Freeze-thaw effects on erosion process in loess slope under simulated rainfall Postprint

Authors: SU Yuanyi, LI Peng, REN Zongping, XIAO Lie, ZHANG Hui, LI Peng

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Abstract

Seasonal freeze-thaw processes have led to severe soil erosion in the middle and high latitudes. The area affected by freeze-thaw erosion in China exceeds 13% of the national territory. So understanding the effect of freeze-thaw on erosion process is of great significance for soil and water conservation as well as for ecological engineering. In this study, we designed simulated rainfall experiments to investigate soil erosion processes under two soil conditions, unfrozen slope (UFS) and frozen slope (FS), and three rainfall intensities of 0.6, 0.9 and 1.2 mm/min. The results showed that the initial runoff time of FS occurred much earlier than that of the UFS. Under the same rainfall intensity, the runoff of FS is 1.17-1.26 times that of UFS; and the sediment yield of FS is 6.48-10.49 times that of UFS. With increasing rainfall time, rills were produced on the slope. After the appearance of the rills, the sediment yield on the FS accounts for 74%-86% of the total sediment yield. Rill erosion was the main reason for the increase in soil erosion rate on FS, and the reduction in water percolation resulting from frozen layers was one of the important factors leading to the advancement of rills on slope. A linear relationship existed between the cumulative runoff and the sediment yield of UFS and FS (R2>0.97, P<0.01). The average mean weight diameter (MWD) on the slope erosion particles was as follows: UFS0.9 (73.84 m)>FS0.6 (72.30 m)>UFS1.2 (72.23 m)>substrate (71.23 m)>FS1.2 (71.06 m)>FS0.9 (70.72 m). During the early stage of the rainfall, the MWD of the FS was relatively large. However, during the middle to late rainfall, the particle composition gradually approached that of the soil substrate. Under different rainfall intensities, the mean soil erodibility (MK) of the FS was 7.22 times that of the UFS. The ratio of the mean regression coefficient C2 (MC2) between FS and UFS was roughly correspondent with MK. Therefore, the parameter C2 can be used to evaluate soil erodibility after the appearance of the rills. This article explored the influence mechanism of freeze-thaw effects on loess soil erosion and provided a theoretical basis for further studies on soil erosion in the loess hilly

regions.

Full Text

Preamble

Freeze-Thaw Effects on Erosion Processes in Loess Slopes Under Simulated Rainfall

SU Yuanyi[12], LI Peng[12]*, REN Zongping[12], XIAO Lie[12], ZHANG Hui[3]

[1] State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi' an University of Technology, Xi' an 710048, China
[2] Key Laboratory of National Forestry Administration on Ecological Hydrology and Disaster Prevention in Arid Regions, Xi' an 710048, China
[3] China JIKAN Research Institute of Engineering Investigations and Design Co. Ltd., Xi' an 710048, China

Abstract: Seasonal freeze-thaw processes have led to severe soil erosion in middle and high latitudes. The area affected by freeze-thaw erosion in China exceeds 13% of the national territory, making understanding the effect of freeze-thaw on erosion processes critical for soil and water conservation and ecological engineering. In this study, we designed simulated rainfall experiments to investigate soil erosion processes under two soil conditions—unfrozen slope (UFS) and frozen slope (FS)—and three rainfall intensities of 0.6, 0.9, and 1.2 mm/min. The results showed that the initial runoff time of FS occurred much earlier than that of UFS. Under the same rainfall intensity, the runoff of FS was 1.17-1.26 times that of UFS, and the sediment yield of FS was 6.48-10.49 times that of UFS. With increasing rainfall duration, rills formed on the slopes. After rill appearance, the sediment yield on FS accounted for 74%-86% of the total sediment yield. Rill erosion was the main reason for the increase in soil erosion rate on FS, and the reduction in water percolation resulting from frozen layers was one of the important factors leading to the advancement of rills on the slope. A linear relationship existed between cumulative runoff and sediment yield for both UFS and FS ($R^2 > 0.97$, $P < 0.01$). The average mean weight diameter (MWD) of eroded particles followed the order: $UFS_{0·9}$ (73.84 m) > $FS_{0·6}$ (72.30 m) > $UFS_{1·2}$ (72.23 m) > substrate (71.23 m) > $FS_{1·2}$ (71.06 m) > $FS_{0·9}$ (70.72 m). During the early stage of rainfall, the MWD of FS was relatively large. However, during the middle to late rainfall stages, the particle composition gradually approached that of the soil substrate. Under different rainfall intensities, the mean soil erodibility (MK) of FS was 7.22 times that of UFS. The ratio of the mean regression coefficient C_2 (MC_2) between FS and UFS corresponded roughly with MK. Therefore, the parameter C_2 can be used to evaluate soil erodibility after rill appearance. This article explored the influence mechanism of freeze-thaw effects on loess soil erosion and provided a theoretical basis for further studies on soil erosion in loess hilly regions.

