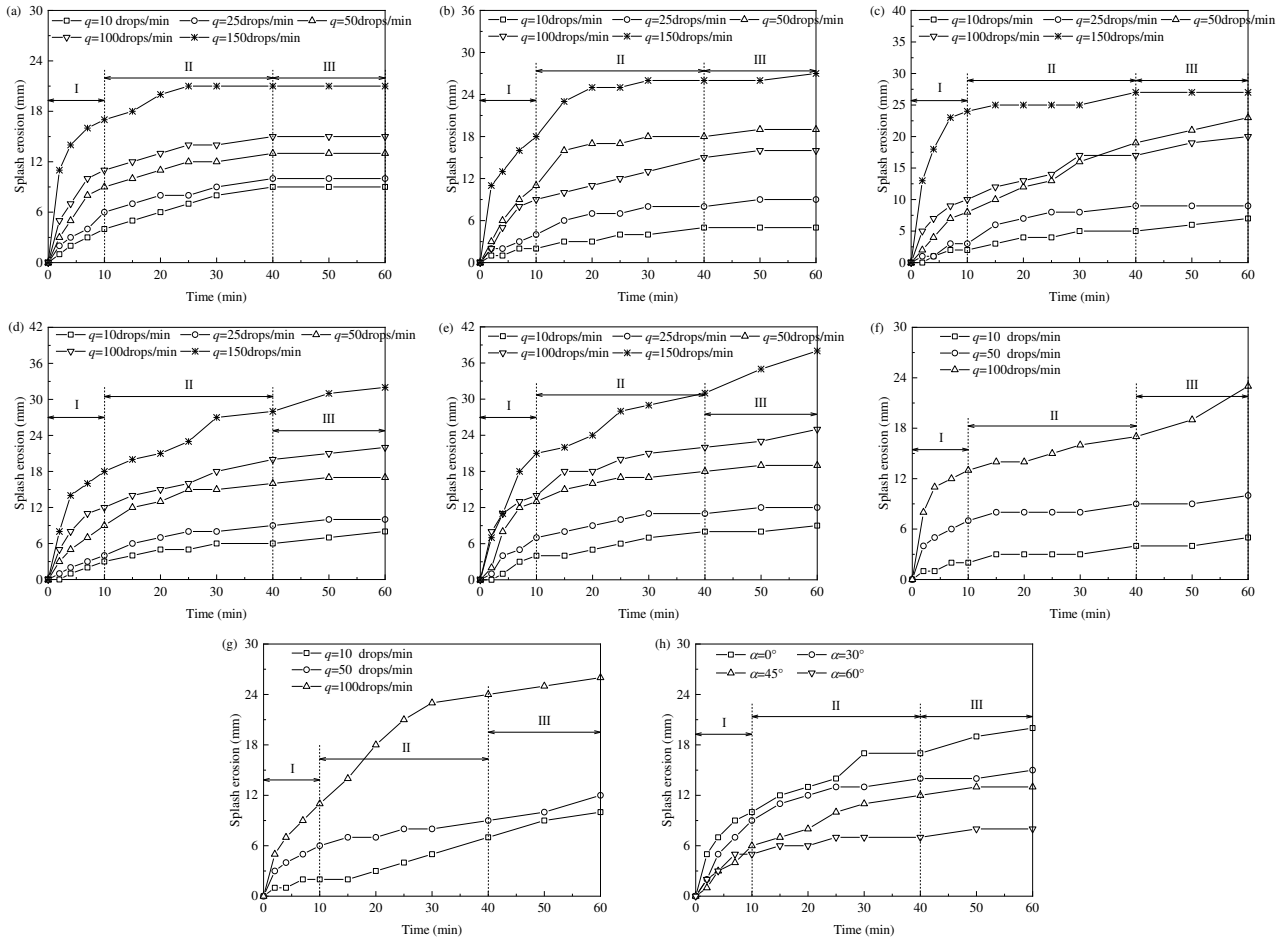


Fig. 5 Time-history curves of splash erosion depth of undisturbed loess under different test conditions: (a)R1, (b)D2, (c)D3, (d)H4, (e)H5, (f)M6, (g)M7, (h)S8~S10

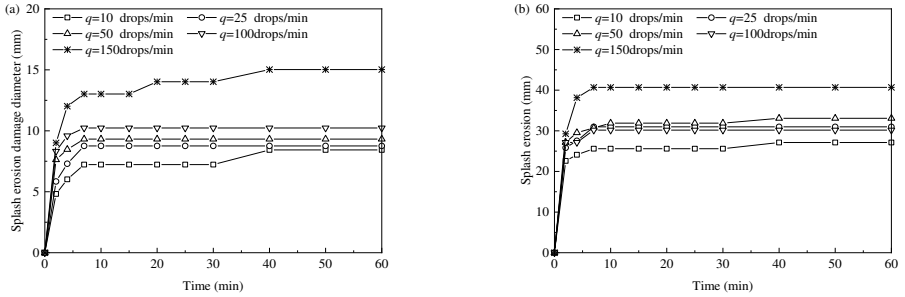
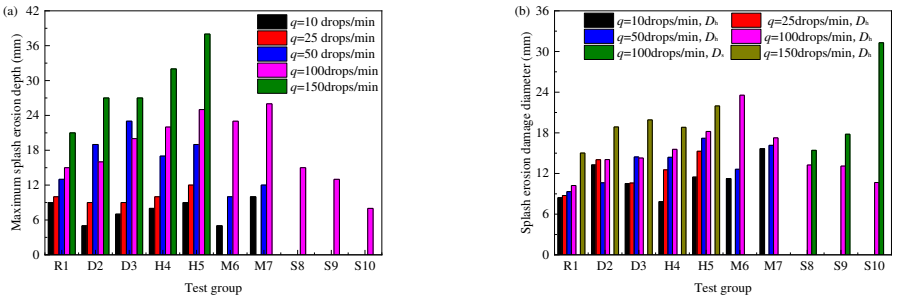


