Physical Modelling of Hydraulic Erosion Rates on Loess Slopes

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Abstract: Soil erosion is a major environmental problem of global concern. In the Loess Plateau region of China, erosion of loess slopes is one of the major modes of soil erosion, causing serious erosional problems. Most current studies of loess slope erosion use qualitative analyses from field investigations, while quantitative analyses from experimental physical simulations are relatively rare. This paper takes slope erosion, which is the most typical mode of loess erosion, as the starting point and investigates the hydraulic erosion process for different initial states using small-scale physical simulations. The slope erosion process can be generalised into two stages: rapid erosion, and slow and uniform erosion. Results of the physical simulations suggested that the initial dry density is negatively correlated with the erosion rate, but the initial water content is positively correlated with the erosion rate. The results of the study are not only of practical significance for the prevention and control of soil erosion on loess slopes, but also of theoretical significance, as they reveal the development of slope gully erosion.

Keywords: loess slope; water erosion; erosion rate; physical modelling; initial dry density; initial moisture content

1. Introduction

Loess is a quaternary accumulation of mainly silt, rich in carbonate, with large pores of yellow or yellowish-brown soil-like sediments, widely distributed around the world [1]. The Loess Plateau of northwest China is the most continuous and largest characteristic area of loess globally and contains the most complete strata [2]. The total area is about 640,000 km², accounting for 6.3% of the land area of China [3,4]. The region of the Plateau in the middle reaches of the Yellow River has the thickest loess deposits and is the most widely distributed area of loess in China, with an area of 275,600 km², accounting for 43.7% of the total loess by area in China [5]. This special geomorphologic environment has experienced serious soil erosion and is one of the most erosional areas in the world, as the average annual erosion amount has reached 15,000 t/km² [6,7]. The changes in hydrological processes and soil erosion in the Loess Plateau of China are the direct response of farmland abandoned vegetation restoration, resulting in runoff generation and long-term reduction of soil erosion [8]. The establishment of a soil erosion model for the Loess Plateau can facilitate the analysis of soil erosion in the Loess Plateau [9,10]. Erosion in this region can change the development and evolution of slope landscapes within river watersheds, and cause road erosion and even large losses of nutrients from the surface soil of agricultural land [11,12]. Some scholars conduct rill tests to understand the process of river erosion [13,14]. Therefore, clarifying the mechanisms and evolution of hydraulic erosion on loess slopes can be used to help effectively combat soil erosion in the region.

Under normal rainfall conditions, natural slope surfaces have a certain level of laminar scour [15]. The erosion intensity in different areas is different, depending on the soil type [16]. Studies have found that water flows much faster on saturated slopes than on
unsaturated slopes, and soil moisture and dry density affect slope erosion [17]. Other scholars have found that rainfall intensity and slope gradient play an important role in slope erosion [18]. Some studies have found through artificial rainfall tests that slope runoff can be divided into three flow zones: laminar flow, flocculation flow, and excessive flow. These studies have shown that water flow under normal rainfall conditions occurs in a laminar state [19,20] and under the scouring effect of laminar flow, soil on slope surfaces can be separated and transported [21]. Erosion resistance has been used as an indicator of the soil’s ability to resist runoff dispersion and suspension, mainly reflecting the internal properties of the soil [22]. In order to better understand the mechanism of soil erosion under water scouring, laboratory flume experiments were conducted with three rainfall intensities and four scouring inflow rates to evaluate their interaction [23,24]. Through rainfall experiments, it was found that there are differences in the expression of characteristic parameters of influencing factors [25,26]. Soil erosion resistance, on the other hand, refers to the ability to reduce runoff damage and mainly reflects external factors [26,27].

Recently, research has shown that the erosion and transport capacity of water flow during loess slope erosion is much greater than the erosion and transport capacity of raindrop strikes. This is the main reason for the current dramatic increase in erosional sand production rates, which is an important source of sediment in small watersheds [14]. In addition, field investigations and indoor soil pan rainfall simulation results have demonstrated that the occurrence of fine channel erosion during slope erosion increases the sand production of slope erosion by several orders of magnitude, with linear fine channel erosion now accounting for about 80% of the total erosion on the Loess Plateau [26,28–30].

