Slope Erosion and Hydraulics During Thawing of the Sand-Covered Loess Plateau

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Abstract: Seasonal freeze-thaw processes have led to severe soil erosion globally. Slopes are particularly susceptible to changes in runoff, it can be useful to study soil erosion mechanisms. We conducted meltwater flow laboratory experiments to quantify the temporal and spatial distribution of hydraulic parameters on sandy slopes in relation to runoff and sediment yield under constant flow, different soil conditions (unfrozen slope: US; frozen slope: FS), and variable sand thickness. The results showed that sand can prolong initial runoff time, and US and FS have significantly different initial runoff times. There was a significant linear relationship between the cumulative runoff and the cumulative sediment yield. Additionally, hydrodynamic parameters of US and FS varied with time and spatially, as the distance between US and FS is linearly related to the top of the slope. We found that the main runoff flow pattern was composed of laminar flow and supercritical flow. There was a significant linear relationship between flow velocity and hydraulic parameters. The flow velocity is the best hydraulic parameter to simulate the trend of slope erosion process. This study can provide a scientific basis for a model of slope erosion during thawing for the Loess Plateau.

Keywords: loess; soil erosion; meltwater flow; runoff and sediment yield; hydraulic parameter

1. Introduction

The hydrodynamic properties of slopes have a decisive effect on runoff and sediment yield. Their study can help in understanding the process and mechanism of slope soil erosion and understanding the parameters of slope water dynamics, which are helpful in the construction of predictive models of slope soil erosion [1–3].

The Loess Plateau is a sand-covered landform that experiences substantial wind and water erosion [4–6]. Due to the differences in physical characteristics, infiltration, hydraulic conductivity, and water holding capacity between the surface sand layer and loess layer, a distinct sand-soil interface is formed between the sand layer and loess layer, and then the typical sand-soil dual structure is formed [7–10]. Zhang et al. [11] found in field rainfall experiments that the runoff and sediment yield processes on the sand-covered slopes are significantly different from those on loess slopes. Under light rain, the sand-covered slopes store rainfall, minimizing runoff, and the sediment content in any runoff that does occur is very large. Wu et al. [12] conducted a qualitative description of the sand-soil interface flow on the sand-covered slope through field surveys. Many scholars have studied the relationship between runoff and sediment yield, erosion processes, and the influence of sand layer size composition on runoff and sediment yield process through laboratory simulated rainfall experiments [6–8]. Tang et al. [13,14] quantitatively studied the spatiotemporal distribution...
of hydraulic parameters under different rainfall intensities and different sand thickness and their relationship with runoff and sediment yield. This study showed that the Reynolds Number can characterize the process of runoff and sediment yield on sand-covered slopes well [15]. However, studies on hydraulic characteristics of this particular landform at the slope scale during soil erosion is relatively limited.

The area of wind-water erosion on the Loess Plateau is in the middle latitude of the temperate zone, with an annual average precipitation of 300–600 mm. About 1/3 of days are below 0 °C each year, and it is windy and sandy in winter and spring with heavy rain in summer [16–19]. The hilly-gullied loess region is significantly affected by freezing and thawing, and snowmelt runoff erosion is a major manifestation of freeze-thaw erosion during thawing [20,21]. This erosion process is also found elsewhere throughout the world. In inland northeastern Oregon, 86% of soil erosion events are caused by freeze-thaw processes and snowmelt runoff [22]. In the northwest coastal region of the United States along the Pacific, over 90% of the total annual snow erosion is caused by melting snow [20]. When the frozen soil thaws, its shear strength decreases, and its erodibility increases, thus making the soil in the thawing period more susceptible to erosion [23–26]. The results of rainfall experiments by Sharratt et al. [27] showed that the impermeable frozen layer of soil prevents water infiltration during thawing, resulting in increased soil surface moisture content, surface runoff, with a high sediment content and soil erosion. The freeze-thaw process changes the structure of the topsoil and thereby influences the water erosion process as well [28,29]. At the same time, part of the hilly-gullied loess region subject to freeze-thaw erosion overlaps with the flakes of sand. Although this area of overlap is not large, it is widely distributed. Due to the overlapping of several types of erosion, “wind erosion, water erosion and freeze-thaw erosion”, this superposition effect causes very serious soil erosion [30]. At present, scholars have done a lot of research on single-force erosion and wind-water composite erosion on the Loess Plateau. However, little research has been done on the problems of soil and water loss caused by multiple erosion types in the above areas.

Therefore, we studied sand-covered loess slopes using laboratory scouring experiments. We analyzed soil erosion characteristics and the spatiotemporal variation in hydraulic parameters of the sand-covered slopes when frozen or not, and described the relationship between hydraulic parameters and runoff and sediment yield. This study can provide a scientific basis for the construction of erosion forecast models for sand-covered loess slopes during thawing periods.

