The dynamic process of slope rill erosion analyzed with a digital close range photogrammetry observation system under laboratory conditions

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ABSTRACT

As the main process of soil erosion in the Loess Plateau of China, rill erosion accounts for a large proportion of the total erosion on the slope. Quantifying the rill shape is crucial for studying the mechanisms and evolution of rill erosion. The objective of this study is to monitor the dynamic process of slope rill erosion using a digital close range photogrammetry observation system during continuous rainfall. Artificial simulated rainfall experiments were conducted, and images were obtained at different time intervals. We used hydrological analysis and profile analysis tools in geographic information system (GIS) technology to extract rill networks and their main parameters to quantitatively describe the erosion processes of rill morphology. The results showed that (1) compared with the error from the traditional runoff sediment measurement method, the average error of the system for estimating soil loss was -7.06% and 1.05%, respectively, and the highest precision for a single observation was 99.46%; (2) the rill erosion process could be divided into several stages: raindrop splashing - eclipse - drop pit - erosion cave - rill cutting head - rill erosion - rill network; and (3) after rainfall lasted for 80 min, the density and the degree of splitting increased continuously, and the maximum rill width and depth both showed fluctuating trends. The area of 7.5 m to 9.5 m away from the top of the surface was the most active area of rill erosion. The digital close range photogrammetric observation system can accurately obtain evolution information about rill erosion morphology during continuous rainfall, which provides a reference for future studies of soil erosion processes.

1. Introduction

Soil erosion is a global concern as well as a serious threat to the environment and to agricultural security (Jiang et al., 2018; Montgomery, 2007; Wu et al., 2018a). The Loess Plateau, situated in the arid and semiarid regions of China, is well known for its significant soil erosion due to human activities and soil erodibility (Feng et al., 2016). Intense soil erosion has shown serious impacts on the ecological environment and sustainable socioeconomic development of China (Li et al., 2006; Stolte et al., 2003; Zheng et al., 2016). In the Loess Plateau, rill erosion is one of the main causes of slope erosion and soil loss (van den Elsen et al., 2003; Wu et al., 2003), accounting for more than 90% of the total slope erosion (Wang, 1998). The development of rills has an important influence on the occurrence of runoff on slopes and changes in landform morphology (Qin et al., 2018a; Stolte et al., 2003; Zheng, 1998). As erosion channels appear on the soil slope, runoff disperses, scours and transports soil particles and other components, and rill erosion is developed (Huo et al., 2011). Once rills are formed, soil erosion on the slope surface will increase rapidly, and the morphology of the slope surface will be constantly changed (Momm et al., 2018; Shen et al., 2018b; Vanwalleghem et al., 2017). With the development of the rill, water depth, flow velocity and erosive force will increase (Cai et al., 2004; Liu et al., 2006); the erosion mode of the slope...
surface will be changed fundamentally; and the erosion intensity will be greatly increased. Fertile topsoil is removed during the erosion process, resulting in a decline in the productivity of cultivated land (Shen et al., 2015). As erosion continues, the surface morphology will eventually change significantly. Thus, monitoring rill erosion processes is of great significance for revealing soil erosion mechanisms.

Recently, many researchers have studied the formation and morphological development of slope rill erosion by a range of indoor and outdoor simulated rainfall experiments and artificial runoff experiments (Borselli et al., 2001; Jiang et al., 2018b; Qin et al., 2018b; Rieke-Zapp and Nearing, 2005 Zheng et al., 1994). In a previous study, rill erosion originated from small drop pits during rainfall, and the occurrence of the drop pits represented the beginning of rill erosion (Zheng et al., 1987). From the perspective of hydrodynamics, rill erosion occurrences in a previous study had critical conditions (Li et al., 2016; Peng et al., 2015), and a Reynolds number, Froude number and unit energy for a water-carrying section were used as hydrodynamic indicators to judge the evolution of the erosion mode (Gong et al., 2011; Lei and Tang, 1998). When the rainfall runoff erosive force is greater than the soil corrosion resistance, rills begin to form and develop, which leads to the transformation of thin sheet flow into rill streams. Runoff velocity and depth increase correspondingly, and erosion characteristics change (Zheng, 1998). The soil erosion process on a loess slope surface was divided into 4 stages: raindrop splash - interrill erosion - rill erosion - runoff erosion after rain; rill erosion is the dominant process of slope erosion (Zheng, 1998). The process of rill morphological development was simulated based on the CA-Rill model (Wu et al., 2015), and the length, width and depth of rills were extracted to describe their geometrical characteristics (Shen et al., 2014; Wu et al., 2018b). Rill morphological changes are complex and rapid, and have obvious spatiotemporal variation characteristics on the slope surface (Berger et al., 2010). However, experiments on rill morphology at the field scale are mostly limited to qualitative or semi-quantitative descriptions, and few have focused on the quantification of rill morphology (Bewket and Sterk, 2003; Zhao et al., 2017). Existing studies of rill erosion have provided an important basis for understanding the dynamic conditions of rill formation, the amount of rill erosion and the spatial characteristics of rills.