Fig. 6 Time-history curves of lateral splash erosion range of undisturbed loess under different test conditions (R1): (a) *D* vs. *t*, (b) *K* vs. *t*



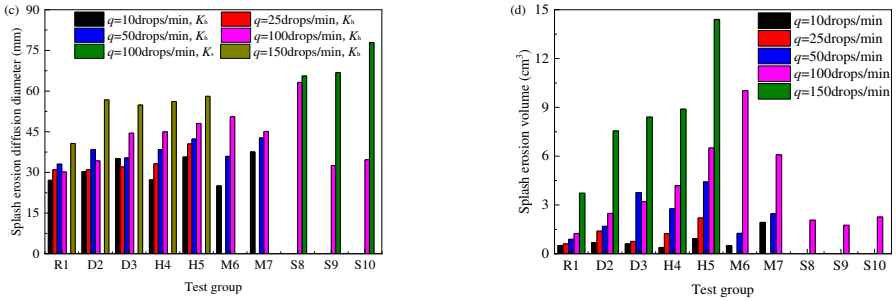


Fig. 7 Test results of splash erosion characteristic indexes of undisturbed loess under different test conditions: (a) Δh_{max}, (b) D, (c) K, (d) V_{loss}

3.2 Analysis of experimental results

3.2.1 Effect of raindrop frequency on splash erosion characteristics

The ratio of the splash erosion depth (Δh_t) at a certain moment to the maximum splash erosion depth (Δh_{max}) is defined as the cumulative percentage of splash erosion depth, and its expression is Eq. (1). Calculated according to Eq. (1), the variation characteristics of splash erosion depth of undisturbed loess under different raindrop frequency conditions are shown in Fig. 8. Combined with Fig. 5 and Fig. 8 , it can be seen that the greater the rainfall intensity, the more obvious the splash erosion depth, and the trend of the time curve of the splash erosion depth under different test conditions is basically the same; the splash erosion depth shows an exponential function of the growth trend with the duration of the rainfall, and the development process can be divided into three phases(Fig.8(a)): ①Rapid growth stage I, rainfall duration of 0 ~ 10 min, the sample surface soil water content is relatively small, the falling raindrops are rapidly absorbed by the sample surface, the surface soil began to develop from unsaturated to saturated state. Under the continuous striking action of raindrops, the soil body at the contact location firstly undergoes deformation and damage, and the soil particles generated are splashed in all directions, gradually forming small splash pits, and with the continuous infiltration of rainwater and continuous striking of raindrops, the depth of splash pits grows at a fast rate, and its time-history curve is of a steeper type, and the splash erosion depth produced in this stage occupies a ratio ranges from 28.57% to 88.89%. ② Slow-growth Stage II, rainfall duration of 10~40 min, the specimen surface soil water content gradually saturated, the rainwater that has not completely infiltrated in the splash pit accumulates to form a thin layer of water, water and soil particles are spattered at the same time, resulting in the weakening of the raindrops on the soil striking effect of splash erosion, splash erosion rate is reduced compared to the first phase I, splash erosion depth time-history curve is diagonal, and the splash erosion depth produced in this stage occupies a ratio ranges from 11.11% to 66.67%. ③ Stable development stage III, the rainfall duration is 40~60 min, the soil around the splash pit is close to saturation, the soil due to the weakening of seepage caused by the splash pit water intensification, coupled with the splash pit depth has been relatively deep, splash erosion of subsoil by raindrops is further attenuated, therefore, the growth rate of splash erosion depth gradually tends to stabilise, and the time-history curve of splash erosion depth shows a flat type, the splash erosion depth produced in this stage occupies a ratio ranges from 0 to 28.57%.

In summary, the cumulative percentage of splash erosion depth generated by rainfall within 0-40 min was more than 71.43%, i.e., the splash erosion deformation damage mainly occurred in the two phases of fast-growth phase I and slow-growth phase II. With the increase of raindrop frequency, the maximum splash pit depth increased significantly, and the maximum splash erosion depth and raindrop frequency conformed to the linear growth relationship (Fig. 8(b)), with a raindrop diameter of 3 mm, for example, the maximum splash erosion depths generated under different raindrop frequencies were 9, 10, 13, 15, and 21 mm, respectively. The maximum splash depth under the conditions of 25, 50, 100, and 150 drops/min was 1.11, 1.44, 1.67, and 2.33 times the raindrop frequency of 10 drops/min, respectively.

$$\lambda = \frac{\Delta h_t}{\Delta h_{\max}} \times 100\% \qquad (1)$$

Where λ is the cumulative percentage of splash erosion depth, %; Δh_t is the splash erosion depth at time t under a certain test condition, mm; Δh_{max} is the maximum splash erosion depth under a certain test condition, mm.

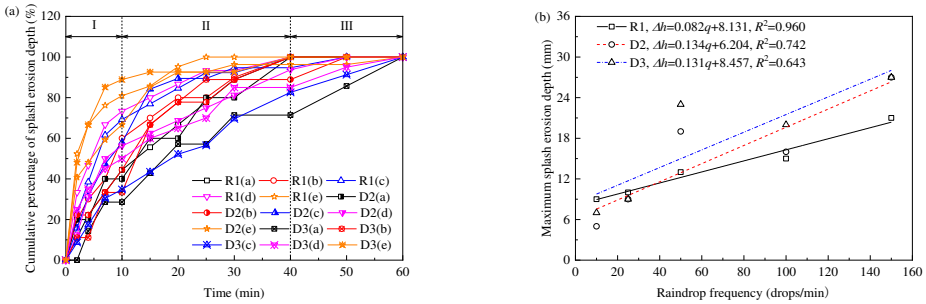


Fig. 8 Characteristics of undisturbed loess splash erosion depth variation under different raindrop frequency conditions (R1, D2, D3): (a) λ vs. t, (b) Δh_{max} vs. q

Note: a means raindrop frequency (q) = 10 drops / min; b means raindrop frequency (q) = 25 drops / min; c means raindrop frequency (q) = 50 drops / min d means raindrop frequency (q) = 100 drops / min; e means raindrop frequency (q) = 150 drops / min.

