A Comparative Study of Developmental Differences in Soil Rill Network Runoff and Slope Sediment Production Process

Zhao Xinkai¹, Gong Jiaguo², Ren Zheng¹, Wang Danyang¹,
Zhao Yong², Yang Miao²,³, Shi Bin¹

¹College of Water Resources and Hydropower, Hebei University of Engineering, handan 056038, Hebei China;
²State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
³College Of Water Resources and hydrological, Hohai University, Nanjing 210098, China ;

Gong Jiaguo Jiaguogong@163.com

Abstract. To explore cultivated loessial soil and dark loessial soil rill network development and differences in slope runoff and sediment process. the three-dimensional laser scanning technology was used, the cultivated loessial soil and the dark loessial soil were taken as the research object, and the rain intensity of 60 mm / h and 90 mm / h was selected, and the simulated rainfall test of the 20° slope was carried out for 1 h. The results showed that the clay content of dark loessial soil was 2.5 times that of cultivated loessial soil. At the beginning of rainfall, the infiltration of black soil was slow, the runoff was earlier, and the runoff of slope was larger than that of loess. The landfall occurred earlier and the slope erosion was larger. but the cultivated loess soil is loose, poor in corrosion resistance and easy to be compacted by raindrops. In the second rainfall, the runoff on the loess slope was 1.4 times higher than that on the dark loess soil, and the erosion on the slope was higher than that on the dark loess soil. From the point of view of the development of rill net, the characteristic index of rill net of dark yellowed soil is larger than that of loess at the beginning of rainfall, but under the condition of rainfall in the middle and late period, the characteristic index of rill net of tilling layer loess is higher than that of dark loess. The rill development of cultivated yellow soil has the characteristics of late generation and fast development.

1. Introduction
Rill erosion is a major erosion in the Loess Plateau area of soil erosion [1]. After rill formation, the erosion amount of slope can be increased several times, and the contribution rate of rill erosion to slope erosion can reach more than 70% [2]. In some cases, the rill erosion can reach 97% of the slope erosion [3]. The generation and development of the rill on the slope has serious damage to the slope erosion. With the advancement of science and technology, new technologies such as 3D laser scanning are widely used in the simulation study of slope rill erosion process [4-5]. For example, the high-precision DEM is obtained by using 3D laser scanning technology, and the characteristic parameters of the rill network are extracted to analyze the evolution process of the rill network [6].
development of new technologies has overcome the limitations of existing measurement techniques and has advanced the study of rill erosion.

The rill on the slope evolved in a way similar to the evolution of the river network described by Horton [7]. With the development of science and technology, the study of the shape of the rill net has gradually changed from the original qualitative description to the quantitative study of the shape parameters of the rill. The evolution of the characteristic parameters of the rill network can quantitatively measure the development of the rill network. For example, the density of rills [8] can reflect the complexity of rill network, and the number of cleavage and number of nodes [6] can reflect the degree of divergence and degree of convergence of rill networks. The study of rill evolution and water-sand process has always been an important topic in the field of soil erosion [9-11], most of which are supported by rill geometry, while rill density, number of branches and joints are less applied. Soil has erosion sensitivity and erosion resistance as an object of erosion [12]. Studies have shown that soil clay content affects soil cohesion, and soils with good agglomerates have strong erosion resistance [13-14]. Studies have also shown that the soil has a large coarse grain content, a large soil gap and a good soil infiltration capacity, while the erosion of soil by slope runoff is reduced [15-16]. Most of the above studies are based on the properties of the soil and do not consider the effects of external factors such as rainfall intensity and soil interaction on slope rill erosion. Based on this, the experiment is based on cultivated loessial soil (mainly sand content) and dark loessial soil (mainly clay and powder content). Under the same conditions, artificial rainfall and three-dimensional laser scanning were used to carry out comparative experimental study. In order to study the difference between the process of runoff and sediment yield and the development of rill net under different rainfall intensity, the mechanism of rill erosion on slope was discussed.