As technology has become more robust and accessible, digital photogrammetry has been developed to generate digital elevation models (DEMs) with sufficient resolution for quantifying soil erosion morphology (Heng et al., 2010; Nounwako and Huang, 2012; Rieke-Zapp and Nearing, 2005; Vandekerckhove et al., 2003), and the grid resolution of a generated DEM on the underlying surface can be 1–15 mm (Aguilar et al., 2009; Brasington and Smart, 2003; Rieke-Zapp and Nearing, 2005). However, soil erosion morphology during ongoing rainfall has rarely been observed (Guo et al., 2016). During the process of rill development, changes of rill morphology are very complex (Lei et al., 1998), and rill erosion patterns can change greatly, even within a few seconds. Therefore, it is necessary to monitor rill morphology in continuous rainfall conditions and obtain instantaneous fine resolution soil surface information at both temporal and spatial scales.

In this study, based on two simulated artificial rainfall experiments, a close range digital photogrammetric observation system was adopted to acquire digital images of soil surfaces during ongoing rainfall events, and to monitor the processes of rill erosion. Combined with ArcGIS technology, we used hydrological analysis and profile analysis tools to extract erosion rill networks and the main characteristic parameters of erosion rills at various time intervals. This study aims to (1) monitor the processes of slope rill erosion during continuous rainfall by using the digital close-range photogrammetry system; (2) extract the characteristic parameters of rill development networks at different time intervals to quantitatively describe the evolution of the erosion rills; and (3) reveal the occurrence mechanism and development processes of erosion rills.

2. Materials and methods

2.1. Experimental design

The experiments were conducted in the artificial simulated rainfall test hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. The artificial rainfall simulation system covers an area of 27 m × 18 m with nozzles mounted at 18 m height (Zheng and Zhao, 2004) (Fig. 1a). The experimental rainfall intensity was set at 90 mm h⁻¹ and 120 mm h⁻¹, respectively. The rain intensity was calibrated before the experiments to ensure that the rainfall was evenly distributed. Four buckets were uniformly arranged above the slope surface of the soil bin to collect rainfall at 2 min after the start of the rainfall, and the average value of rainfall intensity was then calculated. The calibration continued until the difference between the measured rainfall intensity and the set rain intensity was less than 5% (Zhang et al., 2016). The final rainfall intensities were 91.5 mm h⁻¹ and 122.5 mm h⁻¹, and the rain intensity uniformity was greater than 90%.