As shown in Fig. 9, the splash erosion range and volume change characteristics of undisturbed loess under different raindrop frequencies. Combined with Fig. 9 and Table 4, it can be seen that with the increase in raindrop frequency, the splash erosion damage diameter and splash erosion diffusion diameter both show a linear increasing trend (Fig. 9(a)). Take the raindrop diameter of 3 mm as an example, the splash erosion damage diameter generated under the conditions of raindrop frequency 25, 50, 100, and 150 drops/min was 1.04, 1.11, 1.21, 1.78 times the raindrop frequency 10 drops/min, respectively. The splash erosion diffusion diameter D ranges from 8.43 mm to 19.91 mm, the splash erosion diffusion diameter K ranges from 27.11 mm to 56.76 mm, and the splash erosion diffusion diameter K was about 2.21 ~ 3.61 times the splash erosion damage diameter D.

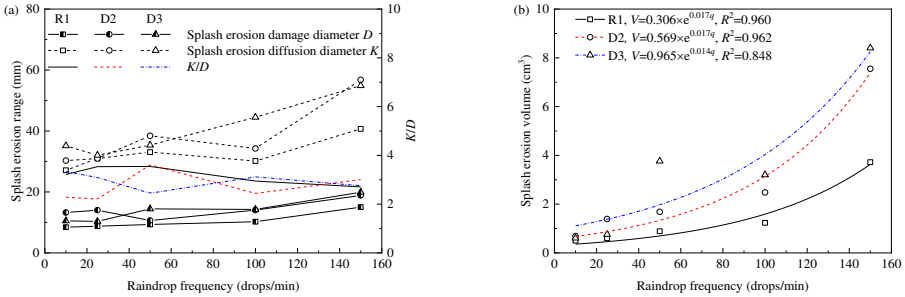


Fig. 9 Characteristics of spallation range and spallation volume change of undisturbed loess under different raindrop frequency conditions (R1, D2, D3): (a) Erosion range, (b) Erosion volume

The soil splash erosion volume increased significantly with increasing raindrop frequency, and the relationship between the relationship can be described by a well-fitted exponential function (Fig. 9(b)). Taking the raindrop diameter of 3 mm as an example, the splash erosion volume under different raindrop frequencies were 0.50, 0.60, 0.89, 1.23, and 3.72cm^3, and the splash erosion volume produced under the raindrop frequency of 25, 50, 100, 150 drops/min were 1.20, 1.77, 2.46, 7.41 times of the raindrop frequency of 10 drops/min, respectively. When the drop frequency was 50 drops/min, the maximum splash erosion depth, range, and volume of the specimen fluctuated, showing a clear "sudden increase" trend. The main reasons are ① When q=50 drops/min, the rainwater infiltration rate was close to the soil permeability, the soil body was more likely to deform and damage under the kinetic energy of the raindrops, so the splash erosion damage effect of the specimen was more significant. ②When q < 50 drops/min, rainwater was predominantly infiltrated, no standing water was produced in the splash pits, and the kinetic energy striking force of the raindrops produced at this rainfall intensity was limited. ③When 50 drops/min

< q < 100 drops/min, a thin layer of water accumulated in the splash pit, leading to a weakening of the raindrops' striking Effect on the soil, and when q>100 drops/min, the larger kinetic energy of raindrops was generated at this rainfall intensity, and the striking capacity of raindrops was significantly increased, which intensifies the splash erosion damage to the soil. This indicates that rainfall conditions are critical in inducing erosion disasters and soil erosion on loess slopes.

3.2.2 Effect of raindrop diameter on splash erosion characteristics

As shown in Fig. 10, the splash erosion range and volume change characteristics of undisturbed loess under different raindrop diameter conditions. From Fig. 10, the maximum splash erosion depths corresponding to raindrop diameters of 3, 4, and 5 mm were 15.0, 16.0, and 20.0 mm, respectively, the maximum splash erosion depths produced by raindrop diameters of 4 mm and 5 mm increased by 6.67% and 33.33%, respectively, compared with raindrop diameters of 3 mm; the maximum splash erosion depth tended to increase with raindrop diameter, and the greater the frequency of raindrops, the more significant the effect of raindrop diameter on the maximum splash erosion depth (Fig. 10(a)). The splash erosion damage diameters D corresponding to raindrop diameters of 3, 4, and 5 mm varied in the ranges of (8.43~15.02), (10.63~18.87), and (10.36~19.91) mm, respectively. The splash erosion diffusion diameter K varied in the range of (27.11~40.69), (30.28~56.76), and (32.03~54.88) mm, respectively. That is, the splash erosion damage diameter and splash erosion diffusion diameter of the soil body both tend to increase with the diameter of raindrops, and the increase of splash erosion diffusion diameter is more obvious(Fig. 9(a), Table 4). Taking the raindrop frequency of 10 drops/min as a reference, the three raindrop diameters (3, 4, and 5 mm) produced 7.41, 10.94, and 13.83 times the volume of soil splash erosion at a raindrop frequency of 150 drops/min as compared to that at a raindrop frequency of 10 drops/min, respectively (Fig. 10(b)).

In summary, under the condition of minor raindrop frequency (q≤25 drops/min), the soil splash erosion volume showed an increasing and then decreasing trend with the raindrop diameter. Under the condition of medium-high raindrop frequency (50 drops/min≤q≤100 drops/min), the soil splash erosion volume increased linearly with the raindrop diameter. Under the condition of significant raindrop frequency (q>100 drops/min), the soil splash erosion volume tended to increase as an exponential function of raindrop diameter.