2. Materials and methods

2.1. Test materials and equipment
The study was conducted at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau in Yangling City, China. Simulating rainfall using a simulated rainfall system. The rainfall simulation system can simulate any rainfall intensity from 30 to 350 mm/h. Four rain gauges were placed evenly around the test soil tank to measure the rain intensity. In order to ensure that the rainfall intensity reaches the planned value, the rain intensity rate is determined before the rainfall begins. The test soil trough is a variable-slope steel trough with a size of 10 m × 1.5 m × 0.6 m, and the slope of the steel trough varies from 0° to 30°. The steel troughs for the test steel troughs are separated from the middle, and two test soil samples of loessial soil and black loess soil are respectively loaded for the control test. The soil samples in this experiment were taken from Yan’an City (cultivated loessial soil) in Shanxi Province and Yangling District (dark loessial soil) in Shanxi Province. The soils such as the grass roots were removed from the two soils and naturally dried, and the mesh was sieved to a diameter of 1 cm for use. The content of sand, powder and clay in the cultivated loess soil is 71.81%, 19.37% and 8.82%, respectively. The content of sand, grain and clay in dark loessial soil was 40.74%, 39.17% and 20.09%, respectively. The slope was measured using a Leica Scanstation 2 3D laser scanner, and the resulting point cloud was dried and converted to a digital elevation model dem (resolution 5 mm × 5 mm). Camera mounted above the earthen trough (Canon EOS 5D Mark II). After the start of the experiment, take a picture of the slope every 2 s to obtain a slope topographic image with a size of 5616 pixels × 3744 pixels and a resolution of 72 dpi. Real-time monitoring of the development of rills on the slope.

2.2. Test design
According to the characteristics of erosive rainfall on the Loess Plateau [17] (I10=1.055mm/min, I5=1.52 mm/min), the rainfall intensity was 60 mm/h and 90 mm/h. Slopes with a slope of about 20° are most widely distributed on the Loess Plateau. In order to make the test results more representative, the slope of the slope is 20°. In order to reflect more objectively the change of rill shape in the process of slope
erosion, a multi-field continuous rainfall scheme was designed in this experiment. According to the characteristics of the natural erosive rainstorm on the Loess Plateau, which is mostly less than 1 h\(^{[18]}\), the duration of each rainfall is set to 1 h. According to the development of the rills on the slope, three experiments were carried out in each group.

In order to ensure the water permeability of the soil, a 10 cm thick sand layer is first laid on the bottom of the tank and a gauze is laid on the sand layer before the test. Fill every 10 cm with 4 layers of earth. The soil was filled in 4 layers per 10 cm layer, and the weight of the two layers was controlled at 1.25 g/cm\(^3\). The upper two layers were used to simulate the tillage layer. During the layered filling process, the soil moisture sensor (TRIM) was layered in the fixed position of the test tank, and the soil moisture data was obtained every minute to monitor the dynamic change of soil moisture. After the earth fill is completed, the slope is firstly pre-rained with a rain force of 30 mm/h. The purpose is to compact the soil particles by raindrops and reduce the spatial variability of potential soil conditions. In order to adjust the slope of soil trough, the 3D laser terrain scanner was used to collect the slope before each experiment, and then the rainfall test was carried out according to the predetermined slope and rainfall intensity of the experiment. Starting from the exit of the test area, the runoff, sediment concentration and other data are monitored every 3 minutes until the end of the rainfall. Thirdly, the 3D laser terrain scanner is used to collect the slope terrain information. After completing one set of tests, take out the test soil, refill it, and then start the next set of tests.

2.3. Data processing

The shape distribution of the rill is mainly reticular. According to this feature, the rill density is chosen to describe the complexity of the thin tube network. The selection of rill bifurcation ratio reflects the degree of dispersion of the development of rill network. The number of merged points of the rills is selected to reflect the degree of development of the rill network on the slope. Rill density might be expressed as:

\[
d = \sum_{i=1}^{n} \frac{L_i}{A} \tag{1}
\]

where \(d\) is rill density (m\(^2\)/m\(^3\)), \(L_i\) is the total length of the \(i\)th rill segment and its bifurcations (m); \(A\) is the area of the selected area (m\(^2\)); and \(i = 1, 2, \ldots, n\) represents the number of measurement points.