The experiment plots consisted of two parallel steel soil bins that were 10 m long, 1.0 m wide and 0.5 m deep, with a collecting device for runoff and sediment at the bottom of the soil bins. The soil bins were set at different gradients of 15° and 20°. The experimental soil was loess taken from the northern part of the Loess Plateau, and the soil particles were dominated by fine sand and silt. The soil was first sieved through a 10 mm sieve to remove stones, plant roots and other debris and then loosely packed in the soil bins (Guo et al., 2016). To ensure good water permeability, 20 cm thick natural sand was laid on the bottom of the soil tank, and then 30 cm thick soil was added to achieve a bulk density of approximately 1.35 g/cm³, which was close to the natural state in the field. Then, soil samples were taken to the laboratory to measure the soil bulk density. After drying at 105 °C for 4 h, the average value of the soil bulk density was calculated. The soil bulk densities of the left and right soil bins were 1.372 and 1.374 g/cm³, respectively. The soil bins were subjected to a relatively low-intensity rainfall (30 mm h⁻¹) to pre-wet the soil surface until it was saturated but had no runoff (Momma et al., 2018); after standing still for 24 h, allowing the redistribution of soil moisture inside the soil bin was uniform and the soil structure was stable. According to the instantaneous rain intensity standard of erosive rainfall in the Loess Plateau of China, i₅ (maximum rainfall intensity of 5 min) is ≥ 1.520 mm min⁻¹ and i₅ (maximum rainfall intensity of 3 min) is ≥ 1.990 mm min⁻¹ (Zhou and Wang, 1987; Zhou and Wang, 1992), the rain intensities of the left and right bins were set to 90 mm h⁻¹ and 120 mm h⁻¹, respectively. Prior to the experiment, two targets were placed around the soil bins to constrain the accuracy of observations.

Two simulated rainfall experiments were conducted on 4th October 2018. The total rainfall duration for both experiments was 150 min. During rainfall application, image acquisitions were conducted at 5-minute intervals using a digital close range photogrammetric observation system (Fig. 1b). We also collected all water and sediment samples for each rainfall experiment, followed by the collection of sediments, drying, weighing and processing to calculate the soil erosion volume. To compare the observation precision of the laser scanning method and digital photogrammetric observation, we used a three dimensional (3D) laser scanner (Leica Scanstation 2) fixed to a tripod and placed in front of the soil bins to obtain the surface terrain (Fig. 1c).
2.2. Data acquisition

2.2.1. Digital close range photogrammetric observation

The digital close range photogrammetric observation system was used to monitor the changing soil erosion surface at different time intervals with continuous rainfall during the two experiments (Guo et al., 2016). This observation system was composed of three subsystems: the image acquisition subsystem, the data transmission subsystem and the image calculation subsystem. Based on wireless network technology, 12 Sony complementary metal oxide semiconductor cameras (CMOS) and industrial personal computers (IPCs) were installed in a steel frame 18 m above the ground to cover the entire surface of the two soil bins (Fig. 1a and b). Cameras collected data in parallel based on network commands, and noise on the images such as raindrops were eliminated by the K-means cluster (Bagirov, 2008; Terada, 2014) in IPCs during data acquisition. The detailed procedures of raindrop removal by using K-means cluster has been introduced by Jiang et al. (2019). The cameras and IPCs were remotely controlled by a dedicated computer to synchronize data collection and storage. The changes in the underlying surfaces were extracted from the digital images to more accurately describe the evaluation process of the soil surface erosion morphology at temporal and spatial scales. The precision of the digital close range photogrammetric observation system reached millimeter level, and the accuracy was more than 99% (Guo et al., 2016).

2.2.2. Runoff and sediment collection

Collecting runoff and sediment is the most reliable method in soil loss experiments (Tan et al., 2012; Wang, 1998). We collected all water and sediment samples for each rainfall experiment at the same time as the digital image acquisitions. Subsequently, we calculated the amount of soil loss and compared the results of runoff and sediment collection with the digital photogrammetric observations.

2.2.3. Laser scanning

A 3D laser scanner manufactured by Leica in Switzerland was used to simultaneously scan the soil erosion surface terrain twice before the beginning of rainfall and after the end of rainfall. The DEM data of the rill erosion patterns thus obtained were compared with the results of the digital close range photogrammetric observations.

3. Data processing and analysis system

3.1. Soil erosion calculation

3.1.1. Runoff and sediment collection method

Soil erosion volume was calculated by the conversion of sediment content per unit runoff, the runoff and soil bulk density data. We collected all runoff and sediment samples for each rainfall experiment, filtered out the clear liquid to obtain the sediment, and measured the volume of the sediment in the runoff barrels. Then, we mixed the water and sediment evenly and took 1000 ml of the mixed sample to measure the net sediment content by using a portable sediment measuring instrument. The soil erosion volume was calculated by Eq. (1):

$$V_i = \frac{Rm}{\delta}$$

where $V_i$ is the unit of soil erosion in the $i^{th}$ time interval (cm$^3$); $R$ is the total amount of water and sediment in the runoff barrel (ml); $m$ is the sediment content of the mixed sample of 1000 ml water and sediment (g/1000 ml); and $\delta$ is the soil bulk density (g/cm$^3$).