2. Materials and Methods

2.1. Material and Device

Two soil types were gathered from the Wangmaogou watershed (37°34′13″–37°36′03″ N, 110°20′46″–110°22′46″ E) of the Loess Plateau in Suide county, Shaanxi Province, China (Figure 1). Soil particle size was measured using a Mastersizer 2000 sediment particle size analyzer. The loess was comprised of 0.20% clay, 72.01% silt, and 27.79% sand. The sandy soil was comprised of 0.72% clay, 14.38% silt, and 84.9% sand. The soil was identified as a silt loam according to the soil classification standard of the United States Department of Agriculture. The dry bulk density of the soil was 1.3 g/cm³, its organic matter content was 2.0 g/kg, and its saturated water content was 46.41%.
To measure soil erosion characteristics, we used a two-part experimental device that consisted of the frozen soil system and the scour experiment (Figure 2). The frozen soil system adopts a freeze-thaw test system implemented by the Xi’an University of Technology. The internal dimensions of the freeze-thaw were 4.5 m (length) × 2.5 m (width) × 2.5 m (height). Its internal temperature varied from −30–40 ± 1 °C. The temperature error was less than 2.0 °C, and there was a refrigeration and heating system, to maintain the experimental conditions. The system contained a runoff collection unit, soil box, sink, steady flow flume, and a water tank. The size of the soil box is 2 m long, 0.2 m wide, and 0.2 m deep with marks at 0.5 m increments on the side of the box to measure section velocities. From the top of the slope to the slope are S1, S2, S3, and S4. A sink of 2 m length, 0.2 m width, and 0.05 m depth was joined on the top of the soil box to make a stable concentrated flow.

2.2. Experimental Design

The scour experiments were conducted at the State Key Laboratory of Eco-hydraulics in the northwest arid region of China (Xi’an University of Technology) in Xi’an in April 2017. We used a local standard runoff plot and calculated the experimental flow rate from the mean precipitation during thawing as 1 L/min after correction. The scour experiment included unfrozen (US) and frozen...
slopes (FS) treatments and four sand thicknesses (0, 1, 2, and 3 cm). To ensure that the initial conditions of the scour experiments were consistent, the slope grade was set to 12°. The rainfall temperature was maintained at 10 °C and remained constant. Each experiment was replicated three times and we present the average of the three replicates. Each scour experiment lasted 15 min after the flow started (Table 1). Before the experiments, the soil samples were air-dried and passed through a 10 × 10 mm sieve to remove impurities such as plant roots. The soil samples were then moistened to a water content of 15% and covered with plastic film for 24 h to evenly distribute the soil moisture. A layer of gauze was laid on the bottom of the soil tank before the tank was filled with a 5 cm layer of sand. To mimic the soil’s dry bulk density, the box was filled with soil in 5 cm layer intervals, and layers were mixed. To avoid confounds of being introduced by the box itself, the slope was designed to ensure erosion would flow through the middle of the box by lowering the slope and raising the sides. Once the box was filled, sand of different thicknesses (0, 1, 2, 3 cm) was layered above the soil in the box, along with water to increase the sand’s water content. The soil tank was then frozen at −20 °C for 24 h and then placed on a scouring device bracket for testing. Since the room’s temperature was higher than that of the freeze-thaw experiment system, the scour experiment also thawed.

Table 1. Design table of scour experimental.

| State of Slope | Treatment | Depth of Sand (cm) | Flow Rate (L/min) | Slope (°) | Initial Soil Moisture Content (%) | Time (min) |
|----------------|-----------|-------------------|-------------------|----------|----------------------------------|------------|
| Unfrozen slopes (US) | U0 | 0 | 1 | 12 | 15 | 15 |
| | U1 | 1 | 1 | 12 | 15 | 15 |
| | U2 | 2 | 1 | 12 | 15 | 15 |
| | U3 | 3 | 1 | 12 | 15 | 15 |
| Frozen slopes (FS) | F0 | 0 | 1 | 12 | 15 | 15 |
| | F1 | 1 | 1 | 12 | 15 | 15 |
| | F2 | 2 | 1 | 12 | 15 | 15 |
| | F3 | 3 | 1 | 12 | 15 | 15 |

The flow rate was determined before the experiment began to ensure the difference between the actual flow and the intended treatment flow was less than 5% for three consecutive trials. After error testing, a formal test was performed by recording the initial flow time and collecting runoff and sediment samples every minute. Dye tracing (KMnO₄) was used to measure the flow velocity of different sections of the box by dividing the travel distance by the mean traveling time multiplied by an adjustment coefficient of 0.65. Samples were collected and the sediment was separated and then dried at 105 °C for 24 h and subsequently weighed.