Keywords: unfrozen slope (UFS); frozen slope (FS); simulated rainfall; soil size selectivity; soil erodibility; loess hilly region

1 Introduction

Seasonal freeze-thaw cycles occur mainly in middle latitudes and are generally characterized by winter freezing and summer ablation (Bochove, 2000; Sahin and Anapali, 2007; Dagesse et al., 2010; Ren et al., 2018; Wang et al., 2018; Su et al., 2020). According to the Second National Soil Erosion Remote Sensing Survey, the area of freeze-thaw erosion in China exceeds 126.98 × 10^4 km^2, accounting for 13.4% of the total national land area (Wang et al., 2020). The middle reaches of the Yellow River in China experience these cycles due to soil temperatures below 0°C and down to -15°C between late October and late March of the following year, with soil temperatures below 0°C for a total of 110 days (Li and Fan, 2014; Cheng et al., 2018). These climatic conditions meet the requirements for freeze-thaw erosion. During the freeze-thaw cycle period, soil thaws in the morning and refreezes at night as temperatures decrease. Soil combines with meltwater, resulting in upper slope soil detachment and downstream sediment transport in rivers. Previous studies showed that the sediment yield from freeze-thaw combined erosion in the loess hilly-gully region can reach at least 30% of channel erosion (Wang et al., 2004). Freeze-thaw has both direct and indirect effects on the physical and chemical properties of soil (Ferrick and Gatto, 2005; Li et al., 2012). Studies also demonstrated that freeze-thaw cycles can effectively change soil structure (Pawluk et al., 1988; Henry et al., 2007), thereby reducing soil shear strength and increasing soil erodibility (Wang et al., 2015). Through laboratory tests, Edwards and Burney (1989) found that sediment yield after a freeze-thaw cycle increased by about 25%. When soil is in a frozen state, the volume expansion of soil water destroys the bonds between soil particles, thereby changing aggregate size distribution (Cruse et al., 2001). Freeze-thaw causes soil particle size to decrease, which has a major impact on water erosion (Layton et al., 1993; Oztas and Fayetorbay, 2003). In partial freeze-thaw erosion zones, the incompletely thawed layer is one of the important factors affecting soil erosion during the spring thawing period (Wischmeier et al., 1971). Frozen soil hinders water infiltration, which leads to greater runoff generation. Consequently, large amounts of sediment are detached and transported by runoff. Kirkby (1980) stated that half of the annual soil erosion in temperate zones occurs due to the thawing of frozen soils. When frozen soil thaws, its shear strength decreases and its erodibility increases, making soil more susceptible to loss during the thawing period (Ting et al., 1983). Sharratt et al. (2000) found that the impervious frozen layer in soil during the thawing period is the main factor leading to increased soil erosion. Previous studies mainly focused on changes in soil erodibility before and after freeze-thaw cycles but few examined the erodibility of partially frozen soil.

The size distribution of eroded sediment during erosion processes can well reflect the changing processes occurring during erosion (Bullock et al., 1988; Wang et al., 2017). Asadi et al. (2007) and Wang et al. (2014) found that the content of clay and silt in eroded sediment is higher during the initial erosion phase. As erosion time prolongs, sediment size gradually becomes larger and finally stabilizes. The size distribution of eroded soil depends on many factors such as soil texture, rainfall characteristics, runoff type, freeze–thaw, and topographical characteristics (Issa et al., 2006; Shi et al., 2012; Koiter et al., 2013). These factors affect soil aggregation. Under the combined action of rainfall and freeze–thaw cycles, slope erosion and sediment particle separation rules may differ significantly from those of single hydraulic erosion cases (Wischmeier and Smith, 1965). However, the erosion and sediment separation processes under this combined erosion have not been fully understood yet (Wang et al., 2013).