3.1.2. Calculation based on digital images

The soil erosion volume measurement was mainly carried out in Cyclone 6.0.3 (Wu et al., 2018a). The digital images at different time intervals were processed to generate three-dimensional point clouds from the digital close range photogrammetric observation system. When the flow channels appeared at the surface, runoff accumulated at the bottom of the channel, making capturing images of the inundated areas difficult and resulting in a sparse point cloud at those locations in the flow channel. To resolve this issue, we repaired the point cloud in the flooded areas by the inverse distance weight interpolation method, which is commonly used in geosciences, based on the existing sparse point cloud and variation.
in the terrain (Guo et al., 2016). The repaired digital point cloud was imported into Cyclone 6.0.3 to identify and remove outliers. The noise-free digital point clouds at different time points (approximately 1324 thousand points) were exported in a .txt format and then imported into Arcgis 10.2 to construct DEMs of the soil surface, and the pixel size of the constructed DEMs was 0.00296 m. The soil erosion volume was then calculated based on the difference between the DEM of the erosion surface before rainfall and DEMs of different time intervals during rainfall. Each grid of the DEM was regarded as a differential unit for volume calculation, and the soil erosion volume was calculated by multiplying the area of the unit by the distance from the grid mesh point to the reference surface. The soil loss was converted by the calculated soil erosion volume and bulk density. The equation was expressed as follows:

\[ V = \sum_{i=0}^{m} \sum_{j=0}^{n} e(i, j) * D_i \]  

(2)

where \( V \) is the soil erosion volume; \( m \) and \( n \) are the number of rows and columns of the DEM, respectively; \( e(i, j) \) is the distance from the point of the DEM grid \((i, j)\) to the reference plane; and \( D_i \) is the area of the DEM grid.

3.2. Rill network extraction and the calculation of rill morphology parameters

We used the hydrological analysis module in the ArcGIS spatial analysis tools to extract the rill networks at different time points and calculate the rill length data based on the extracted rill networks (Bruno et al., 2008). The direction of flow from every cell was the key to extract the rill networks. The D8 (eight direction) algorithm (O’Callaghan and Mark, 1984) was used to calculate the flow path from every cell into its steepest downslope neighbor and the size of the drainage area for each cell. We created fishing nets to cover the extracted rill networks and used the surface analysis module to extract the total surface area of the rills. The density of the rills and the average depth of the rills through the soil erosion volume were determined based on the calculated soil erosion volume and the total area of the bin. The rill cross-sections were generated every 0.5 m on the slope surface using the profile analysis module of ArcGIS 10.2 (Sun et al., 2014) and were then processed to extract the depth and width data of each rill on the unit slope length. The specific operation steps are shown in Fig. 2.

Rill density is the total length of all rills in the unit study area (Bewket and Sterk, 2003), reflecting the degree of slope fragmentation. The calculation formula is as follows:

\[ \rho = \frac{\sum_{n=1}^{m} L_{mn}}{A_0} \]  

(3)

where \( \rho \) is the density of the fine groove (m/m²); \( A_0 \) is the surface area (m²) of the study slope; \( L_{mn} \) is the total length (m) of the \( n^{th} \) rill and its bifurcation on the slope; \( n \) is the fine groove number, and \( n = 1, 2, \ldots \) \( m \) is the total number of rills.

The average rill depth is the weighted average of all rill erosion depths on the slope. The calculation formula is as follows:

\[ \bar{h} = \frac{\sum_{n=1}^{m} h_n A_n}{\sum_{n=1}^{m} A_n} \]  

(4)

where \( \bar{h} \) is the average depth of the rill (m); \( h_n \) is the depth (m) of each rill; and \( A_n \) is the plane area of each rill on the slope (m²).

The total surface area of the rill can also be called the actual damage area of the rill (Erskine et al., 2006), which is the sum of the plane area of all the rills in the study area, calculated by their length and width. The calculation formula is as follows:

\[ A = \sum_{n=1}^{m} A_n \]  

(5)

where \( A \) is the total surface area of the rill (m²).