2.3. Hydraulics Parameter Calculation and Methods

2.3.1. Calculation of Hydraulics Parameters

In this study, flow velocity \( V \), the Reynolds number (Re), Froude number (Fr), and the Darcy–Weisbach roughness coefficient \( f \) were selected as the research objects [31], then were calculated by the expression:

\[ V = V_m \times 0.65 \] (1)

where \( V \) is the mean flow velocity (m/s), \( V_m \) is the observed velocity (m/s), and the flow travel distance is divided by the mean travelling time:

\[ \text{Re} = \frac{VR}{v} \] (2)

where \( v \) is the kinematic viscosity (m²/s), and \( R \) is the hydraulic radius (m), which can be replaced by the value of average flow depth \( h \):
\[ h = \frac{Q}{VbT} \]  

(3)

where \( Q \) is the total runoff in time \( T \) (m³/s) and \( b \) is the width of water surface (m):

\[ \nu = \frac{0.01775}{1 + 0.0337t + 0.000221t^2} \]  

(4)

\( \nu \) (m²/s) is the kinematic viscosity, it was calculated as follows:

\[ \nu = \frac{0.01775}{1 + 0.0337t + 0.000221t^2} \]

where \( t \) is the water temperature (°C):

\[ Fr = \frac{V}{\sqrt{gh}} \]  

(5)

\[ f = \frac{8gh \sin \alpha}{V^2} \]  

(6)

where \( \alpha \) is the slope (°).

The coefficient of variation (CV) indicates the degree of data dispersion, the formula is as follows:

\[ CV = \frac{SD}{Mean} \times 100\% \]  

(7)

where \( CV \) is the coefficient of variation (%), \( SD \) is the standard deviation, and \( Mean \) is the average value.

2.3.2. Methods

The Photoshop (Adobe Photoshop CS4 Extended 11.0.1) was applied to design the experimental system. All statistical analyses were conducted using SPSS (IBM SPSS Statistics Version 21). Figures were generated in Origin 8.5.

3. Results

3.1. Erosion, Runoff, and Sediment Yield

3.1.1. Characteristics Values of Runoff and Sediment Yield

Table 2 showed the characteristic values of runoff and sediment yield under different treatments. Based on the initial runoff time of \( U_0 \), the change in the initial runoff time under different treatments was calculated. It is calculated that the initial runoff time of \( U_1, U_2, \) and \( U_3 \) is significantly longer than that of \( U_0 \), and the initial runoff time of the slope surface under different sand thicknesses has been extended by 3.5 (\( U_1 \)), 4.73 (\( U_2 \)), and 6.36 (\( U_3 \)) times. The initial runoff time of \( F_0 \) is 37.9% earlier than \( U_0 \). The initial runoff time of \( F_1, F_2, \) and \( F_3 \) did not change much compared with \( U_0 \), but compared with \( U_1, U_2, \) and \( U_3 \), the initial runoff time was much longer. Sand-covered slopes prolong initial runoff times and the effects become longer as the thickness of sand-cover increases. The initial runoff time of \( F_S \) was significantly shorter than \( U_S \). The total runoff under different treatments increased in the following order: \( U_0 < U_3 < U_1 < U_2 < F_3 < F_2 < F_1 < F_0 < F_1 \). The CV of runoff under different treatments was between 2.48% and 22.14%, and the fluctuation range of the runoff was small, indicating that the impact of sand cover and soil freezing on the slope runoff process is small. The total sediment yield across different treatments declined in the order \( U_0 < U_1 < U_2 < U_3 < F_0 < F_1 < F_2 < F_3 \). Based on the total sediment yield of \( U_0 \), the total sediment yield under different treatments are 3.37 (\( U_1 \)), 4.35 (\( U_2 \)), 4.96 (\( U_3 \)), 8.38 (\( F_0 \)), 8.88 (\( F_1 \)), 10.85 (\( F_2 \)), and 10.98 (\( F_3 \)) times. The CV of the sediment yield of \( U_S \) was between 27.8% and 63.3%, which indicates that the sediment yield process of \( U_S \) had a large degree of fluctuation. The increasing sand thickness increased the CV which indicates that the sediment yield of the slope varies drastically. The CV of \( F_S \) was between 3.33% and 35.22%. Under the same conditions of sand cover thickness, the CV of \( F_S \) was much smaller than that of \( U_S \), which indicates that the sediment yield of \( F_S \) was relatively stable.
Table 2. Initial runoff time, runoff and sediment yield under different treatments.

| Treatment | Initial Runoff Time (s) | Runoff Total Runoff/L CV(%) | Sediment Yield Total Sediment Yield/kg CV(%) |
|-----------|-------------------------|-----------------------------|---------------------------------------------|
| U0        | 39.38                   | 9.64                        | 22.14                                       |
| U1        | 138.01                  | 11.01                       | 14.05                                       |
| U2        | 186.36                  | 11.3                        | 15.51                                       |
| U3        | 250.58                  | 10.69                       | 20.67                                       |
| F0        | 24.45                   | 13.82                       | 2.48                                        |
| F1        | 31.91                   | 14.18                       | 6.17                                        |
| F2        | 34.02                   | 13.46                       | 13.86                                       |
| F3        | 32.41                   | 12.24                       | 11.93                                       |