3. Results and analysis

3.1. Runoff process of cultivated loessial soil and dark loessial soil slope

Runoff of two kinds of soil slope increased with rainfall duration (Figure 1). In the first rainfall during 60 mm/h rainfall, the two soils were mainly infiltrated. Under the condition of 60 mm/h rainfall, the first rainfall, the two soils were mainly infiltration, and the slope runoff increased slowly with the rainfall duration. Figure 1 and table 1 show the dark loessial soil slope starts to flow after 8 min of rainfall, and the runoff slowly increases to 287 ml/s. The cultivated loessial soil began to flow after half an hour of rainfall, and the runoff slowly increased to 79 ml/s. The cultivated loess is mainly composed of sand particles, while the dark loess is mainly composed of clay and powder particles. The porosity of cultivated yellow soil is larger, the infiltration is more at the beginning of rainfall, and the runoff is small. The runoff of slope is smaller than that of dark loess. After the second rainfall, the runoff of the cultivated loess slope increased significantly and eventually increased to about 860 ml/s. However, the runoff on the slope of the dark loessial soil is very stable, and the runoff of the slope is basically stable at about 300 ml/s. Comparing the two soil slope runoff processes, the runoff of the cultivated loessial soil slopes surpassed the dark loessial soil. Analysis of the reasons, on the one hand, the cultivated loessial soil in the first rainfall infiltration more, less runoff, the soil moisture content in this rainfall exceeds the dark loessial soil, on the other hand, the cultivated loessial soil is dominated by sand, the soil is loose, in the raindrop splashing effect, more easily compacted. Under the influence...
of these two aspects, the slope runoff exceeds the dark loess. After the third rainfall, the runoff of the two soils increased first and then reached a stable state. The runoff of loess slope is stable at 990 ml/s or so, and that of black loess slope is about 350 ml/s. During this rainfall, both kinds of soil runoff processes fluctuate greatly. The rainfall was mainly due to the rill collapse, runoff showed greater instability.

Under the condition of rain intensity of 90 mm / h, the runoff process of the two soil slopes and the runoff process under the condition of rain intensity of 60 mm / h are basically similar. Compared with the rain intensity of 60 mm / h, the rainfall erosivity and runoff erosivity increased significantly, and the initial runoff time and the occurrence time of the drop sill were advanced (table 1). The initial runoff time of cultivated loessial soil and dark loessial soil was 27 min and 5 min earlier, and the time of occurrence of drop sill was 26 min and 13 min, respectively. It can be seen that the runoff from the slope of the cultivated loessial soil is more responsive to the change of rainfall intensity.

![Slope runoff process under rainfall conditions of 60 mm/h rainfall intensity](image)

![Slope runoff process under rainfall conditions of 90 mm/h rainfall intensity](image)

**Figure 1. Slope runoff process under different rainfall conditions**

| Rainfall Intensity (mm h⁻¹) | Initial runoff time of the first rainfall (min) | Produce drop sill time (min) |
|-----------------------------|-----------------------------------------------|------------------------------|
|                             | cultivated loessial soil | dark loessial soil | cultivated loessial soil | dark loessial soil |
| 60 mm/h                     | 38 | 8 | 49 | 27 |
| 90 mm/h                     | 11 | 3 | 23 | 14 |

### 3.2. Sediment yield process of cultivated loessial soil and dark loessial soil slope

The sediment concentration on the runoff of the slope is basically fluctuating with the rainfall duration (Figure 2). Under the condition of 60 mm / h, in the first rainfall, both soil slopes were mainly caused by sheet erosion and splash erosion, and the sediment concentration was low. At the beginning of rainfall, there was no rill in the slope, and the sediment concentration of both soil slopes was stable below 20 kg / m³. The dark loessial soil began to produce drop sill on the slope after the rainfall. The drop hole provides boundary conditions for the development of rills and is the beginning of rill erosion.
The sediment concentration of runoff on the dark loessial soil slope increased sharply after 30 min of rainfall, and increased rapidly from 20 kg/m³ to about 175 kg/m³. The cultivated loess soil began to fall after the rainfall of 49 min. The sediment concentration of runoff on the cultivated loess soil slope began to increase sharply after 55 minutes of rainfall, and increased rapidly from 20 kg/m³ to about 169 kg/m³. It can be seen that the generation of rills greatly improves the sand production on the slope, and there is a certain lag in the response of the sand production on the slope to the rill. After the second rainfall, the sediment concentration of the cultivated loessial soil increased rapidly from 290 kg/m³ to 810 kg/m³. The sediment concentration of cultivated loessial soil increased from 150 kg/m³ to 210 kg/m³. During this rainfall, the rill network of cultivated yellow soil is active, the runoff carries a large amount of sediment on the slope, and the sediment yield on the slope increases significantly. In the dark yellowing zone, the soil rill net developed slowly, and the sand production increased slowly. After the third rainfall, the sediment yield of the two kinds of soil slopes reached a stable state. The sediment concentration of the cultivated loess soil is finally stable at 800 kg/m³. The sediment concentration of the dark loess soil is finally stable at 800 kg/m³. In this rainfall, the sand production process on the slope also showed great fluctuations. It was also due to the serious collapse of the fine gully in the rainfall. It can be seen that the development of the rill network has a great influence on the sand production on the slope.