Due to differences in surface conditions and climate change, large differences exist in the characteristics of soil erosion during the thawing period among various local areas in the middle reaches of the Yellow River. These differences may affect soil erosion, in turn impacting soil dislodgement and transport. In this study, we conducted indoor simulated rainfall experiments to analyze soil erosion processes under different treatments, focusing on the influence of frozen soil thawing on soil erosion and sediment size distribution, to provide a baseline for further understanding of the soil water erosion mechanism on thawing slopes.

2.1 Materials and Devices

The soil was collected from abandoned farmland in the Wangmaogou watershed (37°34 13 -37°36 03 N, 110°20 46 -110°22 46 E) located on the Loess Plateau of China. This region lies within the temperate semi-arid continental monsoon climate zone, with an annual mean temperature of 10°C, a maximum of 39°C in July, and a minimum of -27°C in January (Zhao et al., 2017; Chang et al., 2019a, b). Therefore, during winter and early spring, soil undergoes several freeze–thaw cycles. The watershed is a two-branched depression on the left bank of the Wuding River, with an area of 5.97 km^2. The mean annual precipitation is 475 mm in the basin (Xiao et al., 2019a, b). Land use types in the basin are mainly grassland, sloping farmland, terraced land, and woodland (Shi et al., 2019, 2020). Soil particle size was determined using a Mastersizer 2000 sediment particle size analyzer (Malvern Instruments, UK). This analysis revealed that clay, silt, and sand accounted for 0.20%, 72.01%, and 27.79%, respectively. The soil was identified as silt loam according to the USDA (United States Department of Agriculture) soil classification standard. The dry bulk density of the soil is about 1.3 g/cm^3, organic matter content is 2.0 g/kg (Zhang et al., 2019), and saturated water content is 46.41%.

The experimental apparatus consists of three parts: the frozen soil system, the test soil trough, and the rainfall system. The frozen soil system (4.5 m length × 2.5 m width × 2.5 m height) adopts the freeze–thaw test system of Xi' an University of Technology. The temperature variation range is -40°C to 30°C ($±$1°C), which can meet the test requirements. The soil tank is a wooden impervious structure, with corners and periphery fixed by angle iron anchors, and the soil tank is mounted on a trolley so it can be moved. The dimensions of the box holding the soil are 2.00 m long, 0.75 m wide, and 0.35 m deep. A flume collects runoff and sediment at the lower end of the soil box (Fig. 1a [Figure 1: see original paper]). A rainfall simulator with different nozzle types is used to vary rainfall intensity. The nozzle is mounted 5.2 m above the soil surface to ensure drops reach terminal velocity, and rainfall intensity varies from 0.5 to 2.0 mm/min (Fig. 1b).

Fig. 1 Experimental device diagrams: (a) test equipment real diagram and (b) schematic diagram of the simulated rainfall system

2.2 Experimental Design

The simulated rainfall experiments were conducted at the State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China (Xi' an University of Technology) in Xi' an in October 2016. The experiment included two slope conditions (unfrozen slope (UFS) and frozen slope (FS)) and three rainfall intensities (0.6, 0.9, and 1.2 mm/min). Each experiment was replicated three times and the results represent the average of three replicates. To ensure consistent initial conditions for the rainfall simulation experiments, the slope gradient was set to 15°. The rainfall temperature during the tests was maintained at 15°C. Before testing, soil samples collected in the field were passed through a 5 mm sieve to remove roots, stones, and other debris.