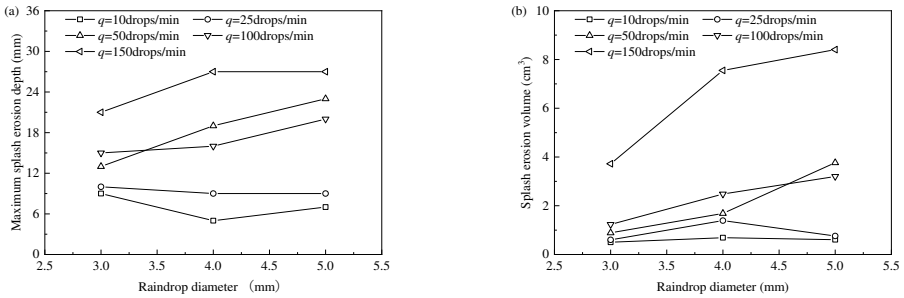


Fig. 10 Characteristics of splash erosion extent and volume change of primary loess under different raindrop diameter conditions (R1, D2, D3): (a) Erosion depth, (b) Erosion volume

3.2.3 Effect of raindrop falling height on splash erosion characteristics

Fig. 11 shows the variation characteristics of splash erosion depth of undisturbed loess under different raindrop drop heights. Combined with Fig. 5 and Fig. 11, when the raindrop drop height h=1000 mm (D3), the maximum splash erosion depth ranges of I, II, and III stages were [2.0 24.0], [5.0 27.0], and [7.0 27.0] mm, and the percentages were [28.57% 88.89%], [11.11% 66.67%], and [0 28.57%], respectively. When the raindrop drop height h=1500mm (H4), the maximum splash erosion depth range produced by the three stages of I, II, and III were [3.0 18.0], [6.0 28.0], and [8.0 32.0] mm in the order of [37.50% 56.25%], [31.25% 50.00%], and [5.88% 25.00%], respectively. When the raindrop drop height h = 2000 mm (H5), the maximum splash erosion depth range produced by the three stages of I, II, and III were [4.0 21.0], [8.0 31.0], and [9.0 38.0] mm in the order of [44.44% 68.42%], [26.32% 44.44%], and [5.26% 18.42%], respectively. The test further showed that the splash erosion depth increased

exponentially with the rainfall duration, and the spallation deformation damage mainly occurred in the two stages of I and II (Fig. 11(a)). Taking the rainfall intensity of 100 drops/min as an example, the maximum splash erosion depths corresponding to the drop heights of 1000, 1500, and 2000 mm were 20.0 mm, 22.0 mm, and 25.0 mm, respectively. The maximum splash erosion depths generated under the conditions of drop heights of 1500 mm and 2000 mm increased by 10.00% and 25.00% compared with that of drop height of 1000 mm (Fig. 11(b)); the maximum splash erosion depth was positively correlated with the raindrop drop height, and this phenomenon had the same characteristics as the influence of raindrop diameter on the maximum splash erosion depth.

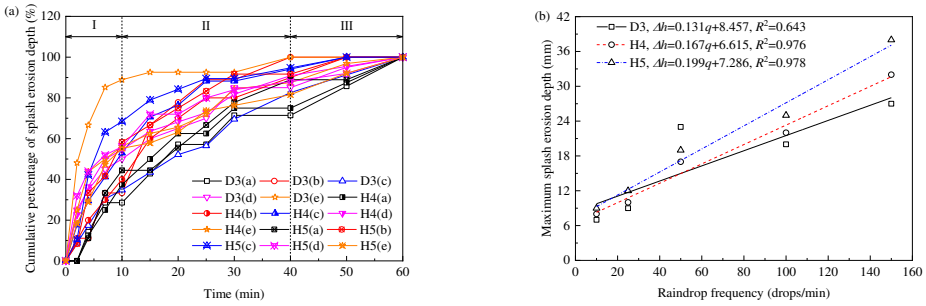


Fig. 11 Characteristics of splash erosion depth variation of primary loess under different raindrop drop height conditions (D3, H4, H5): (a) λ vs. t, (b) Δh_{max} vs. q

As shown in Fig. 12, the splash erosion range and volume change characteristics of the undisturbed loess under different raindrop drop heights. Combined with Figure 12 and Table 4, it can be obtained that the corresponding splash erosion damage diameter D under different rainfall intensities for three raindrop drop heights of 1000, 1500, and 2000 mm varied in the ranges of (10.36~19.91) mm, (7.85~18.81) mm, and (11.47~21.97) mm, and the splash erosion diffusion diameter K varied in the ranges of (32.03~54.88) mm, (27.24~56.16) mm, and (35.68~58.08) mm, which the splash erosion damage diameter and splash erosion diffusion diameter of the soil body increased gradually with the increase of raindrop drop height; under the same test conditions, the splash erosion diffusion diameter was about (2.45~3.47) times of the splash erosion damage diameter. The maximum splash erosion volume generated under the three conditions of raindrop drop heights of 1000, 1500, and 2000 mm were 8.41, 8.89, and 14.41 cm^3, respectively. Taking the raindrop drop height of 1000 mm (D3) as a reference, the splash erosion volume of soil generated under the condition of raindrop drop height of 1500 mm was 0.64, 1.63, 0.73, 1.31, and 1.06 times higher than that of the raindrop drop height of 1000 mm, respectively, and the soil splash erosion volume under the condition of raindrop height 2000mm was 1.53, 2.90, 1.17, 2.03 and 1.71 times of the raindrop height 1000mm respectively. The splash erosion volume of the undisturbed loess under the condition of different raindrop heights showed an exponential growth trend with the frequency of raindrops, and the larger the raindrop height was, the more obvious the increase in the splash erosion volume of the soil body was. This shows that the key to influence the degree of soil splash erosion lies in the size of the kinetic energy of raindrops, the larger the kinetic energy of raindrops is, the stronger the splash erosion effect on the soil.