The degree of rill dissection is defined according to the ground cleavage degree, which refers to the sum of the total surface area of all rills in the unit study area. It is a dimensionless parameter and can reflect the distribution of rills more intuitively. The calculation formula is as follows:

\[ \mu = \frac{\sum_{n=1}^{m} A_n}{A_0} \]  

(6)

where \( \mu \) is the degree of rill dissection, and \( A_n \) is the surface area of the \( n^{th} \) rill on the slope (m²).

4. Results and discussion

4.1. Soil erosion at different time intervals

4.1.1. Runoff and sediment collection and photogrammetric observation

By calculating the digital image of the underlying surface obtained by the digital close-range photogrammetry observation system, the soil erosion amount of the left and right soil bins at different time intervals during the ongoing rainfall was obtained, and the results were compared with those obtained from the runoff and sediment collection method (Table 1). The total soil erosion of the left and right bins measured by the digital close range photogrammetric system were 291,258 cm³ and 452,180 cm³, respectively. Compared with the runoff and sediment collection method, the relative errors of the digital close range photogrammetric system were 2.58% and 3.87%, respectively. Fig. 3 showed that with the extension of rainfall duration, the soil erosion observed by the two methods showed an overall upward trend, and the measurement
Table 1

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<th>Relative error (%)</th>
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Note: Relative error = (photographometry - runoff sediment) / runoff sediment * 100%.

Fig. 3. Observation results of soil erosion at different times.

Fig. 4. Relative error of measurement results between photogrammetry and runoff sediment.

The results of the two methods at different time intervals were very close. In addition, the sediment yield of the right slope was larger than that of the left slope at the same time point, which indicated that different slope gradients and rainfall intensities had an impact on soil erosion.

Fig. 4 shows the variation trend of the relative errors of soil erosion measurements between the two observation methods at different time points. The figure shows that during the initial 50 min, the relative errors between the two observation methods were largest, and with the extension of the rainfall duration, the observation errors gradually decreased and became stable. The main reasons for this dynamic were that soil moisture content was low at the initial stage of rainfall, the rainwater infiltrated into the soil rapidly, and the soil bulk density changed constantly. In addition, a large number of loose soil particles were splashed by raindrops, which influenced the measurement accuracy of the digital close range photogrammetric method. With the extension of rainfall duration and the intensification of soil erosion, the underlying surface morphology changed significantly, and the observation accuracy of the digital photogrammetry observation method increased. The average relative errors of all measurements for the left and right soil bins were -7.69% and 0.95%, respectively, indicating that the average observation accuracy of the digital close range photographic observation system was more than 90%.
of sight of the two instruments likely affected their performance in measuring the progress of rill erosion in the experimental plots. Installing the laser scanner vertically above the soil bins may have enabled a more consistent comparison, but was not possible due to water-proofing issues.

4.2. Rill erosion morphology development process

The digital close range photogrammetry observation system was used to obtain a digital point cloud of the rill erosion morphology development at different time intervals (Fig. 6). The digital point cloud was imported into ArcGIS 10.2 to generate the DEM. The hydrologic analysis module in the ArcGIS spatial analysis tools was used for extracting and quantifying the characteristics of the rill network (Fig. 7), and 100 mm² was considered to be the optimal drainage threshold area to extract the rill network. Fig. 7C1–C7 and D1–D7 show the rill network when the rainfall lasted for 30 min, 60 min, 80 min, 90 min, 110 min, 130 min, and 150 min under the condition of a 15° slope and 90 mm h⁻¹ rain intensity. Table 5 shows the rill morphological indicators extracted from the rill network at different time intervals.