Under the condition of 90 mm/h, the sediment yield process of the two soil slopes and the slope runoff process under the condition of rain intensity of 60 mm/h are basically similar. Under the rain of 60 mm/h, the sediment concentration of cultivated loess soil exceeded that of dark loess soil in the second rainfall. However, under the rain of 90 mm/h, the sediment concentration of the cultivated loess soil exceeded that of the dark loess soil in the first rainfall. It can be seen that the increase of rainfall intensity increases the runoff erosivity and promotes the sand production process on the slope.

3.3. Development process of rill network on cultivated loessial soil and dark loessial soil slope

Extraction of rill network is based on ARCgis hydrological analysis method. Flow accumulation threshold was set as 150[8], which can ensure enough upstream drainage area to produce rills with their depths > 1 cm[19]. Compare the high-definition photos taken during the experiment and delete the...
non-existent rills. The spatial distribution of the rill network under three rainfall conditions is shown in Figure 3. The shape of the rill network is similar to that of the river network.

Figure 3. Development process of rill network under three rainfalls (Left is cultivated loessial soil, right is dark loessial soil)

Table 2 shows the variation of the characteristics of the rill network with the rainfall event under different rain intensity conditions. Under the condition of 60 mm/h rain intensity, the first rainfall, the rill density of cultivated loessial soil and dark loessial soil was 0.53 m/m² and 1.95 m/m², the rill bifurcation ratio was 3.27 and 4.29, and the rill combination number was 18 and 40, respectively. Comparing the characteristic parameters of the two soil rill networks, the development of the dark loessial soil network is larger. Mainly due to the same conditions, the dark loessial soil slope is more prone to production flow at the beginning of rainfall. In this rainfall, the average runoff of the dark loessial soil slope is 3.72 times larger than that of the cultivated loessial soil (table 3). Dark loess is washed by serious water flow, and the tracer effect of trench head, the widening effect of trench wall and the cutting action of furrow bottom are all greater than that of topsoil loess after the formation of thin gully. After the second rainfall, compared with the first rainfall, the rill density of the cultivated loessial soil and the dark loessial soil increased by 8.33 and 1.27 times, the rill bifurcation ratio increased by 5.57 and 1.77 times, and the rill combination number increased by 5.27 and 1.1 times, respectively. In this rainfall, the characteristics of the rill network of the cultivated loessial soil have increased significantly, and the rill network is active. Although each index of black loess has also increased, the increase is small, and the development of rill net is not as strong as that of cultivated loessial soil. On the one hand, the clay content of dark loessial soil is 2.5 times that of cultivated loessial soil, the clay content is high, and the cohesiveness is strong. It is easy to form cluster structure and improve the anti-dispersion ability of soil layer. On the other hand, with the advance of rainfall, the runoff on the sloping surface of cultivated yellow soil is 1.79 times of that on the dark yellow soil (Table 3), and the cultivated yellow soil is subjected to more serious water erosion. After the third rainfall, compared with the second rainfall, the rill density of cultivated yellow soil increased by 1.19 times, the densities of dark loess rill decreased by 1.03 times, and the rill furrow ratio decreased by 1.06 times. The rill bifurcation ratio of the dark loessial soil increased by 1.19 times, and the rill combination number of the cultivated loessial soil and the dark loessial soil decreased by 1.22 times and 1.25 times, respectively. In this rainfall, most of the characteristics of the two soil rill networks showed a small trend. Mainly due to the fact that in the rainfall of this event, the rill head extends to
the top of the slope, and the traceability of the rill head is weakened. Under the effect of the increasing width of the rill, the rill piracy is serious, resulting in a large number of secondary rill disappear.