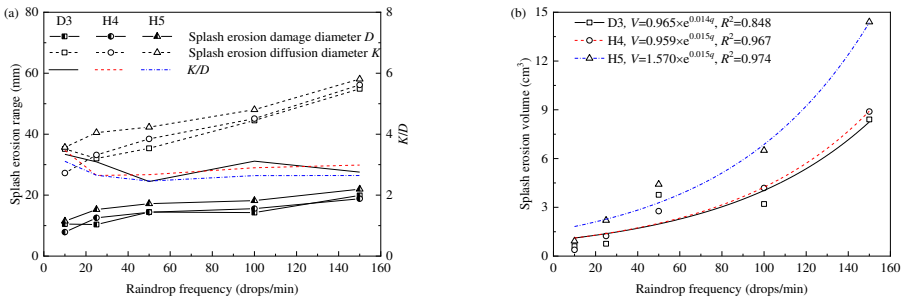


Fig. 12 Characteristics of splash erosion range and volume of undisturbed loess under different raindrop drop height conditions (D3, H4, H5): (a) Erosion range, (b) Erosion volume

3.2.4 Effect of soil moisture on splash erosion characteristics

As shown in Fig. 13 is the characteristic of the change of splash erosion depth of undisturbed loess under different initial water content conditions. Combining Fig. 5 and Fig. 13, it can be obtained that the dry specimen (initial water content of 4.50%, M6), the undisturbed specimen (initial water content of 14.50%, D3), the humidified specimen (initial water content of 33.58%, M7). In Stage I, the cumulative percentage ranges of the erosion depth generated were [40.00% 70.00%], [28.57% 50.00%], and [20.00% 50.00%]; In Stage II, the cumulative percentage ranges of the erosion depth generated were [73.91% 90.00%], [71.43% 85.00%], and [70.00% 92.31%]. Under different initial moisture content conditions, there was a significant difference in the trend of splash erosion depth with time. In the rapid growth stage I, the cumulative percentage of splash erosion depth of the dry specimens was higher than that of the relatively undisturbed and humidified specimens, while in the slow growth stage II, the cumulative percentage of splash erosion depth of the humidified specimens was higher than that of the relatively undisturbed and dry specimens in the strong rainfall conditions.

The maximum splash erosion depth showed a linear increase with the raindrop frequency under different initial moisture content conditions. For a raindrop frequency of 100 drops/min, the maximum splash erosion depths of the dry, undisturbed, and humidified specimens were 23.0, 20.0, and 26.0 mm, respectively. The maximum splash erosion depths of the dry and humidified specimens were 1.15 and 1.30 times that of the undisturbed specimens. The maximum splash erosion depth generated at a raindrop frequency of 10 drops/min showed an increased trend with the initial moisture content. Additionally, the maximum splash erosion depth generated at a raindrop frequency of 50 drops/min showed an increasing and then decreasing trend with the initial moisture content. And the maximum splash erosion depth generated at a raindrop frequency of 100 drops/min showed a decreasing and then increasing trend with the initial water content. The main reason for this phenomenon is that under low rainfall intensity (q=10 drops/min), rain to infiltration-based, the specimen does not produce water. The infiltration of rainwater softens the strength of the soil body, and the depth of splash erosion showed a continuously increasing trend with the increase of the initial water content of the soil. In the event of heavy rainfall (q=50 drops/min), the splash erosion depth of the dry specimen was less than that of the undisturbed specimen due to its high initial strength. In contrast, due to the humidified specimen approaching saturation, the infiltration of rainwater was relatively slow, and the impact of raindrops on the soil was weakened by a thin layer of water inside the splash erosion pit, so the depth of splash erosion of the humidified specimen was also smaller than that of the undisturbed specimen. In heavy rainfall (q=100 drops/min), the continuous striking effect of raindrops on the soil body was intensified. Despite the formation of a thin water layer in the splash erosion pit, this was insufficient to weaken the striking effect of raindrops. Consequently, the depth of splash erosion showed a continuous trend of increasing with the initial water content of the soil.

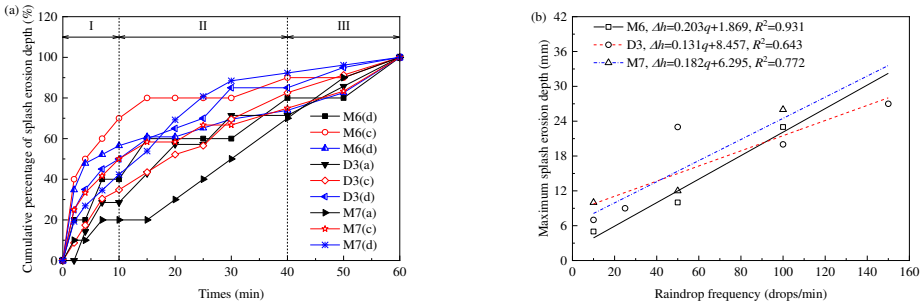


Fig. 13 Characteristics of splash erosion depth variation of undisturbed loess under different initial water content conditions (D3, M6, M7): (a) λ vs. t, (b) Δh_{max} vs. q

As shown in Fig. 14, the splash erosion range and splash erosion volume change characteristics of undisturbed loess under different initial water content conditions. From the figure, it can be seen that under the same initial water content conditions, the splash erosion damage diameter D and splash erosion diffusion diameter K increase with the

increase of raindrop frequency, and the splash erosion diffusion diameter K was about (2.14~3.34) times the splash erosion damage diameter D (Fig. 14(a)). When the raindrop frequency is 10 and 50 drops/min, the splash erosion range of the specimen shows an increasing tendency with the increase of the specimen's initial water content. At a raindrop frequency of 100 drops/min, the dry specimen had the largest spattering range, the humidified specimen had the second largest, and the undisturbed specimen had the smallest. The splash erosion volume of undisturbed loess with different initial moisture contents increased exponentially with the frequency of raindrops, and the change of the initial moisture content of the specimens had a significant effect on the splash erosion volume of the soil (Fig. 14(b)). When the frequency of raindrops was 10 drops/min, the splash erosion volume increased with the initial moisture content. When the frequency of raindrops was 50 drops/min, the splash erosion volume of the undisturbed specimen was the largest, followed by that of the humidified specimen, and the smallest one of the dry specimen. When the frequency of raindrops was 100 drops/min, the splash erosion volume of the dry specimen was the largest, followed by that of the humidified specimen and the smallest one of the undisturbed specimen, and the splash erosion volume of the dry and humidified specimens were 3.13 and 1.45 times of the as-is specimen, respectively. The splash erosion volume of dry and humidified specimens were 3.13 and 1.45 times of the undisturbed specimens, respectively.