Due to the complexity and stochastic nature of the development of hydraulic erosion on loess slopes, and the limitations of experimental conditions, studies of this process have so far been qualitative and there is a lack of quantitative studies of the hydraulic erosion mechanism and erosion rates on loess slopes. In this paper, the relationship between the erosion rate of loess slopes and its influencing factors is quantified, the characteristics of the hydraulic erosion process are analysed, and the mechanism of hydraulic erosion on loess slopes is revealed.

2. Materials and Methods

2.1. Materials

The test soil used in this experiment was taken from a typical loess section in Xi’an, China. The sampling site is shown in Figure 1. The sample was from Q3 Ma Lan loess and the sampling depth was 4 m. We stripped the surface soil, cleared the surface disturbed soil, and sampled the undisturbed soil. The basic physical properties of the sample in situ are shown in Table 1.

Table 1. Loess properties at the in situ experimental site.

| Density (g/cm³) | Water Content (%) | Percent Clay Φ < 0.005 mm | Percent Silt Φ < 0.074 mm | Percent Sand Φ > 0.074 mm | Hydraulic Conductivity (cm/s) |
|----------------|-------------------|---------------------------|---------------------------|---------------------------|-----------------------------|
| 1.27           | 13.3              | 25.8                      | 73.9                      | 0.3                       | 1.60 × 10⁻⁴                  |
2.2. Experimental Apparatus

The test device is a self-developed loess sample scour instrument (Figure 2). The loess sample scour instrument is composed of two parts: water supply system and scour system. The water supply system uses a constant flow head to control the flow rate to ensure a stable flow rate. The scouring system mainly consists of a scouring tank, an energy dissipation pool, and a sample loader. When the test equipment is complete, the slope erosion process and erosion amount are monitored in real time with the digital image real-time monitoring system until the soil sample is washed to destruction. The sample box used in this instrument is a rectangular ring knife, the size of the ring knife is 10 cm × 20 cm × 10 cm (Length × width × height), and it is open both below and above the sample area.

Five target moisture contents of the test soil were set, namely: 10%, 12%, 14%, 16%, 18%. Additionally, five test soil dry densities were set: 1.2 g/cm$^3$, 1.3 g/cm$^3$, 1.4 g/cm$^3$, 1.5 g/cm$^3$, 1.6 g/cm$^3$. 

Figure 1. Location of the study site in Shanxi, eastern Loess Plateau, China.

Figure 2. Apparatus used in the test.
1.5 g/cm$^3$, 1.6 g/cm$^3$. Hence, the combination of five moisture contents and five dry densities resulted in 25 test conditions in total.

A test soil sample was first dried and placed on a rubber sheet where it was crushed and impurities such as roots and stones were removed with a 2 mm sieve. Sieved samples were mixed, and sub-samples taken to determine their moisture content. The mass of water needed to raise the test soil to the target moisture content was then calculated and added. To perform this, 1 kg of soil sample was placed on an enamelled tray, and the corresponding amount of water was weighed out and sprayed evenly on the soil sample with a spray bottle. The wet sample was then mixed evenly and then weighed again after spraying. The soil sample was then sealed and placed in a humidifying dish container for 24 h to let the water fully and evenly mix through the soil.

Samples with different moisture contents and dry densities were prepared by the press method and weighed together with the ring knife for total mass. The preparation of the sample directly affects the accuracy of the test, so it is important to ensure that the sample is intact and free from cracks, that no gaps are left between the sample and the square ring knife, that the ring knife is not deformed, and that the top and bottom sides are kept at the same level as the soil sample. Soil samples were prepared according to remoulded soil to study the different stages of soil erosion to simulate the change in slope during rainfall [17,18].

2.3. Experimental Procedure

The slope of the scour trough was first fixed at a slope angle of 20 degrees. Specimens were then mounted to the specimen tank. Water was discharged into the energy dissipation pool at a constant flow rate, the water depth was measured, and the flushing time recorded. During the test, in order to ensure uniform injection of water and to abate local disturbance of the water flow, a constant head water supply device was used to control the flow rate, maintaining a constant water flow of 20 cm$^3$/s.