The soil samples were then moistened to reach a water content of about 15%. Before filling the box with soil, a layer of gauze was placed on the bottom of the soil tank and a 5-cm thick layer of sand was placed on top of the gauze. According to the designed dry bulk density of the soil samples (1.30 g/cm^3), the box was filled with 5-cm thick layers of soil at a time, after which the topsoil was slightly roughened before the next layer was added to ensure close combination between soil layers. The total soil depth was 20 cm. To avoid wall effects on the erosion process, the slope was designed to be high in the middle and low on both sides. Soil boxes for the unfrozen slope were kept in the laboratory at 5°C–8°C room temperature. Some soil boxes were placed inside the freezer, and the soil was frozen for at least 24 h at -18°C to -22°C to ensure complete freezing. Soil boxes for the frozen slope were used for experiments immediately. To prevent soil moisture evaporation, all soil boxes were covered with plastic film, which was removed just before testing.

Rainfall intensity was determined before each test. Uniformity was measured by six rainfall gauges, and measurements were taken three times before testing and averaged. When rainfall uniformity exceeded 85% and the difference between measured and target rainfall intensity was less than 5%, the formal rainfall test could proceed. Runoff duration was set to 60 min. Runoff and sediment in the storage bucket were collected every three minutes and runoff volume was measured. Sediment was separated after settling the muddy water, then dried at 105°C for 24 h and weighed. The sediments were sieved through a 2 mm mesh for particle size composition determination using the Mastersizer 2000. Pretest results showed that no runoff occurred on the slope under 0.6 mm/min rainfall intensity. Therefore, in subsequent tests, the rainfall erosion process under this intensity was not analyzed.

2.3 Measurements and Data Analyses

Particle sorting characterizing the erosion process is expressed by the mean weight diameter (MWD; Bissonnais, 1996). Sediment size distribution was calculated as follows:

$$MWD = \sum_{i=1}^{7} x_i w_i$$

where x_i is the mean diameter of the ith size class (mm); w_i is the percentage of particles in the ith size class (%); and i is divided into seven grades (<0.005, 0.005-0.100, 0.100-0.200, 0.200-0.500, 0.500-1.000, 1.000-2.000, and >2.000 mm).

Soil erodibility data were obtained from indoor simulated rainfall tests. The formula for calculating the soil erodibility factor K in the Universal Soil Loss Equation (USLE; Weindorf, 2006) is:

$$K = \frac{A}{R \times L \times S \times C \times P}$$

where K is soil erodibility (kg · h/(MJ · mm)); A is the amount of soil loss (kg/m^2); R is the rainfall erosivity factor (MJ · mm/(m^2 · h)); L is the slope length factor; S is the slope factor; C is the crop management factor; and P is the management practice factor. Factors C and P were set to 1 under the conditions of this test.

A one-way ANOVA (analysis of variance) and Duncan' s multiple range test were used to determine whether differences between indicators and ratios were significant (P = 0.05). All statistical analyses were conducted using SPSS 21.0 (IBM, USA). Figures were generated in Origin 8.5 (OriginLab, USA). Photoshop (Adobe Systems Incorporated, USA) was applied to design the simulated rainfall system.

3.1.1 Characteristics of Runoff and Sediment Yield

In both FS and UFS, rills appeared during the rainfall process, but the timing of rill occurrence under similar hydraulic conditions differed between the two slopes (Table 1), with results also appearing different (Fig. 2 [Figure 2: see original paper]). According to relevant theories and experimental phenomena, erosion increases sharply after rill formation (Shen et al., 2016). These experiments used the time of rill occurrence as a threshold, dividing the erosion process into two stages: before rill appearance (-stage) and after rill appearance (-stage). The rills formed on UFS were shorter and shallower (Fig. 2a), while the gullies on FS were more developed and longer (Fig. 2b). The development speed and extent of rills directly affect slope erosion intensity. For the same rainfall intensity, runoff initiation time on FS was much shorter than on UFS. The initial runoff time of FS under rainfall intensities of 0.9 and 1.2 mm/min was 18.7 and 6.4 min earlier than UFS, respectively. As rainfall intensity increased, slope runoff rate increased significantly. When rainfall intensity increased from 0.9 to 1.2 mm/min, runoff rates of FS and UFS increased by 78.08% and 65.06%, respectively. For FS, significant differences in runoff rate occurred under different rainfall intensities ($P < 0.05$). Under weak rainfall intensity (0.6 mm/min), no runoff was recorded for UFS. However, FS produced runoff under these conditions due to the frozen layer. Slope erosion amount increased with rainfall intensity. Under the same treatments, sediment yield rate was much higher in the -stage than in the -stage. When rainfall intensity increased from 0.9 to 1.2 mm/min, sediment yield rates of FS and UFS increased by 40.8% and 4.03% in the -stage, respectively, and by 93.8% and 36.81% in the -stage, respectively. Furthermore, erosion on FS was much greater than on UFS. Under rainfall intensities of 0.9 and 1.2 mm/min, sediment yield rates of FS were 9.61 and 7.10 times those of UFS in the -stage, respectively, and 6.1 and 4.31 times those of UFS in the -stage, respectively. For FS, significant differences in sediment yield occurred under different rainfall intensities in the -stage ($P < 0.05$). This demonstrated that water was blocked by the frozen soil layer, which had a significant impact on hydraulic erosion.