Figure 2 showed the eroded topography under different treatments, with significant differences in surface morphology. On the unfrozen slopes and frozen slopes with different sand thicknesses, a rill appeared during the runoff process. However, under the same hydraulic conditions, the rill appeared in different shapes. For the US, the rill initially developed on the slope top and bottom, which extended to the slope middle at the same time. In U0, the rill showed a discontinuous distribution, and the development of the rill was primarily on the top (S1) and bottom (S4) of the slope. In U1, U2, and U3, the rills were continuous but shallow in depth. For the FS, the rill had the same characteristics. During the experimental processes, the rill initially only developed on the slope top and gradually extended to the slope bottom. The connected rill gradually appeared on the frozen slope (Figure 3).

Figure 3. Eroded topography under different treatments. Note: S1 (2, 3, and 4), Section 1 (2, 3, and 4).

3.1.2. Correlation between Accumulative Runoff and Accumulative Sediment Yield

A function is fitted to the relationship between cumulative runoff and cumulative sediment yield for each experiment. The fitted equation is \( M = CQ + D \), where \( M \) (kg) is the cumulative sediment yield, \( Q \) (L) is the cumulative runoff, and \( C \) and \( D \) are regression coefficients. All fitting equations were significant at \( p < 0.001 \) (Table 3). The coefficient \( C \) was defined as the sediment yield coefficient. \( MC \) was the mean of regression coefficient \( C \). This coefficient obeys a certain change law. The \( MC \) of the US and FS were 0.31 and 0.67, respectively. The \( MC \) of the FS was 2.16 times than that of the US, indicating that the dependency of sediment yield on runoff was stronger for the FS than for the US.
Table 3. Cumulative runoff and cumulative sediment yield fitted equation.

| Treatment | Fitted Equation | MC  |
|-----------|----------------|-----|
| U0        | $M = 0.093 \, Q + 0.029$ | $R^2 = 0.997$, $p < 0.001$ | 0.31 |
| U1        | $M = 0.283 \, Q - 0.016$ | $R^2 = 0.990$, $p < 0.001$ | 0.67 |
| U2        | $M = 0.397 \, Q - 0.035$ | $R^2 = 0.972$, $p < 0.001$ |       |
| U3        | $M = 0.465 \, Q + 0.263$ | $R^2 = 0.930$, $p < 0.001$ |       |
| F0        | $M = 0.565 \, Q + 0.001$ | $R^2 = 0.999$, $p < 0.001$ |       |
| F1        | $M = 0.593 \, Q - 0.361$ | $R^2 = 0.987$, $p < 0.001$ |       |
| F2        | $M = 0.740 \, Q + 0.566$ | $R^2 = 0.986$, $p < 0.001$ |       |
| F3        | $M = 0.778 \, Q + 1.003$ | $R^2 = 0.993$, $p < 0.001$ |       |

3.2. Hydraulics of Slope Runoff

3.2.1. Spatiotemporal Variations of Flow Velocity

For the US, the flow velocity varies from 0.23 to 0.35 m/s during the tests, and its fluctuation range is small (Figure 4a). For the FS, the flow velocity varies from 0.18 to 0.35 m/s during the test, and its fluctuation range is relatively large (Figure 4). Under the condition of the same sand thickness, the mean values of flow velocity on the FS were 85.92% (F0/U0), 96.13% (F1/U1), 84.84% (F2/U2), and 88.47% (F3/U3) of the US, respectively. During the entire experiment, the flow velocity of the US and FS generally showed a downward trend (Figure 4). However, due to the conversion from erosion between inter-rill erosion to rill erosion during the erosion phase, the flow velocity changed due to the occurrence of rills. In the early stage of runoff, erosion was mainly between inter-rill erosion, the slope was relatively smooth, the runoff resistance was small, and the flow velocity was large. When the rill was generated on the slope, the flow velocity decreased significantly, and it occasionally rose with the backwater and reaches unconnected rills. In later stages of the experiment, the flow velocity tended to stabilize because the rill no longer developed. The variability of the flow velocity was mainly due to the increased resistance caused by the ground surface, the runoff energy consumption caused by the water flow down-cut, and the collapse of the soil on the side of the rill. Due to the abundance and looseness of sand, the fluctuation of U3 flow velocity is more severe.