A container collecting the sediment-laden discharge water was placed below the test rig on a scale. Water release was immediately stopped, and the scouring time recorded, when the maximum scouring depth of the specimen reached 2 cm or when the water flow on the surface of the specimen changed from laminar flow to fine channel flow. The test was immediately terminated at the moment of formation of a fine channel, i.e., when the integrity of the soil sample was destroyed.

The specimen was then removed and the volume of collected muddy water was measured. A sample containing mud was taken and the total mass and volume of the specimen recorded on a video to calculate the amount of mud and sand. The soil sample was then replaced, and the above steps repeated for different working conditions.

Mud samples were then dried and the mass of the dried samples ($G_d$) was determined, the mud content of the mud-and-water sample were found, and the mass of the natural water content was given by deriving from the formula for calculating the water content, from which the flush volume is calculated.

$$G = G_d + G_w = G_d/W.G_w = G_d/(1 - W)$$

where $G$ represents the mass of soil sample (g); $G_d$ represents the mass of the dried soil sample (g); $G_w$ represents the mass of the water in soil sample (g); $W$ represents the water content.

3. Results and Discussion

3.1. Sample Test Analysis

The hydraulic erosion process on the slope surface of the loess specimen is shown in Figure 3. From this figure, it can be seen that the surface of the specimen is first face-flowed to produce sheet erosion. With the increase in scouring time, the slope surface gradually exhibits fine furrows, and the water flow changes from sheet diffuse flow to concentrated...
linear flow. Following this description, the hydraulic erosion process of the loess slope can be generalised as shown (Figure 4).

![Figure 3. The erosion process for different initial cross-sections of flow.](image1.png)

![Figure 4. A schematic interpretation of the erosion process for different initial cross-sections of flow.](image2.png)

From the laboratory simulation test results (Figure 4), it can be seen that under the same water content conditions, the process of forming a drop pit is slower when the initial dry density of the specimens is smaller. The development of fine grooves is also later when the initial dry density of the specimens is smaller. The appearance of the drop pit has a certain degree of randomness, and the appearance of a drop pit is a sign of the beginning of fine groove erosion. It is also a prerequisite for the development of fine channels.

Soil particles on the surface of the specimen are easily dispersed, and in the process of scouring, local unevenness in the slope surface will cause it to produce the phenomenon of a drop early on. When the runoff flows through the drop pit, some of the soil particles at the edge of the drop pit are eroded by runoff shear and gravity and will become very unstable and easy to disperse. At the same time, when the runoff flows into the drop pit, the phenomenon of energy dissipation further aggravates the size of the drop pit. As the scouring progresses, the drop pits continue to develop, and the beginnings of a fine gully emerge. The drop pits continue to develop until they are penetrated, forming a fine gully, the slope begins to develop a fine gully, the head of the gully continues to develop upwards, the walls of the gully continue to widen, the bottom of the gully continues to cut down, and the fine gullies evolve into a network of fine gullies in the form of a river network by interconnecting, annexing, and bifurcating themselves.
3.2. Stage and Characteristics of Process Curve of the Sediment Percentage

The sediment content process curve is a direct reflection of the erosion rate and its change process and can be used to characterise the change in erosion rate over time. From the experimental sediment content process and cumulative curve (Figure 5), combined with the experimental phenomena and the actual erosion of the loess slope, the hydraulic erosion process of the loess slope can be generalised into two characteristic stages, i.e., the rapid erosion stage and the slow and uniform erosion stage.

The first stage is the rapid erosion stage, in which the sand production rate of the slope surface fluctuates greatly, with alternating maxima and minima. The rate of sand production starts to increase again when pits appear again on the slope and develop rapidly.

The second stage is the slow and uniform erosion stage, which is characterised by a relatively stable state at this flow rate, with little change in sediment content over time. The fine channel is basically formed, and the flow rate of the fine channel is relatively stable during scouring, increasing slightly with the duration of scouring. As the area of catchment increases with the development of the fine channel, the flow rate in the channel increases and the flow velocity accelerates, and after the development of the channel to the top of the slope, the flow rate in the channel stabilises. The creation and development of fine channels makes the slope surface runoff complex, and there is no obvious regularity in the sand production rate on the slope surface; however, the greater the number of fine channels on the slope surface, the more fully developed the slope surface erosion becomes.