3.1.2 Runoff and Sediment Yield Under Different Treatments

Figure 3a [Figure 3: see original paper] shows temporal variations in runoff rate under different rainfall intensities on UFS and FS. Runoff rate under different treatments exhibits a typical pattern where intensity increased rapidly at the beginning of rainfall before gradually stabilizing during the later period. The runoff rate of FS quickly reached a steady state, while that of UFS took longer to stabilize. Under 0.9 mm/min rainfall intensity, FS runoff rate became stable around the 15th minute, while UFS runoff rate increased gradually until the 53rd minute. For 1.2 mm/min rainfall intensity, runoff rates for both slopes increased rapidly from the 1st to 10th minute after runoff initiation, with FS runoff rate quickly approaching 1200 mm/min while UFS reached 900 mm/min. Under the same rainfall intensity, runoff yield rate was larger for FS than for UFS (Fig. 3a), indicating that the frozen layer both reduced initial runoff time and increased slope flow intensity, thus leading to increased runoff yield rate. Combined results from Table 1, Figures 2 and 3a suggest that rill influence on slope runoff process was limited, since slope runoff yield rate changed only slightly after rill formation.

Figure 3b presents temporal variations in sediment yield rate under different rainfall intensities on UFS and FS. Taking 1.2 mm/min as an example, FS sediment yield could be divided into two stages. Erosion in the -stage (0–12 min) was dominated by inter-rill erosion, during which sediment yield originated mainly from erosion between rills on the slope, with an average sediment yield of only 139.65 g/min. During the -stage, as small rills gradually appeared and developed rapidly, sediment yield rate increased to 523.00 g/min. Sediment yield on UFS can also be characterized by two stages (Fig. 3b). During the -stage (0–33 min), inter-rill erosion dominated, and sediment yield rate (19.67 g/min) was low, representing only 14.09% of FS. During the -stage (33-60 min), rill erosion gradually appeared on the slope and sediment yield rate increased drastically to 121.46 g/min, which was only 0.23 times that of FS. These results demonstrated that erosion processes on FS and UFS were similar, but rills on FS appeared earlier, developed more rapidly, and led to greater erosion intensity than on UFS.

Fig. 3 Temporal variations in (a) runoff rate and (b) sediment yield rate under different rainfall intensities. The numbers 0.6, 0.9, and 1.2 after UFS and FS represent rainfall intensities (mm/min).

3.1.3 Correlation Between Cumulative Runoff and Cumulative Sediment Yield

The soil erosion process in this experiment was divided into the -stage and -stage. The former is dominated by rainfall erosion, while the latter is dominated by runoff erosion. The entire slope erosion process obtained from our experiment was therefore analyzed according to these two stages.

A function was fitted to the relationship between cumulative sediment yield and cumulative runoff for each test. In the -stage and -stage, cumulative sediment yield showed good fit with cumulative runoff as follows (Eqs. 3 and 4):

$$y = C_1 x + D_1 \quad (\text{-stage})$$

$$y = C_2 x + D_2 \quad (\text{-stage})$$

where y is cumulative sediment yield (kg); x is cumulative runoff (L); and C_1, C_2, D_1, and D_2 are regression coefficients (Table 2).