![Figure 4. Variations in flow velocity under different treatments over time. (a) Unfrozen slope, (b) frozen slope.](image-url)

In space, the $V$ of the US and FS and the distance from the top of the slope can be represented by a linear function (US: $R^2 = 0.893$, $p > 0.05$; FS: $R^2 = 0.952$, $p < 0.05$). For the US, the $V$ increases continuously as the distance from the top of the slope increases; for the FS, the $V$ increases first to the maximum and then decreases as the distance from the top of the slope increases. At the same section, the $V$ of the US decreases with the increase of the sand thickness, and then increases; the $V$ of the FS increases with the increase in the sand thickness. Regression analysis showed that the $V$ can be
described by a linear function of the distance from the top of the slope (Table 4). The fitted equation showed that there is a certain range in which the \( V \) increases continuously as the slope length increases. Therefore, the slope length is very important. In some cases, precautions should be taken to mitigate the harm of downhill scour. Setting intercepting trenches and terraces on the slope can greatly reduce the slope length and thus reduce the erosion of runoff.

**Table 4. Variations of flow velocity with the distance from the top of the slope (m/s).**

| Treatment | Distance from the Top of the Slope E/m | Fitted Equation |
|-----------|--------------------------------------|-----------------|
|           | 0.5  | 1       | 1.5  | 2       |                     |
| U0        | 0.26 | 0.29    | 0.29 | 0.32    | \( V_u = 0.071E + 0.212 \) |
| U1        | 0.21 | 0.27    | 0.33 | 0.29    | \( R^2 = 0.893, p > 0.05 \) |
| U2        | 0.22 | 0.31    | 0.31 | 0.35    |                     |
| U3        | 0.23 | 0.33    | 0.37 | 0.39    |                     |
| F0        | 0.19 | 0.20    | 0.26 | 0.33    |                     |
| F1        | 0.18 | 0.21    | 0.31 | 0.37    | \( V_f = 0.091E + 0.146 \) |
| F2        | 0.19 | 0.22    | 0.29 | 0.28    | \( R^2 = 0.952, p < 0.05 \) |
| F3        | 0.24 | 0.25    | 0.33 | 0.32    |                     |

Note: The parameter “\( E \)” means the distance from the top of the slope, the same to below.

3.2.2. Spatiotemporal Variations of the Reynolds Number

From open channel hydraulics, the runoff flow is laminar when the \( Re < 500 \), the runoff flow is turbulent when the \( Re > 2000 \), and the runoff is transitional when the \( Re \) is between 500 and 2000. During the entire experiment, the \( Re \) ranged from 149.2 to 533.69 under US and FS, indicating that most of the runoff is laminar (Figure 5). For the US, the average value of the \( Re \) increased across conditions in this order: U0 < U1 < U2 < U3. There was little change in \( Re \) in the U0 treatment over time (range 155.63 to 204.82). The \( Re \) of U1, U2, and U3 increased over time, and the \( Re \) of U3 at the end of the experiment exceeded 500. For the FS, the \( Re \) in F1, F2, and F3 were approximately identical, all increasing slowly over time. The F0 increased rapidly from 0 to 5 min, and then showed a slow downward trend.

![Figure 5](image)

**Figure 5.** Variations in Reynolds number under different treatments over time. (a) Unfrozen slope, (b) frozen slope.

In space, the \( Re \) of the US and FS and the distance from the top of the slope can be represented by a linear function (US: \( R^2 = 0.712, p > 0.05 \); FS: \( R^2 = 0.998, p < 0.01 \)). For the US, the \( Re \) was largest (\( Re > 500 \) for U1, U2, and U3) at 0.5 m from the top of the slope. As the distance from the top of the slope increased, the \( Re \) decreased. In the same section, the \( Re \) of the sand-covered slope was significantly larger than U0 (Table 5). For the FS, the \( Re \) was largest at 0.5 m from the top of the slope, and runoff was a transitional flow; only the \( Re \) of F0 is greater than 500. As the distance from the top of the slope
increased, the $Re$ decreased. As the distance from the top of the slope increased, the $Re$ decreased. In the same section, the $Re$ of F0 was greater than that of the sand-covered slope. At the same sand thickness, the $Re$ of F0 was greater than U0. The $Re$ of sand-covered slopes of US was larger than that of FS.

| Treatment | Distance from the Top of the Slope E/m | Fitted Equation |
|-----------|--------------------------------------|-----------------|
| U0        | 0.5   | 164.56 | 172.46 | 181.68 | $Re_u = -135.01E + 484.59$ |
|           | 1     | 194.56 | 209.84 | 225.10 |
| U1        | 2     | 300.48 | 309.84 | 319.19 |
|           | 3     | 319.19 | 328.55 | 337.91 |
| U2        | 4     | 312.48 | 321.84 | 331.20 |
|           | 5     | 321.20 | 330.56 | 339.92 |
| U3        | 6     | 320.92 | 329.28 | 338.64 |
| F0        | 7     | 319.64 | 328.99 | 338.35 |
| F1        | 8     | 318.36 | 327.71 | 337.07 |
| F2        | 9     | 317.08 | 326.43 | 335.84 |
| F3        | 10    | 315.80 | 325.15 | 334.50 |

3.2.3. Spatiotemporal variations of the Froude Number

The critical value of subcritical flow and supercritical flow is 1. If the $Fr$ is greater than 1, it is a supercritical transition of flow, otherwise, it is a subcritical flow. The $Fr$ gradually decreased over time (Figure 6). The $Fr$ in the US ranged from 3.88 to 5.24, and the $Fr$ of the FS ranged from 2.93 to 4.85. This indicated that the runoff on the slope is supercritical during the experiment. For the US, the $Fr$ of U0 was greater than the $Fr$ of the sand-covered slope. The changes in the $Fr$ of U1, U2, and U3 over time were roughly the same. For the FS, the $Fr$ decreased faster with time as compared to the US, and showed a clear layering phenomenon.

