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Digital close range photogrammetry for the study of rill development at flume scale

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ABSTRACT

Soil erosion is a continuous process of detachment, transportation, and deposition of soil particles. Obtaining accurate descriptions of soil surface topography is crucial for quantifying changes to the soil surface during erosion processes. The objective of this study was to develop an improved close-range photogrammetric technique to assess soil erosion under rainfall conditions. Based on high overlapping image acquisition, digital point cloud matching, digital elevation model (DEM) generation and soil erosion calculation, a digital close-range photogrammetric observation system was explored and established. The results showed that the established digital photogrammetric observation system could accurately calculate the digital point cloud from the underlying surface with a 2 min time interval and a 1.5 mm spatial resolution. In addition, based on the DEM generated from digital point clouds, the amount of soil erosion in different topographic positions within various time periods was calculated. The digital photogrammetric observation methods explored in our study provide a reliable way to monitor soil erosion processes, especially under rainfall conditions. This approach can accurately resolve the evolution of the underlying surface soil erosion, which is of great importance in understanding soil erosion mechanisms.

1. Introduction

Soil erosion is an important environmental issue in many parts of the world. Detachment and transportation of soil particles during the erosion process can result in soil degradation, water pollution and damage to drainage networks (Morgan, 2005; Peter Heng et al., 2010). During an erosion event, the soil surface is continuously transforming. Depending on the volume of soil transported, erosion processes can result in considerable topographic variations that can have broad effects on agricultural practices (Liu et al., 2004; Peter Heng et al., 2010). Various technologies have been developed by soil and geomorphology scientists to acquire detailed information on the variation in the soil surface caused by erosion (Nouwakpo and Huang, 2012).

Contact techniques, such as the erosion pin and rillmeter, have long been used to understand changes in the soil surface during erosion (Elliot et al., 1997; Kronvang et al., 2012). Although the change in the length of the exposed part of the pin can be used to calculate the amount of erosion that has occurred after an erosion event, the accuracy of the erosion pin technique is limited by the low spatial coverage due to the small number of pins (Sirvent et al., 1997; Zhang et al., 2011). The rillmeter technique can acquire precise data for the measurements of soil surface geometry, but it can disturb the soil surface during the measurement process due to the contact between the rillmeter device and the soil surface (Elliot et al., 1997). As technology has become more robust and accessible in recent years, non-contact soil surface techniques, such as laser scanning and digital close-range photogrammetry, have been adopted to overcome the limitations of contact methods (Babault et al., 2004; Nouwakpo and Huang, 2012).

Both laser scanning and digital close-range photogrammetric techniques have been widely used to generate DEMs with sufficient resolution for micro-topographic analysis (Aguilar et al., 2009; Babault et al., 2004; Nouwakpo and Huang, 2012; Rieke-Zapp and Nearing, 2005). Comparatively, digital photogrammetry allows for faster data acquisition and a wider vertical range of the DEM (Aguilar et al., 2009; Rieke-Zapp and Nearing, 2005). In addition, a camera is easier to handle, and a digital photogrammetric system allows operators to scale according to their own requirements (Frankl et al., 2015; Rieke-Zapp et al., 2001). Therefore, digital photogrammetry enables the possibility of instantaneous data capture.

Previous investigations have proved the usefulness of high-resolution digital close-range photogrammetry in soil erosion studies. The experimental plots in those studies varied between 0.09 and 16 m^2, and the grid resolution of generated DEMs ranged from 1 to 15 mm (Abd Elbasit et al., 2009; Aguilar et al., 2009; Brasington and Smart, 2003; Peter Heng et al., 2010; Rieke-Zapp and Nearing, 2005).

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However, none of the previous methods observed ongoing soil erosion processes during rainfall events, principally because the equipment was not waterproof. Consequently, understanding soil erosion during rainfall was not achieved (e.g., Rieke-Zapp and Nearing, 2005). Under natural rainfall conditions, soil erosion is a continuous process. To study the evolution of erosion, soil surface topography must be monitored at both fine temporal and spatial scales.

In addition, during an erosion event, when runoff accumulates and flows in narrow channels, it is difficult to obtain soil surface images of the inundated area, especially at the sidewall and bottom of the eroding rill. Obtaining soil surface information from the sidewall and bottom of the channel is another challenge when using the digital photogrammetry technique.

To address these issues, this study aims to (1) develop an improved photogrammetric approach for soil surface measurements that can monitor the soil erosion process at fine temporal and spatial scales and capture instantaneous images during ongoing rainfall and (2) assess the accuracy of the developed photogrammetric approach in detecting changes in soil erosion by comparing the amount of soil erosion calculated using the photogrammetric approach, laser scanning, and traditional runoff and sediment collection method.