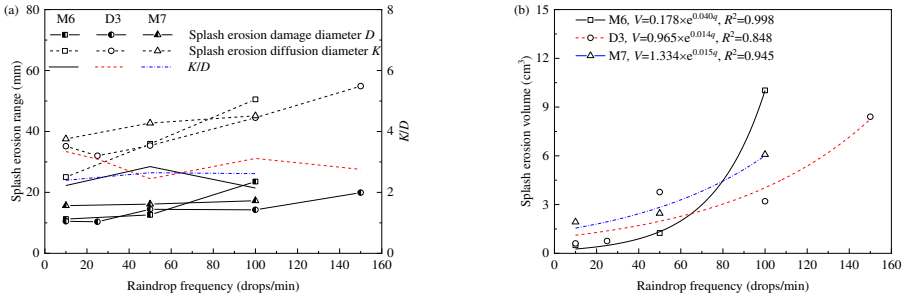


Fig. 14 Characteristics of splash erosion extent and splash erosion volume change of undisturbed loess under different initial water content conditions (D3, M6, M7): (a) Erosion range, (b) Erosion volume

Combined with Table 4, it can be seen that the splash erosion damage morphology of specimens with different initial water content varied significantly, and during the rainfall period, the dry specimen had the highest degree of water absorption, the undisturbed specimen was the next highest, the humidified specimen was the smallest, and the water accumulated around the splash erosion pits on the surface of the humidified specimens under strong rainfall was obvious. This further indicates that soils with higher initial water content are susceptible to splash erosion under light rainfall conditions, while soils with lower initial water content are susceptible to splash erosion under heavy rainfall conditions. The main reason for this is that, under small rainfall conditions, rainwater is mainly infiltrated, and the erosion strength of the soil body gradually decreases with the humidification of the soil body, while under strong rainfall conditions, the kinetic energy of raindrops is large, and the striking force is strong, and the dry specimens are less resistant to erosion due to rapid expansion, cracking and destruction of agglomerates after absorbing water.

3.2.5 Effect of surface slope on splash erosion characteristics

Fig. 15 shows the characteristics of the change in the splash erosion depth of undisturbed loess under different surface slope conditions. From Fig. 5(h) and Fig. 15, with the increase of surface slope, the growth trend of the splash erosion depth time-history curve gradually slowed down, and the final splash erosion depth produced was obviously reduced; the cumulative percentage of splash erosion depth produced in the fast I and slow II stages under the working conditions of D3 (0°), S8 (30°), S9 (45°), and S10 (60°) were 85.00%, 93.33%, 92.31%, and 87.50%, i.e., the cumulative percentage of splash erosion depth generated in the I and II phases showed an increasing trend with the slope of the surface. The maximum splash erosion depth generated in the D3, S8, S9, and S10 conditions were 20.0, 15.0, 13.0, and 8.0 mm, respectively. The maximum splash erosion depths generated in the

S8, S9, and S10 conditions were about 0.75, 0.65, and 0.40 times that of the D3 condition, and there was a linear attenuation relationship between the maximum splash erosion depths and the slope of the ground surface.

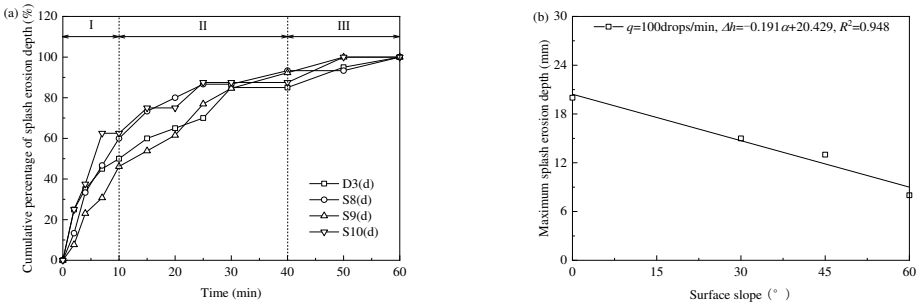


Fig. 15 Characteristics of the variation of splash erosion depth of primary loess under different surface slope conditions (D3, S8, S9, S10): (a) λ vs. t, (b) Δh_{max} vs. q

The splash erosion range of the specimen in the horizontal direction (perpendicular to the slope direction) tended to decrease with the increase of the surface slope, the splash erosion range in the slope direction tended to increase with the increase of the surface slope, and the splash erosion damage range in the horizontal direction was smaller than that in the slope direction. In the horizontal direction, the splash erosion diffusion diameter K was about (2.48~4.77) times the splash erosion damage diameter D. In the slope direction, the splash erosion diffusion diameter K was about (2.49~4.25) times the splash erosion damage diameter D. The shape of the splash erosion pits varied markedly with the slope of the ground surface, progressing from approximately "cylindrical" ~ "wedge-shaped" ~ "fluted" (Table 4, Fig. 16(a)). The main reason is that the horizontal specimen under raindrop splash is mainly subjected to raindrop impact, whereas the inclined specimen under the influence of surface gradient is not only subjected to raindrop impact but also subjected to hydrodynamic cutting of runoff water in the direction of the slope. Slope erosion damage from point sputtering, local potholes to the evolution of erosion grooves, that is, along the direction of the slope ultimately presents a "gully" shape, which is also the Loess Plateau area slope surface more gully shape of one of the important factors affecting the surface.