Figure 5. Curves of representative sediment discharge and cumulative curves of the representative sediment discharge. Initial water content (12%) sediment (a); Initial water content (12%) cumulative sediment (b); Initial water content (16%) sediment (c); Initial water content (16%) cumulative sediment (d).

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3.3. Influence of Initial Dry Density on Erosion Rate

The relationship between the average erosion rate of the specimens and the initial dry densities is shown in Figure 6. As can be seen (Figure 6), there is a significant negative correlation between the initial dry density of the specimens and the erosion rate. This result indicates that the resistance of the loess to scour and erosion increases significantly with increasing initial dry density at the same initial moisture content. The main reason for this is that as the initial dry density increases, the shear strength index of the loess specimen increases, and the critical initiation shear force of the loess particles increases [31].

3.4. Influence of Initial Moisture Content on Erosion Rate

The relationship between the average erosion rate of different initial moisture content specimens under the same initial dry density conditions is shown in Figure 7. It can be seen from Figure 7 that the initial moisture content of the specimen and the erosion rate show a significant positive correlation, i.e., the erosion rate of the loess specimen increases with the increase in the initial moisture content under the same initial dry density conditions. The main reason for this is that as the initial water content increases, the salt crystal film around the particles is dissolved and the strength of the association between the particles is gradually weakened, resulting in a reduction in inter-particle cohesion. In addition, the increase in water content weakens the matrix suction and capillary action between the soil particles, which, together with the lubricating effect of free water, ultimately leads to a reduction in the resistance of the loess to erosion [31].
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Figure 6. The relationship between loess erosion velocity and the initial dry density.
Figure 7. The inverse correlation between loess erosion velocity and the initial water content.

Figure 7. The inverse correlation between loess erosion velocity and the initial water content.
4. Conclusions

The following conclusions can be drawn.

(1) The hydraulic erosion of the loess slope is mainly based on fine channel erosion. Soil particles on the surface of the specimen are easily dispersed. In the process of scouring, some drop pits will first appear on the slope surface, and some soil particles at the edge of the drop pits are subject to runoff shear and gravity. The drop pits then continue to develop, and the beginnings of a fine gully appear as the drop pits merge.

(2) The hydraulic erosion process of loess slopes can be generalised into two characteristic stages, namely the rapid erosion stage and the slow uniform erosion stage. In the second stage, fine gullies are formed and the flow rate through the gullies is relatively stable during scouring. The creation and development of fine channels makes the slope surface runoff complex, and there is no obvious regularity in the slope surface sand production rate. However, the greater the number of fine channels on the slope surface, the greater the slope surface erosion volume will be.

(3) The erosion rate of loess was significantly negatively correlated with its initial dry density, but positively correlated with its initial moisture content. This result indicates that the resistance to scouring and erosion of loess increases significantly with the increase in initial dry density under the same initial moisture content. The main reason for this is that as the initial dry density increases, the shear strength index of the loess specimen increases, and the critical starting shear of the loess particles also increases. As the initial water content increases under the same initial dry density conditions, the erosion rate of the loess specimen increases. The main reason for this is that as the initial water content increases, the salt crystal film around the particles is dissolved and the strength of the association between the particles is gradually weakened, resulting in a reduction in the cohesion between the particles. That is to say, with the increase in initial dry density or the decrease in initial water content, the erosion resistance of loess increases.

Author Contributions: Conceptualization, X.-A.L.; Formal analysis, Y.-H.D.; Funding acquisition, X.-A.L.; Methodology, Y.-H.D.; Supervision, X.-A.L.; Writing-original draft, H.Z.; Writing-review & editing, J.L. and F.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of China, grant numbers 41172255 and 41572264.

Data Availability Statement: All data used in the study are confidential in nature, so the research data are not shared.

Acknowledgments: This work presented in this paper was supported by the National Natural Science Foundation of China (41172255, 41572264).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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