Fig. 6A1–A7 and B1–B7 are the digital point clouds observed by the photogrammetric observation method at different time intervals with different rainfall intensities and slope gradients. The point cloud images revealed that the entire course of rill erosion on the left slope were composed of raindrop splashing - sheet erosion - drop pit - erosion cave - intermittent rill - continuous rill - rill erosion - rill network, while the processes of intermittent rill and continuous rill did not occur in the right slope. These rill development processes are common in the gully and hilly areas of the Loess Plateau. At the early stage of erosion, the soil moisture content was low, the water flow was mainly infiltration, the water infiltration speed was fast, and raindrop erosion was the main erosion mode. With an increase in soil water content, the infiltration effect was weakened, runoff on the slope began to increase, and the appearance of surface flow weakened the impact of raindrops (Zhang et al., 2017); then, the erosion began to change from raindrop splash erosion to sheet erosion, and the volume of runoff sediment increased gradually. As the rain continued, due to the uneven distribution of energy caused by the initial topography of the slope surface and the aggravation of the imbalance of surface erosion, the slope runoff gradually converged to form a concentrated stream, which continuously washed the soil. Subsequently, a drop pit appeared on the slope surface, which marked the beginning of rill erosion (Govers et al., 2007). However, the erosion rill development may have been influenced by different factors such as the rainfall intensity, soil property, slope, slope length and soil moisture content before soil erosion (Berger et al., 2010; Hao et al., 2019; Shen et al., 2018a); thus, the time and the location of the rills that began to develop between different slope surfaces varied. The first drop pit appeared at the position of 3 m from the bottom of the right slope when the rainfall lasted for only 10 min, while it appeared at the bottom of the left slope when the rainfall lasted for more than 30 min.

After the formation of the first drop pit, the erosion ability of the water flow increased rapidly, and the small drop pits gradually developed into erosion caves (Fig. 6A1 and B1). At this stage, the depths of erosion caves on the left and right slopes were 0.051 m and 0.059 m (Table 3), respectively. The catchment area in the upper slope surface was small and the slope surface was flat, while the water flow was relatively uniform; as a result, the runoff erosion was weak, and the slope was dominated by small streams. Only a sparse network of rills occurred at the bottom of the slope (Fig. 7C1), and the density of the rills was only 0.401 m/m², while the plane area of the rills was 0.063 m². When the rainfall lasted for 60 min, the rills developed continuously as the headcut advanced forward (Fig. 6A2 and B2), and the rill network became denser (Fig. 7C2).

4.1.2. Laser scanning and photogrammetric observation

Table 2 shows that the soil erosion volumes of the left bin measured by laser scanning and digital close range photogrammetry were 44090.16 cm³ and 23147.7 cm³, respectively, as the rainfall lasted for 60 min. Compared to the error of the runoff sediment method, the observation errors of the laser scanning and digital close range photogrammetry were 102.24% and 6.18%, respectively. As the rainfall lasted for 90 min, the amounts of soil erosion measured by laser scanning and digital close range photogrammetry were 241071.13 cm³ and 262126.84 cm³, respectively, and the observation errors of both methods relative to the runoff sediment method were -8.03% and 2.28%, respectively. The total soil erosion volumes observed on the right slope of the experiment by the laser scanning method and the digital close range photogrammetry were 407,971.36 cm³ and 452,180 cm³, respectively. The observation errors of the total soil erosion amount measured by laser scanning and digital close range photogrammetry relative to the runoff sediment method were 6.28% and 3.87%, respectively. The results from the observations showed that the digital photogrammetric observation method more accurately observed the variation in soil loss than the laser scanning method. Due to the linear laser transmission, the beam could not reach all parts of the bottom and sidewall of the channels, resulting in missing data. The black patches in Fig. 5b illustrate the missing data from laser scanning (Aguilar et al., 2009; Gessesse et al., 2010). The 3D laser scanner was fixed to a tripod for this experiment and placed in front of the plots to obtain the soil surface morphology, and, thus, failed to detect some areas due to its angle of orientation. Comparatively, the digital photogrammetric observation system is instrumented with 12 cameras for image acquisition, which are fixed perpendicular to the slope and can obtain sufficient information from the bottom and sidewall of the channels. This method made up for the defects of missing data in laser scanning observations. The different points
Table 2
Comparison of digital photogrammetry and laser scanning observations.