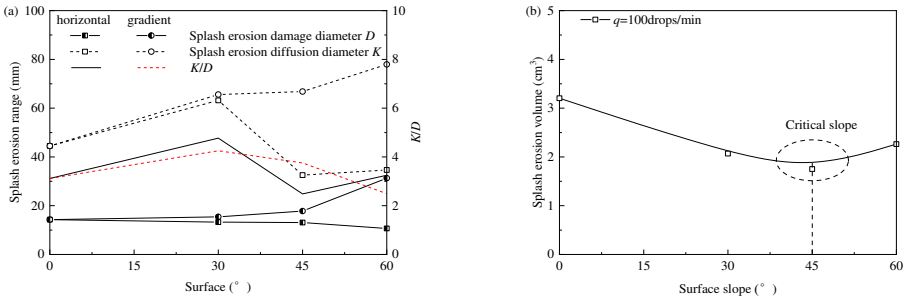


Fig. 16 Characteristics of splash erosion extent and splash erosion volume change of undisturbed loess under different surface slope conditions (D3, S8, S9, S10): (a) Erosion range, (b) Erosion volume

The volume of soil splash erosion produced under the D3, S8, S9, and S10 conditions was 3.20, 2.07, 1.75, and 2.62 cm^3, respectively, i.e., the maximum volume of soil splash was found on the 0°slope, followed by the 60°slope, and the minimum was found on the 45°slope (Fig. 16(b)). It can be seen that loess slopes are bound to have a critical slope at which rainfall erosion or soil erosion of the slope is minimized. In summary, it can be concluded that surface slope is an important factor influencing the amount of soil rainfall splash erosion deformation and splash erosion morphology, and the improvement of slope conditions (Zhang et al., 2023), enhancement of slope drainage paths (Chen et al., 2020), upgrading of slope erosion resistance (Jin et al., 2021; Liu et al., 2019), and prevention of large rainfall infiltration is an important way to prevent rainfall erosion disasters on slopes in loess plateau areas.

4 Discussion

Quantitative characterization of erosion features is an essential basis for assessing rainfall erosion hazard and its prevention and control on loess slopes, so quantitative prediction of splash erosion characteristics of undisturbed loess under rainfall is necessary. According to the analysis in section 3.2, it can be seen that there are significant differences in the splash eroison characteristics of the primary loess under different test conditions and were affected by the coupling of multiple factors, and it was obviously difficult to quantitatively describe the splash erosion characteristics of the primary loess under the influence of the coupling of multiple factors. The test results showed that rainfall intensity, duration, and soil conditions were essential factors affecting the splash erosion characteristics, and the greater the rainfall intensity and the longer the rainfall duration, the more significant the soil splash erosion deformation and damage effects (Fig. 17(a)). Based on the test data, focusing on the rainfall intensity and duration, the statistical prediction model of the rain drop splash erosion characteristic indexes (Δh_t, Δh_{max}, D, V_{loss}) of the undisturbed loess was established. Since the test results have a certain degree of randomness, it is assumed that the parameters obey the law of normal distribution, so a 95% confidence interval is taken to analyze the data statistics. The upper and lower limits of the 95% confidence boundaries and the mean results are obtained in turn, and the calculation results are shown in Fig. 17(b-d) and Table 5.

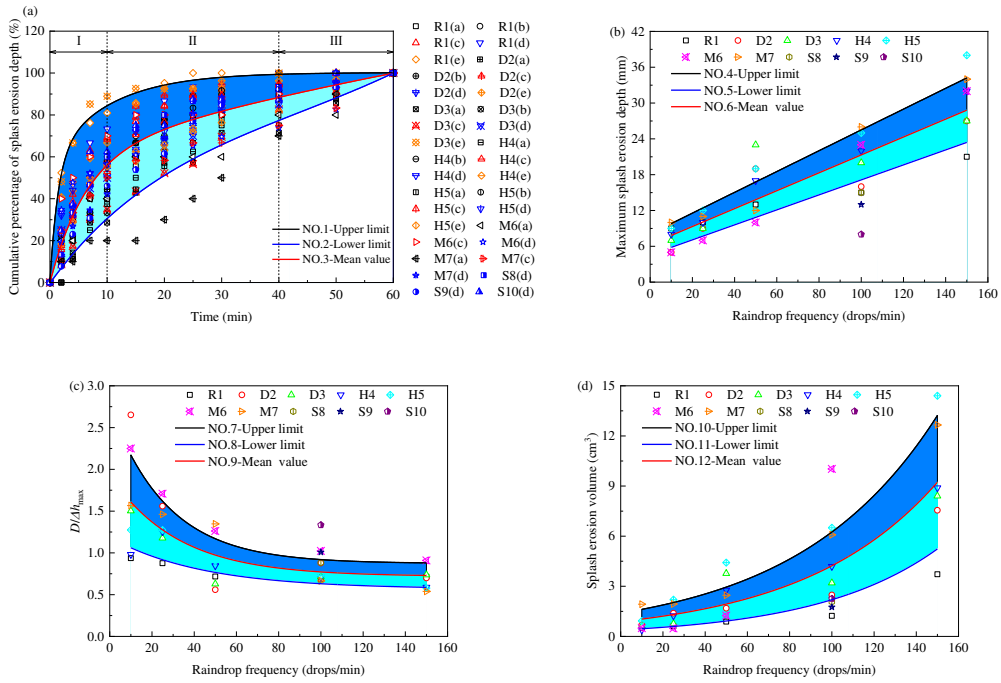


Fig. 17 Statistical prediction model for indicators of in-situ loess raindrop splash erosion characteristics: (a) λ vs. t, (b) Δh_{max} vs. q, (c) $D/\Delta h_{max}$ vs. q (d) V_{loss} vs. q

Table 5 Parameters of model fit for statistical prediction of splash erosion characteristic indicators

Splash Indicator	Confidence Curves	Fitting Equation	Fitting Parameters				
			A_1	B_1	A_2	B_2	C
λ	Upper 95% confidence curves-NO.1	$\lambda = A_1 \times e^{(-t/B_1)} + A_2 \times e^{(-t/B_2)} + C$	−41.731	10.301	−58.436	1.416	100.249
	Lower 95% confidence curves-NO.2		−79.085	21.516	3.329	−27.533	75.431
	Mean value-NO.3		−129.221	167.609	−61.120	6.287	190.274
Δh_{max}	Upper 95% confidence curves-NO.4	$\Delta h_{max} = A_1 \times q + B_1$	0.174	8.066	--	--	--
	Lower 95% confidence curves-NO.5		0.126	4.569	--	--	--
	Mean value -NO.6		0.150	6.318	--	--	--
$\frac{D}{\Delta h_{max}}$	Upper 95% confidence curves-NO.7	$\frac{D}{\Delta h_{max}} = A_1 \times e^{(-q/B_1)} + C$	1.880	27.072	--	--	0.873
	Lower 95% confidence curves-NO.8		1.219	31.942	--	--	0.719