In space, the $Fr$ of the US and FS and the distance from the top of the slope can be represented by a linear function (US: $R^2 = 0.899, p > 0.05$; FS: $R^2 = 0.956, p < 0.05$). The $Fr$ under different treatments increased with the distance from the top of the slope (except U2 and F3). The maximum $Fr$ of U2 and F3 occurred at 1.5 m from the top of the slope. For the US, the $Fr$ of U0 in different sections was greater than the $Fr$ of sand-covered slopes. Under the same section, the $Fr$ had no obvious change law with the increase of sand thickness (Table 6). Under the same sand thickness, the $Fr$ of the US was larger than the $Fr$ of the FS.
Table 6. Variations of Froude number with the distance from the top of the slope.

| Treatment | Distance from the Top of the Slope E/m | Fitted Equation |
|-----------|----------------------------------------|-----------------|
|           | 0.5         | 1              | 1.5         | 2             |
| U0        | 3.37        | 4.47           | 4.67        | 5.32          |
| U1        | 1.86        | 2.89           | 3.67        | 3.66          |
| U2        | 1.40        | 3.74           | 3.76        | 4.34          |
| U3        | 1.76        | 2.98           | 4.07        | 4.29          |
| F0        | 1.35        | 1.45           | 1.92        | 3.18          |
| F1        | 1.25        | 1.68           | 3.39        | 4.03          |
| F2        | 1.37        | 1.62           | 2.72        | 2.86          |
| F3        | 1.74        | 2.38           | 3.56        | 3.24          |

F_{U0} = 1.488E + 1.656, \quad R^2 = 0.899, \quad p > 0.05

F_{U1} = 1.362E + 0.656, \quad R^2 = 0.956, \quad p < 0.05

3.2.4. Spatiotemporal Variations of the Darcy-Weisbach Roughness Coefficient

As shown in Figure 7, the f has volatility, but generally increases gradually with time. The range of the f for the US and the FS is 0.06–0.56 and 0.08–1.81, respectively. For the US, there was little change in f of U0, and the change of the f of sand-covered slope with time showed strong fluctuation. This phenomenon may be caused by sediment pick-up. This occurred due to the back water and increased resistance, and forced the f value to increase during the experiment. For the FS, the f of F0 increased sharply with time, and the change of the f of F3 with time was relatively gentle. In the case of frozen soil, the average value of the f decreased with the increasing sand thickness.

![Figure 7](image-url)

**Figure 7.** Variations in the Darcy-Weisbach roughness coefficient under different treatments over time. (a) Unfrozen slope, (b) frozen slope.

In space, the f of the US and FS and the distance from the top of the slope can be represented by a linear function (US: R^2 = 0.719, p > 0.05; FS: R^2 = 0.972, p < 0.05). Under different treatments, the f decreased as the slope length increased. Given the same thickness of sand cover and the same section, f was greater in FS than that in US (Table 7).
Table 7. Variations of Darcy-Weisbach roughness coefficient with the distance from the top of the slope.

| Treatment | Distance from the Top of the Slope E/m | Fitted Equation |
|-----------|----------------------------------------|-----------------|
|           | 0.5 | 1   | 1.5 | 2   |                  |
| U0        | 0.21| 0.09| 0.08| 0.06|                  |
| U1        | 0.72| 0.25| 0.13| 0.13| $f_U = -0.348E + 0.694$ |
| U2        | 1.04| 0.14| 0.13| 0.09| $R^2 = 0.719, p > 0.05$ |
| U3        | 0.65| 0.24| 0.11| 0.09|                  |
| F0        | 1.71| 1.57| 0.85| 0.26|                  |
| F1        | 1.57| 0.95| 0.33| 0.16| $f_F = -0.754E + 1.695$ |
| F2        | 1.18| 1.09| 0.45| 0.36| $R^2 = 0.972, p < 0.05$ |
| F3        | 0.78| 0.43| 0.17| 0.19|                  |