Table 2 Fitted equations for cumulative runoff and cumulative sediment yield under different erosion stages

Treatment	-stage	-stage
$UFS_{0\cdot 9}$	$y = 0.033x - 3.052$ ($R^2 = 0.9975^{**}$)	$y = 0.049x - 37.537$ ($R^2 = 0.9986^{**}$)

Treatment	-stage	-stage
$UFS_{1\cdot 2}$	$y = 0.021x + 11.128$ ($R^2 = 0.9823$**)	$y = 0.083x - 174.74$ ($R^2 = 0.9786$**)
$FS_{0\cdot 6}$	$y = 0.269x + 23.462$ ($R^2 = 0.9865$**)	$y = 0.424x - 142.10$ ($R^2 = 0.9968$**)
$FS_{0\cdot 9}$	$y = 0.297x - 3.618$ ($R^2 = 0.9976$**)	$y = 0.575x - 469.78$ ($R^2 = 0.9981$**)
$FS_{1\cdot 2}$	$y = 0.176x + 67.248$ ($R^2 = 0.9861$**)	$y = 0.463x - 704.45$ ($R^2 = 0.9972$**)

*Note: MC_1, mean regression coefficient C_1; MC_2, mean regression coefficient C_2; **, P < 0.01 level.*

From the mathematical concept of the model and actual runoff yield, coefficients C_1 and C_2 are defined as sediment yield coefficients. These coefficients were found to follow certain patterns. The C_1 for the -stage was always smaller than that for the -stage, and the C_1 and C_2 of UFS were much smaller than those of FS. During the -stage, C_1 of FS was 9 times (0.9 mm/min) and 8.38 times (1.2 mm/min) that of UFS, while during the -stage, C_2 of FS was 11.73 times (0.9 mm/min) and 5.58 times (1.2 mm/min) that of UFS.

3.2.1 Variation of MWD During Slope Erosion

Although large differences exist between variations in MWD of eroded sediment particles on UFS and FS, temporal variations of MWD on the same slope type under different rainfall intensities were consistent (Fig. 4a [Figure 4: see original paper]). Between 0 and 12 min after rainfall runoff began, MWD of particles on both slopes increased rapidly and became larger than that of substrate particles. However, MWD of particles on FS was larger and increased with rainfall intensity, while that of UFS remained relatively small. Between 12 and 27 min, MWD of both slopes decreased rapidly, with a sharper decrease for FS. MWD of both FS and UFS showed an increasing trend during 27–54 min, but with large fluctuations for UFS particles, whereas fluctuations for FS were small. After the 54th minute, MWD gradually stabilized for both slopes and approached the substrate particle MWD. Under the conditions of this experiment, changes in MWD of natural eroded sediment particles were mainly influenced by soil freeze-thaw and slope runoff sorting characteristics. The average MWD values were: $UFS_{0\cdot 9}$ (73.84 m) > $FS_{0\cdot 6}$ (72.30 m) > $UFS_{1\cdot 2}$ (72.23 m) > substrate (71.23 m) > $FS_{1\cdot 2}$ (71.06 m) > $FS_{0\cdot 9}$ (70.72 m) (Fig. 4b). Under the same soil treatment, MWD of eroded sediment particles did not differ significantly under different rainfall intensities (P > 0.05). However, significant differences existed between $UFS_{0\cdot 9}$ and $FS_{0\cdot 9}$ and $FS_{1\cdot 2}$ in MWD (P < 0.05). Under the same rainfall intensity, MWD of UFS was larger than that of FS.

Fig. 4 Temporal variations of (a) mean weight diameter (MWD) of particles and (b) average MWD. Different lowercase letters represent significant differences between different rainfall intensities at the 0.05 level.

3.2.2 Variation of Different Grain-Size Sediment Particles

Sediment sizes of UFS and FS were classified as clay (<0.002 mm), fine silt (0.002–0.020 mm), coarse silt (0.020–0.050 mm), and fine sand (>0.050 mm). As shown in Figure 5 [Figure 5: see original paper], clay content was 0.200% for the loess. The total clay (<0.002 mm) content of UFS and FS varied from 0.025% to 0.163%, suggesting that little clay was dispersed. During the rainfall process, the percentage of clay (<0.002 mm) remained stable for all treatments. The sediment was principally composed of coarse silt (0.020–0.050 mm) and fine sand (>0.050 mm), which accounted for about 45% and 36% of the sediment, respectively (Table 3). Under different stages, coarse silt content remained essentially unchanged with rainfall intensity for both UFS and FS. Coarse silt content was greater for FS than for UFS in the -stage. The coarse silt and fine sand contents of FS were both smaller than those of UFS in the -stage. For UFS, fine silt content was greater in the -stage than in the -stage. For FS, fine silt content was greater in the -stage than in the -stage. Compared with UFS, FS had a larger content of fine silt.