<table>
<thead>
<tr>
<th>Rainfall duration (min)</th>
<th>Soil erosion (left bin) (cm³)</th>
<th>Relative Error (%)</th>
<th>Soil erosion (right bin) (cm³)</th>
<th>Relative Error (%)</th>
<th>Runoff and sediment collection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laser scanning</td>
<td>Photogrammetry</td>
<td>Runoff and sediment collection</td>
<td>Laser scanning</td>
<td>Photogrammetry</td>
</tr>
<tr>
<td>After 90</td>
<td>241071.13</td>
<td>262126.84</td>
<td>262126.84</td>
<td>-8.03/2.28</td>
<td>-</td>
</tr>
<tr>
<td>150</td>
<td>285161.00</td>
<td>291258</td>
<td>283927.39</td>
<td>0.43/2.58</td>
<td>407971.36</td>
</tr>
</tbody>
</table>

Fig. 6. Digital point cloud observed by the photogrammetric method at different time intervals in two rainfall experiments.

The rill density developed to 0.799 m²/m², and the plane area of the rill increased to 0.384 m². The depth of the erosion rills obviously increased, and the maximum depth of the rills on both slopes reached to 0.113 m and 0.149 m; at this stage, the maximum length of the rills developed to 0.426 m and 0.623 m.

When the rainfall lasted for 80 min, the drop pit gradually developed into intermittent rills (Fig. 6A3). At this stage, the maximum rill depth of the left and right slopes increased rapidly to 0.200 m and 0.241 m, respectively, and the density of the rills also increased rapidly as well. When the rainfall lasted for 90 min, with the increase in the traceability erosion and undercut erosion, the sidewall of the eroding rill continuously collapsed. As a result, the intermittent rills located on the same flow path were developed and connected into continuous rills (Fig. 6A4), the number of rills gradually increased, a rill network was formed, the density of the rills reached 3.422 m²/m², the plane area of the rills increased to 1.028 m², and the branch intersection of the rill was also increased.

During the period from 90 to 150 min after the rainfall started, with the undercutting at the bottom of the trench and the lateral erosion at the trench wall, the headward erosion increased continuously (Bennett and Liu, 2016; Vanwallegem et al., 2017; Zhang et al., 2019), the connected rills developed gradually, and the soil
erosion intensity and the number of rills increased significantly; afterwards, the development of the rill network gradually remained stable. By the time the rainfall had lasted for 150 min, the density of the rill network on the left slope was 5.193 m/m², and the plane area of the rills was 1.960 m²; eventually, a relatively complete network of rills developed (Fig. 6A7 and B7). During the later stage of rill development, as the rill headcut advanced and deepened, the rills in the 15° slope surface mainly developed along the slope direction, and the maximum rill length increased from 0.599 m at 80 min to 1.104 m at 150 min. Due to the erosion of water flow, the stability of the rill wall reduced; when the soil block lost balance, the whole block collapsed, thus widening the rill. The rills in the slope surface of 20° developed less along the slope direction, increased mainly in width and depth, the mean width of the longest rill increased...
from 0.114 m at 80 min to 0.197 m at 150 min and the maximum rill depth developed from 0.024 m at 90 min to 0.107 m at 150 min. In short, the main modes of erosion in the early and late stages were headward erosion and lateral erosion, respectively.

4.3. Spatial distribution of soil erosion

4.3.1. 3D morphology simulation and elevation change rate

To more intuitively describe the changes of soil erosion morphology and the spatial distribution of erosion intensity in different erosion stages, we selected the development of soil erosion rills to represent the 3D morphology of the erosion slope (Wells et al., 2016; Wijdenes et al., 2000) and calculate the elevation change rate (ER) of each raster grid cell at each time interval (Momm et al., 2018). We imported the digital point data of slope surface erosion morphology at different time intervals into ArcGIS10.2 to generate DEMs, and the DEM surface (DEM$_{tm}$) obtained before the rainfall was taken as a reference plane to subtract the DEM surface (DEM$_{tn}$) of the erosion morphology at point $t_n$; subsequently, the elevation difference of the erosion surface in each time interval was obtained. The DEM surface (DEM$_{tm}$) was the erosion morphology at point $t_m$, and ER (m/min) is defined as follows:

$$ ER_{tm} = \frac{DEM_{tm} - DEM_{tn}}{t_n - t_m} $$

(7)

The 3D morphology of the slope surface was simulated in ArcScene 10.2 (Figs. 8 and 9). The magnitude of the elevation difference represented the intensity eroded by the rainfall of each grid at the surface position. With the extension of rainfall duration, the difference of rill erosion elevations increased gradually, indicating that the erosion intensity increased gradually. The region with positive elevation value in the images represented the area where the slope was eroded, and the green area shows where the erosion intensity was large. The 3D simulation of the erosion surface morphology can effectively reflect the change and the distribution of soil erosion.