3.3. Quantification of Hydrodynamic Parameters of Slope Erosion under US and FS

3.3.1. Relationship between Flow Velocity and Hydraulic Parameters under US and FS

The flow velocity is one of the basic factors that affect the hydraulic parameters such as Reynolds number ($Re$), Froude number ($Fr$) and Darcy-Weisbach roughness coefficient ($f$). Figure 8 showed the relationship between flow velocity and hydraulic parameters. The $Re$ decreased with increasing $V$ in both the US ($R^2 = 0.797$) and the FS ($R^2 = 0.871$), while the $Fr$ increased with increasing $V$ in the US ($R^2 = 0.913$) and the FS ($R^2 = 0.977$). The $f$ decreased with increasing $V$ on the US ($R^2 = 0.857$) and the FS ($R^2 = 0.946$). Comparing the fitting coefficients of the various relations, it can be found that due to the influence of soil freeze, the flow velocity has less influence on the hydrodynamic parameters. All the determination coefficients ($R^2$) were high (from 0.797 to 0.977), and there was a significant linear relationship between flow velocity and hydraulic parameters ($p < 0.01$). This may be due to the fact that hydrodynamic parameters are also affected by flow depth and sediment concentration.
Figure 8. Relationship between flow velocity and hydraulic parameters. (a) $Re$ with $V$, (b) $Fr$ with $V$, (c) $f$ with $V$.

3.3.2. Interrelations of Flow Velocity and Hydraulic Parameters with Runoff Rate Response under US and FS

Table 8 showed the correlation between runoff rate with flow velocity ($V$) and hydraulic parameters ($Re$, $Fr$, and $f$) under different treatments. It can be seen from the equation that the above flow velocity and hydraulic parameters can be used to describe the runoff process under experimental conditions to a certain extent (Table 8). In terms of fitting effect for the runoff process of the US, the test parameters can be arranged in the order of $V > Fr > Re > f$. For the runoff process on the FS, the test parameters can be arranged in the order of $Fr > Re > V > f$. The runoff rate, flow velocity, and hydraulic parameters have a significant linear relationship ($p < 0.01$), and $R^2$ is above 65%. By fitting the data of flow velocity, hydraulic parameters, and sediment yield rate, it is found that although there is a certain relationship between them, this relationship is not significant ($p > 0.05$).

Table 8. Correlation between runoff rate with flow velocity and hydraulic parameters.

| Runoff/L | V(m/s) | Hydraulic Parameters |
|----------|--------|----------------------|
|          |        | $Re$                 |
| US       | $R = -6.394V + 2.559$ | $R = 0.0033Re - 0.443$ | $R = -0.278Fr + 1.788$ | $R = 1.207f + 0.445$ |
|          | $R^2 = 0.813$, $p < 0.01$ | $R^2 = 0.725$, $p < 0.01$ | $R^2 = 0.767$, $p < 0.01$ | $R^2 = 0.655$, $p < 0.01$ |
| FS       | $R = -1.474V + 1.273$ | $R = 0.0013Re + 0.437$ | $R = -0.084Fr + 1.141$ | $R = 0.167f + 0.791$ |
|          | $R^2 = 0.787$, $p < 0.01$ | $R^2 = 0.85$, $p < 0.01$ | $R^2 = 0.866$, $p < 0.01$ | $R^2 = 0.668$, $p < 0.01$ |

Note: $R$ was the runoff (L).

4. Discussion

4.1. Effects of Slope, Sand Cover, and Soil Freezing on Soil Erosion

For the US, the initial runoff time of the sand-covered slope increased, and the effect was clearer with the increasing sand thickness (Table 2). This is consistent with the research results of Zhang et al. and Tang et al. [8,13]. This relationship occurred due to the high porosity of aeolian sand soil [6]. The greater the sand thickness, the greater the water storage effect, and ultimately the initial runoff time increases greatly. For the FS, the initial runoff time was significantly reduced under different sand thicknesses because the water present in the soil surface layer and the water in the soil pores condense to form an “ice cap”. In early stages, the “ice cap” hindered the inflow and infiltration, resulting in a significant reduction in the initial runoff time [32,33].

The total runoff and total sediment yield on the slope are related to the degree of erosion on the slope during soil erosion [7]. We found the total runoff under different treatments was 1.02 to 1.28 times than that of U0, and the total sediment yield under different treatments was 1.97 to 10.94 times
than that of U0 (Table 2). Frozen soil and sand cover on the slope both lead to changes in the total runoff and total sediment yield. The reasons are as follows: (1) When the temperature drops below 0 °C, the water stored in the sand layer and the water in the soil pores freeze into ice, and the volume expands, which reduces soil stability. The bottom layer of the water-tight layer forms an impervious layer, the runoff flows along the contact surface, the friction between the water flow and the slope surface is reduced, and a small ditch is quickly formed, which increases the amount of erosion and eventually leads to increased soil erosion [34–38]; (2) frozen soil greatly shortens the initial runoff time and the appearance time of rill, which makes it easier to generate runoff on the slope surface, and also more likely to generate a fine ditch, leading to increased erosion [39–42]. The upper-most sand layer can prolong the initial runoff time and store more water. When the slope begins to produce water, the stored water will drain along with the runoff and carry more sediment, increasing sediment yield [4–6]. For the US and FS, the sediment yield of sand covered slope is 3.37~4.96 and 1.06~1.13 times of U0 and F0, respectively. In this study, the sediment yield under different treatments increased with the increasing runoff. There was a linear relationship between the cumulative runoff and cumulative sediment yield under different treatments (Table 3). This study further supported the previously reported relationships [43].