Table 3 Average percentage (%) of effective particle size of sediment under different treatments

Treatment	Fine silt	Coarse silt	Fine sand
	I-stage	II-stage	I-stage
$UFS_{0\cdot9}$			
$UFS_{1\cdot2}$			
$FS_{0\cdot6}$			
$FS_{0\cdot9}$			
$FS_{1\cdot2}$			

3.3 Soil Erodibility

Estimates of soil erodibility based on measured data from simulated rainfall tests (Table 4) demonstrate that soil erodibility of FS is always greater than that of UFS under different rainfall intensities. The ratio of MK (mean soil erodibility) between FS and UFS was 7.22, and the ratio of MC_2 between FS and UFS was 7.38. These two values were roughly equivalent. For rainfall intensities of 0.9 and 1.2 mm/min, soil erodibility of FS was 13.46 and 7.16 times that of UFS, respectively. This result was consistent with the magnitude of slope erosion.

Table 4 Soil erodibility factor (K) calculated from rainfall simulation experiments for UFS and FS

Treatment	A (kg/m^2)	MA (kg/m^2)	R (MJ · mm/(m^2 · h))	LS	K (kg · h/(MJ · mm))	MK (kg · h/(MJ · mm))
$UFS_{0\cdot9}$						
$UFS_{1\cdot2}$						
$FS_{0\cdot6}$						
$FS_{0\cdot9}$						
$FS_{1\cdot2}$						

Note: A, amount of soil loss; MA, mean amount of soil loss; R, rainfall erosivity factor; LS, slope length and slope factor; MK, mean soil erodibility.

4.1 Effects of Freeze-Thaw on Slope Erosion and Sediment Yield

As shown in Figure 3a, FS had a higher runoff rate than UFS. The runoff rates of FS and UFS were related to thawing of the surface frozen layer. Li et al. (2009) confirmed the significant effects of FS on runoff and infiltration. FS produced higher runoff volume compared with UFS during experiments because water present in the soil surface layer and water in soil pores condensed to form an "ice cap." At the beginning of rainfall, the slope remained frozen and infiltration rate was low, so flow rate was high. As rainfall continued, soil temperature on the slope increased, and frozen soil within a certain depth from the surface gradually thawed, resulting in similar runoff yield rates for the two slopes. These results are consistent with previous studies (Øygarden, 2003; Zhou et al., 2009; Wang et al., 2018).

As shown in Figure 3b, FS had a larger sediment yield rate than UFS. During rainfall, the presence of a surface frozen layer reduced infiltration and increased surface runoff and erosion capacity. Increased runoff in turn acted on the frozen soil, which prompted thawing of the slope and continued release of erosive material (Zhang et al., 2018). The feedback between increased runoff and thawing accelerated erosion occurrence. During tests, fluctuations in sediment yield occurred, which may be related to rill development position and erosion mode. Numerous falling ridges formed at the bottom of the slope, after which rills formed and sediment yield increased. As rainfall continued, rills developed further and erosion was aggravated, manifesting as traceability erosion and side wall collapse. By the end of rainfall, sediment yield increased significantly (Fig. 2) due to inferior erosion and large amounts of slump (Wang, 2004). The linear relationships between cumulative runoff and sediment yield under both UFS and FS presented in this study lend further support to previously reported relationships (Wang et al., 2010; Xiao et al., 2011; Wang et al., 2017). The values of C_1 and C_2 may be related to slope thawing rate, thawing depth, and degree of erosion development during rainfall.