Fig. 10 displays the ER of the left erosion surface at different time intervals, which reflects the distribution of newly increased erosion areas on the slope surface based on the original erosion, and the rills developed along the direction of the slope from the position of the newly increased erosion region. The magnitude of the ER represents the erosion rate and it increased gradually over time. The region with a small negative value of ER indicates that the erosion rate was faster, the erosion intensity was large, and the erosion activity was more severe. The region of the ER value near 0 indicates that the erosion rate and the erosion intensity were small and generally occurred in the upper part of the slope and surrounding areas of the slope. Within the first 30 min of rainfall, erosion occurred on the entire slope, but the erosion intensity was small. After 80 min of rainfall, the ER was faster and the erosion area increased gradually.

4.3.2. The maximum rill width and depth vary with the unit length of slope surface

We used the profile analysis module of ArcGIS 10.2 to extract the rill width and depth with the unit length of the left slope surface. The slope length in the experiment was 10 m, but no significant
erosion occurred in the area of 0–3 m from the top. Therefore, section analysis was carried out 3 m away from the top of the slope with a 0.5 m interval. Through the profile analysis, the maximum rill widths and depths, varying with the unit slope length at the rainfall durations of 30 min, 60 min, 80 min, 90 min, 110 min, 130 min and 150 min, were obtained (Figs. 11 and 12).

In the first 80 min, erosion occurred only in the area of 6–10 m from the top of the slope, and the maximum rill width and depth increased first and then decreased with the increase of the unit length of the slope. After 80 min, the rill developed at the position of 3.5 m away from the top of the slope, and the fluctuating trend of the maximum rill width was not obvious compared with the trend of the maximum rill depth between the region of 3.5 m and 7.5 m away from the top of the slope (Fig. 11); this result indicated that undercut erosion was greater than lateral erosion at the same position on the slope surface. The variation of maximum rill width and depth was highly obvious between 7.5 m and 9.5 m. According to the ER at different time intervals and rill erosion patterns, the area from 7.5 m to 9.5 m away from the top of the slope was the most active area of erosion rill development. The section positioned at 7.5 m on the slope surface was the inflection point, as it denoted the position of the watershed between the two intermittent rills. Because the erosion intensity of the inflection point was weaker, the values of the maximum rill width and depth at the inflection point were smaller than the upper and lower areas.

5. Conclusions

In this study, successive rainfall experiments at rainfall intensities of 90 and 120 mm h\(^{-1}\) were conducted to monitor the morphological development of rill erosion with our digital close range photogrammetry observation system. Rill networks and the main parameters of the erosion rills were extracted to quantitatively describe rill morphology development. Comparing the traditional runoff and sediment method with the digital close range photogrammetry observation method showed that, as rainfall duration increased, the observation accuracy of the digital close range photogrammetry observation system also increased. The average errors of the estimation precision of the soil loss in the left (rainfall intensity: 90 mm h\(^{-1}\)) and right (rainfall intensity: 120 mm h\(^{-1}\)) soil bins were -7.06\% and 1.05\%, respectively, and the single observation accuracy was up to 99.46\%. Additionally, the observation accuracy of digital close range photogrammetry was greater than that of laser scanning. The evolution process of rill erosion was characterized by distinct stages: raindrop splashing - eclipse - drop pit - erosion cave - rill cutting head - rill erosion - rill network. The development pattern of rills was mainly headward erosion in the early stage and lateral erosion in the later stage of soil erosion. After the rainfall lasted for 80 min, the density of the rill network began to increase rapidly, and the erosion intensity increased continuously. Furthermore, the section positioned at 7.5 m on the slope surface was the inflection point, as it denoted the position of the
watershed between the two intermittent rills, and the area in the slope surface between 7.5 m–9.5 m away from the top of the slope was the most active area of erosion.

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