4.2. Effects of Slope Sand Covered and Soil Freezed on Hydraulic Parameters

Runoff on the slope is the driving force of soil erosion [44]. The movement of sediment particles will be affected by the runoff [45]. Therefore, there is a close relationship between slope runoff, sediment movement, and hydraulic parameters. In this study, the underlying condition is the main factor affecting hydraulic properties. The hydraulic characteristics of the slope are mainly affected by various factors such as sand cover and soil frozen [15,46]. Sand cover on the slope changed the infiltration capacity of the soil, which in turn changed the runoff of the slope. Therefore, the topography of the sand cover slope changed greatly during the experiment (Figure 2). Compared with the rill formed by U0, the sand-covered slope in the US formed wide and deep due to runoff erosion, and the runoff depth is increased, resulting in changes in hydraulic characteristics. The research results of Tang et al. [15] showed that the flow pattern of water greatly influences the erosion of sand-covered slopes. This study showed that flow velocity and hydraulics parameters can describe the runoff process under different treatments. Among them, $R^2$ of $V$, $Re$, and $Fr$ all reached more than 70% (Table 8). Since the data of flow velocity can be obtained directly by the experiment, the flow velocity can be used to better describe the runoff process of the US and FS. However, some seemingly effective hydraulic parameters cannot explain the process of sediment yield on the FS. Frozen soil condenses the water in the soil surface layer and pores into an “ice cap” that hinders runoff infiltration. The infiltration capacity of the slope is reduced, the runoff on the slope is larger, and the erosion is greater [47–49]. Therefore, during the experiment, narrow and deep ditches were quickly formed on the FS, resulting in changes in hydraulic characteristics. In addition, the limited observation technology during the erosion process leads to poor fitting of hydraulic parameters and sediment yield on the FS. Despite these shortcomings, the results of this study can still provide a reference for the establishment of a model of erosion on sand-covered loess slopes during thawing.

4.3. Implications for the Relationship between Hydraulic Parameters and Slope Erosion

Global climate change will cause the local permafrost area to melt in advance in the seasonal freeze-thaw area, thus changing the erosion situation in this area. Therefore, in the past few decades, soil erosion resulting from climate warming has captured strong attention in cold regions [49–51]. During the thawing period of winter and spring, the soil erosion in the wind water erosion crisscross zone of the Loess Plateau is usually the result of the combined action of water erosion, wind erosion, and freeze-thaw erosion. However, the problem of soil erosion caused by the combined action is far more than the harm of single action erosion itself. The superposition of different types of erosion has led to huge changes in soil erosion [30,52–55]. In future research, the analysis and quantitative description of composite erosion and single erosion should be encouraged. While it is necessary to measure the impact of each type of erosion on total erosion, it is also necessary to analyze the
relationship between hydraulic parameters, runoff, and sediment yield. According to the different effectiveness of hydraulic parameters, selecting the appropriate hydraulic parameters to establish an evaluation model is key \cite{56,57}. This information will help us clarify the feedback relationship between the soil erosion process and the hydrodynamic process from a scientific perspective. At the same time, erosion changes in local areas can also be predicted more comprehensively.

5. Conclusions

Flume tests were performed to study the mechanism of hydrodynamics erosion on the steep sand-covered Loess slopes during the thawing period to improve our understanding of the mechanisms of runoff and sediment yield and to establish a model of soil erosion during thawing. The results showed that the initial runoff time increases with the increase of sand thickness. Under the same sand thickness, the initial runoff time of FS is significantly shorter than the US. For the US, the total sediment yield of different sand thicknesses was significantly higher than that of U0. The cumulative runoff and sediment yield of different treatments can be expressed as a function of $M = CQ + D$. During the entire experiment, the flow velocity in the US and FS treatments generally showed a downward trend. The distance between the hydraulic parameters of US and FS and the top of the slope can be expressed as a linear function. The main flow pattern of runoff was composed of laminar flow and supercritical flow. Linear equations can be used to describe the relationship between flow velocity and the main hydraulic parameters including Reynolds number, Froude number, and Darcy-Weisbach roughness coefficient. Different hydrodynamic parameters show varying degrees of effectiveness in describing slope erosion processes. Flow velocity is the best hydraulic parameter to simulate the trend of slope erosion process.

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Abbreviations

The following abbreviations are used in this manuscript:

- US: unfrozen slope
- U0 (1,2,3): unfrozen slope, the thickness of sand covering is 0 (1,2,3) cm
- FS: frozen slope
- F0 (1,2,3): frozen slope, the thickness of sand covering is 0 (1,2,3) cm

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