4.2 Effects of Freeze-Thaw on Soil Size Selectivity

Soil particles exhibited different size distributions during erosion and transport, reflecting changes affecting the erosion process (Farenhorst and Bryan, 1995; Sutherland et al., 1996). Runoff erosion dynamics on UFS were limited, making it difficult to form longer rills (Fig. 2a). In the long period after runoff initiation on the slope, soil erosion was dominated by inter-rill erosion, and eroded particles were mainly fine particles; fine silt content was higher while coarse silt content was relatively low. At runoff initiation, FS runoff rate increased rapidly and erosion power was large, resulting in higher coarse silt content in eroded sediment while fine silt content was lower. As rainfall continued, rills gradually formed on FS, and the slope gradually developed a slope-gully system (Fig. 2a). Following this, erosive sediment was generated from both -stage and -stage. The -stage usually caused fine particles to be enriched in sediment, while rill erosion had a weaker sorting effect on eroded sediment particles, resulting in more complex composition of eroded sediment particles (Wan and El-Swaify, 1998). However, in the later rainfall period, which saw further rill development, the proportion of rill erosion in total erosion increased, leading to gradual stabilization of slope erosion particles and sediment particle distribution approaching the original one. During soil erosion, differences in soil size selectivity between UFS and FS may be due to changes in soil properties caused by soil freezing.

4.3 Effects of Freeze-Thaw on Soil Erodibility

Global climate change will cause premature ablation of local frozen soil areas in seasonally freeze-thaw regions, thus changing hydraulic erosion characteristics. As differences in physical properties before and after soil freezing affect soil erodibility, UFS and FS showed different erosion and sediment yield processes during tests (Wang et al., 2019, 2020). In this test, soil erodibility after freezing was much greater than that of the control slope, consistent with results of Wischmeier et al. (1971). When soil freezes, pore water between soil particles generates various forms of ice crystal intrusion, resulting in increased soil volume. Ice crystal expansion in soil pores broke bonds between particles and changed agglomerate size in soil (Gatto, 2000). When local temperature began to rise and expansive soil began to melt, larger pores formed and soil corrosion resistance decreased. The ratio of MK between FS and UFS was 7.22. The ratios of MC_1 and MC_2 between FS and UFS were 9.15 and 7.38, respectively. In the -stage, freeze-thaw effects on soil erosion were large, and sediment yield on FS was much larger than on UFS. The ratio of MK between FS and UFS was similar to the ratio of MC_2. This indicated that soil erodibility can be evaluated by MK and MC_2. This finding was inconsistent with results of Wang et al. (2017). However, it should be noted that the ratio of MC_2 was not equal to the ratio of MK. The value of K only reflected average soil conditions, while the value of C_2 may reflect changes in accumulated sediments eroded under different soil treatments (UFS and FS) after rill occurrence. Therefore, C_2 could be an indicator for expressing soil erodibility in the -stage, providing a reliable basis for predicting changes in local water erosion.

5 Conclusions

The initial runoff time of FS was 6.4 to 18.7 min earlier than that of UFS under different rainfall intensities. Runoff and sediment yield of FS were much larger than those of UFS, and differences between FS and UFS were significant. However, both showed a similar pattern of rapid runoff increase followed by stabilization. Under the same rainfall intensity, rill occurrence on FS was 21 min earlier than on UFS. Sediment yield on UFS and FS could be divided into I-stage and II-stage, but FS had higher erosion intensity than UFS. A linear relationship existed between cumulative runoff and cumulative sediment yield for both slopes. The MWD of eroded slope particles followed the order: $UFS_{0\cdot 9}$ (73.84 m) > $FS_{0\cdot 6}$ (72.30 m) > $UFS_{1\cdot 2}$ (72.23 m) > substrate (71.23 m) > $FS_{1\cdot 2}$ (71.06 m) > $FS_{0\cdot 9}$ (70.72 m). During the early rainfall stage, MWD of FS was relatively large, with coarse silt being preferentially transported. However, during middle to late rainfall stages, transported particles on FS gradually changed to fine silt and clay, and particle composition gradually approached that of the soil substrate. The MK of FS is 7.22 times that of UFS. The ratio of MC_2 between FS and UFS corresponded roughly with MK. Therefore, C_2 could be used to evaluate soil erodibility after rill appearance. This study improved understanding of freeze-thaw and rainfall intensity effects on erosion processes. These results were based only on loess, so varying responses of other soil types to rainfall should be further investigated.

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Note: Figure translations are in progress. See original paper for figures.