	Mean value -NO.9		0.620	43.909	--	--	0.567
V_{loss}	Upper 95% confidenc curves-NO.10	$V_{loss} = A_1 \times e^{(B_1 \times q)}$	1.394	0.015	--	--	--
	Lower 95% confidence curves-NO.11		0.387	0.017	--	--	--
	Mean value -NO.12		0.888	0.016	--	--	--

Among them, NO.1 and NO.2 are the upper and lower limits of 95% confidence intervals for the cumulative percentage of splash erosion depth, respectively. NO.4 and NO.5 are the upper and lower limits of 95% confidence intervals for the maximum splash erosion depth, respectively. NO.7 and NO.8 are the upper and lower limits of 95% confidence intervals for the splash erosion diameter, respectively. NO.10 and NO.11 are the upper and lower limits of 95% confidence intervals for the splash erosion volume of the soil, respectively. NO.10 and NO.11 are the upper and lower limits of the 95% confidence interval for the splash erosion volume of the soil, respectively. NO.3, NO.6, and NO.9 are the mean values of the corresponding splash erosion indicators. The fitting expressions for the splash erosion depth, maximum splash erosion depth, splash erosion damage diameter, and soil splash erosion volume curve equations are Eq. (2), Eq. (3), and Eq. (4), respectively.

$$\begin{cases} \Delta h_t = \Delta h_{max} \lambda \\ \lambda = A_1 \times e^{(-t/B_1)} + A_2 \times e^{(-t/B_2)} + C \end{cases} \quad (2)$$

Where: Δh_t is the splash erosion depth at time t, mm; Δh_{max} is the maximum splash erosion depth, mm; λ is the cumulative percentage of splash erosion depth, %; t is the rainfall calendar time, s; A_1, A_2, B_1, B_2, C are the fitting coefficients, the specific values are shown in Table 5.

$$\Delta h_{max} = A_1 \times q + B_1 \quad (3)$$

$$D = \Delta h_{max} \left[A_1 \times e^{(-q/B_1)} + C \right] \quad (4)$$

$$V_{loss} = A_1 \times e^{(B_1 \times q)} \quad (5)$$

In summary, combined with equations (2), (3), (4), and (5), the depth of in situ loess splash erosion, splash erosion damage diameter, and splash erosion volume of the change range can be initially quantitatively predicted, which can be used to provide a basis for calculation for engineering practice and theoretical analysis.

5 Conclusions

(1) In the raindrops hit and water infiltration under the joint action of the surface of the undisturbed loess gradually splash erosion deformation damage, and then the formation of similar "cylindrical" splash erosion pits, splash erosion pits from small to large, from shallow to deep. The undisturbed loess splash erosion deformation damage process presents "raindrops hit - water infiltration - soil humidification softening - soil particles splash loss-shallow and small splash pits-deep and large splash pits" development law.

(2)The splash erosion depth (Δh_t) shows an exponential growth trend with the rainfall duration. Its development process can be divided into a rapid growth stage I (0~10min), a slow growth stage II (10~40min), and a stable development stage III (40~60min), splash erosion deformation and damage mainly occur in the two stages of I and II, and the cumulative percentage of splash erosion depth in the two stages of I and II is more than 71.43%. The maximum splash erosion depth (Δh_{max}) shows a linear growth relationship with the raindrop frequency. The splash erosion damage diameter (D) and splash erosion diffusion diameter (K) with the raindrop frequency are positively correlated, the splash erosion diffusion diameter is about (2.14~4.77) times of the splash erosion damage diameter. The splash erosion volume (V_{loss}) with the raindrop frequency shows an exponential function relationship .

(3) Raindrop diameter and raindrop drop height on the soil splash erosion deformation of the influence of the more significant, light rain intensity small rain diameter and heavy rain intensity large rain diameter of the soil are more prone to splash erosion damage; maximum splash erosion depth, splash erosion range and splash erosion volume and raindrop drop height are positively correlate. Affect the degree of sputtering of the soil body in the key to the size of the raindrop kinetic energy, the greater the kinetic energy of the raindrops, and the more its sputtering

of the soil body erosion effect is more substantial.

(4) Changes in initial water content have a significant effect on the splash erosion characteristics of the undisturbed loess, compared with the undisturbed loess, the cumulative percentage of splash erosion depth of the dry specimens shows a first fast and then slow development trend, while the humidified specimens change in the opposite direction. The soil with a higher initial water content is prone to splash erosion damage under the condition of small rainfall intensity, while the soil with lower initial water content is prone to splash erosion damage under the condition of heavy rainfall.

(5) The shape of the splash pits evolves from approximate "cylindrical" to "wedge" to "groove" with the increase of surface slope, and the distribution of the splash erosion depth time curve slows down with the rise of surface slope and the maximum splash erosion depth has a linear decay relationship with the surface slope. The maximum splash erosion depth and the surface slope show a linear attenuation relationship. The soil body's splash erosion volume with the surface slope's increase show a first decrease and then an increase in the development trend. That is, there is a reasonable critical slope. In the essential conditions of the slope of the soil body, splash erosion volume is the smallest.

(6) Based on the experimental results, empirical expressions for predicting four characteristic indexes of raindrop splash erosion for in situ loess splash erosion depth, maximum splash erosion depth, splash erosion damage diameter, and soil splash erosion volume are proposed, which will provide a theoretical basis for the research on the prediction of soil splash erosion in loess hill and gully areas.

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Data availability

The data supporting this study are available when reasonably requested from the first author (QMM).

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