2. Material and methods

2.1. Experimental design

All experiments were conducted in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau. We conducted two simulated rainfall experiments, the first on 19 July 2013 and the second on 4 July 2014 (Table 1). The dimensions of the experimental plots were $5.0 \times 1.0 \times 0.5\ m^3$ steel soil bins set at a gradient of 15° to the horizontal (Fig. 1). Loess soil common in the area of Loess Plateau, China was used in the two experiments. The soil was first sieved through an 8 mm soil sieve then loosely packed in the soil bin. The soil surface was prewetted several times over a period of 5 days before the experiment, allowing the settlement of the loose soil surface (Gessesse et al., 2010). The total rainfall duration for the two experiments was 190 min and 150 min for the first and second experiments, respectively. To test the accuracy of the developed photogrammetry approach under various conditions, rainfall intensity and time intervals of image acquisition were designed differently according to previous rainfall simulation experiments (Berger et al., 2010; Rieke-Zapp and Nearing, 2005). In the first experiment, rainfall intensity during the first 60 min was 60 mm/h and increased to 90 mm/h during the final 130 min. Image acquisition was conducted at 30, 50, 70, 90, and 100 min, then every 10 min until 190 min. In the second experiment, rainfall intensity was 90 mm/h throughout the experiment and image acquisition was conducted every 10 min.

Pictures of the soil surface were obtained during rainfall using an industrial CCD (charge-coupled device) camera, which was hand controlled by the operator walking around the soil bin. Image collection frame rate was set to 15 frames/s, and the average distance of data acquisition to the surface was 80 ± 5 cm, resulting in a density of digital images of 150–170 frames/m^2. Image acquisition for the entire plot took approximately 2 min. Raw image data were captured in a waterproof high-speed hard disk drive, then transferred to a host computer and then further transferred to three parallel computers for analysis. Scale bars were placed around the bin and marked as white on a black background.

Table 1
Experimental design and image acquisition.

	Experiment 1	Experiment 2
Soil bulk density (g/cm^3)	1.30	1.18
Rainfall intensity (mm/h)	Before 60 min: 60 After 60 min: 90	90
Image acquisition time interval (min)	30, 50, 70, 90, 100, 110, 120, 130, 140, 150 … 190	10, 20, 30, … 150
Observations	14	15
Image acquisition frame rate (frame/s)	15	15
Image acquisition density (frame/m^2)	150–170	150–170

Before each rainfall experiment, we tested the precision of the developed photogrammetry approach by measuring the diameter of a selected spherical target 40 times. To test the accuracy of the digital photogrammetry, we compared this method with physical observations. Physical observations were conducted by placing cylindrical and rectangular objects of a known size in the steel soil bin before the rainfall experiment, and the digital photogrammetric observation method was used to measure and calculate their geometric size. We also collected all water and sediment samples for each rainfall experiment, followed by the collection of sediment, drying, weighing and processing to calculate the soil erosion volume. The surface terrain was simultaneously scanned using a Leica ScanStation 2 laser scanner while photogrammetric images were collected. To compare the observation precision of the laser scanning method and digital photogrammetric observation, digital point clouds were calculated from both the laser-scanned images and photogrammetric images.

2.2. Design of digital photogrammetric observation systems

The digital photogrammetric observation system was composed of two subsystems: the image acquisition subsystem and the image interpolating and calculation subsystem (Fig. 2). The image acquisition subsystem consisted of an industrial CCD camera, PICO machine, solid-state drive, touch control panel, DC (direct current) power supply, waterproof adapter and waterproof case. The image interpolating and calculation subsystem consisted of a data storage unit, a host computer and nine parallel computers. We wrote code for image acquisition, task assignment (assigning tasks to the parallel computers), sub-block division and matching, and soil erosion calculations. The code used in 3D point cloud reconstruction was available as part of the open source VL Feat library (www.vlfeat.org) and OpenCV (http://opencv.org/).

2.2.1. Image acquisition subsystem

Because raindrops affected the imagery during rainfall, we designed an industrial CCD camera with a waterproof housing to ensure reliability during rainfall conditions (Fig. 3a). The camera was hand controlled during the capture of soil surface information on the sidewall and bottom of the channel. We took photos at a close range (80 ± 5 cm) from the soil surface, which constrained the field of view and reduced raindrops passing through the view. The CCD camera has a matrix of 1624 × 1232 picture elements (pixels). The distance between two pixel centers was 0.004 mm. The collection frame rate of the CCD camera was 12–20 frames/s, which resulted in a minimum of 8-fold overlapping, that is, a feature point was found in at least in 8 different images (Table 2).

The PICO machine controlled the acquisition system, which was responsible for command control, data reception and forwarding. System commands and data were transferred by a TCP/IP (Transmission Control Protocol/Internet Protocol) network and a gigabit ethernet hardware interface. Software parameters were adjusted during the acquisition process using the touch-control surface (Fig. 3b). Moreover, as the equipment was designed to be waterproof, real-time monitoring via the capture screen on the control panel was achieved.

2.2.2. Image calculation subsystem

The huge amount of images collected required sufficient storage data computational power to execute the large amount of computations. As off-the-shelf consumer computers were inadequate for