Under the condition of rain intensity of 90 mm/h, the development process of the rill network of cultivated loessial soil and dark loessial soil is similar to that of the rill network under the condition of rain intensity of 60 mm/h. Compared with the rain intensity of 60 mm/h, the rain intensity increases, the rainfall erosivity and runoff erosivity increase, and the rill network develops more severely. The rill density and rill combination number of both soils were larger than those of 60 mm/h. However, the rill bifurcation ratio of the two soils is stronger than the 60 mm/h rain in the first rainfall, but less than 60 mm/h in the latter two rainfalls. Mainly due to the increase of rill erosion, the development of rill net is accelerated. In the early stage of rill development, there were more furrows. After rainfall in the middle and late stage, the intensity of rill connection and rill reclamation was more than 60 mm/h, The development of the rill experienced a process from simple to complex.

| Table 2. Characteristics of rill net with rainfall under different slope conditions |
|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Rainfall intensity (mm h⁻¹)     | Rainfall event                  | Rill density (m m⁻²) | Rill bifurcation ratio | Rill combination number |
|                                 |                                 | Cultivated Loessial Soil | Dark Loessial Soil | Cultivated Loessial Soil | Dark Loessial Soil |
| 60                              | 1ˢᵗ                             | 0.52                         | 1.95                         | 3.27                         | 4.29                         | 18                          | 40                          |
|                                 | 2ⁿᵈ                             | 4.33                         | 2.48                         | 18.23                        | 7.61                         | 95                          | 44                          |
|                                 | 3ʳᵈ                             | 5.18                         | 2.40                         | 17.15                        | 9.06                         | 74                          | 33                          |
| 90                              | 1ˢᵗ                             | 1.02                         | 2.59                         | 8.5                          | 4.41                         | 38                          | 64                          |
|                                 | 2ⁿᵈ                             | 4.86                         | 4.08                         | 17.67                        | 11.5                         | 101                         | 87                          |
|                                 | 3ʳᵈ                             | 6.05                         | 4.10                         | 7.33                         | 5.6                          | 121                         | 81                          |

| Table 3. Average runoff of two soil slopes |
|--------------------------------------------|--------------------------------|
| Rainfall intensity (mm h⁻¹)                | Soil type | Average runoff (ml s⁻¹) |
|                                            |           | 1ˢᵗ                      | 2ⁿᵈ                      | 3ʳᵈ                      |
| 60                                          | Cultivated Loessial Soil    | 62.58                    | 522.64                   | 833.79                   |
| Dark Loessial Soil                           | 233.01                | 291.34                   | 361.84                   |
| 90                                          | Cultivated Loessial Soil    | 277.23                   | 616.50                   | 1322.94                  |
| Dark Loessial Soil                           | 433.34                | 452.73                   | 587.23                   |

4. Conclusion
The content of sand grains in cultivated loessial soil is high, while the content of clay and powder in dark loessial soil is higher. Under the condition of two kinds of rain intensity, the infiltration of dark loess is less, the runoff time is earlier, and the runoff of three kinds of rainfall slope increases steadily until the stable runoff is achieved. The runoff increased slowly on the slope of the first rainfall, and the loess soil infiltration was more in the tilling layer. The cultivated loess soil is loose and easy to be compacted by raindrops. By the second rainfall, the runoff on the slope of the cultivated loess soil increased significantly, and the third rainfall reached a stable level. The initial runoff time of cultivated loess soil was advanced by 27 min, and the dark loess soil was advanced by 5 min. It can be seen that the runoff from the slope of the cultivated loessial soil is more responsive to the change of rainfall intensity.
The size of cultivated loess particle is large, and the infiltration amount is large, so it is not easy to produce runoff on the slope. Although it is difficult to cause erosion, soil stability is poor. Once erosion occurs, slope erosion increases sharply. Under the condition of two kinds of rain intensity, the sediment concentration on the loess slope is lower than that at the beginning of the rainfall, and the sediment content of the soil during the second rainfall is 2.7 times that of the dark loess soil. The development of rill in the cultivated layer of yellow soil has the characteristics of late generation and fast development. The development of black soil rill has the characteristics of early development and slow development.

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