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Effects of rock fragment content, size and cover on soil erosion dynamics of spoil heaps through multiple rainfall events

Jiaorong Lv[a,b], Han Luo[a,c,1], Yongsheng Xie[a,c,*]

[a] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China
[b] University of the Chinese Academy of Sciences, Beijing 100049, China
[c] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China

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ABSTRACT

Spoil heaps are the main sources of soil erosion on disturbed land surfaces as an artificial accelerated erosion form, and rock fragments are an important component of spoil heaps. This study examined different fragment contents (0, 20, 40, 60 mass percentage) and sizes (1–4, 4–7, 7–10 cm) on hydrological processes, sediment yielding processes and rock fragment cover evolution through three sequential simulated rainfalls with a constant intensity of 1.5 mm min^{-1}. The rock fragments in spoil heaps were found to reduce the soil loss amount by 35.23–76.84% through effects on runoff production and rock fragment cover. Runoff rates decreased with increasing rock fragment content, and size class 4–7 cm had the strongest reduction effect, but for a definite treatment runoff rates have little change in three rainfall events. The expanding rock fragment cover with cumulative rainfall in the multiple rainfall events, which increased fastest during the first rainfall period led to a significant decreasing soil detachment rate. Multiple regression analysis shows that the average detachment rate under each rainfall event could be estimated using a power function of average runoff rate and median rock fragment cover. These findings indicated that the presence of rock fragments in spoil heaps has an obvious mitigating effect on soil erosion, with the rock fragment content making a larger percentage contribution than rock fragment size.

1. Introduction

With the high-speed economic development occurring in China, artificial accelerated soil losses on severely disturbed surfaces caused by production and construction activities are becoming increasingly serious. Such erosion causes serious land degradation and leads to tension between urban construction and ecological protection (Jimenez et al., 2013; Nearing et al., 2017b; Rodrigues and Silva, 2012; Shi et al., 2016; G. Wang et al., 2012). Engineering spoil heaps, special landforms on disturbed land surfaces that are generally piled up in the form of soil-rock mixtures, are the most important sources of the accelerated soil losses (Peng et al., 2014; Zhao et al., 2012). Rock fragments resting on or embedded in the soils have important effects on soil erosion characteristics, including hydrological and sediment yielding processes (Cerdà, 2001; Poesen and Lavee, 1994). Therefore, it is necessary to understand how rock fragments influence hydrological and sediment yield from spoil heaps to help predict and further to control soil erosion and reduce pressure from environmental protection.

Rock fragments change the soil feature and microtopography, making hydrological processes more complex than occur in homogenous soils (Cousin et al., 2003). For clay loam soil, Nasri et al. (2015) indicated that the presence of rock fragments produce preferential flow channels by increasing macropores, meanwhile impermeable rock fragments increase pore tortuosity, which extends the path of soil water movement (Zhou et al., 2011) to decrease water infiltration. The content and size of rock fragments both can influence soil hydrological processes by affecting how the macropores quantity and the tortuosity change (Ma and Shao, 2008; Zhou et al., 2011). Moreover, Zavala et al. (2010) suggested that infiltration was promoted because the surface water storage was increased when the rock fragments rested on the surface. Studies also showed that the rock fragment cover will reduce the flow velocity and restricted the splash effect, thus increasing the time that the runoff flows through the slope and avoiding soil crust, therefore the infiltration is promoted (Abrahams et al., 2015; Guo et al.,

* Corresponding author at: Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China.

E-mail address: ysxie@ms.iswc.ac.cn (Y. Xie).

[1] Han Luo contributed equally to this work and should be considered as co-first authors.

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2010; Poesen et al., 1990). Through the effects on infiltration and runoff generating as well as the microtopography, soil loss process is influenced by rock fragments (Bunte and Poesen, 1993; Nearing et al., 2017a; X. Wang et al., 2012).

However, different, and even contrasting results, have been observed for the relationship between rock fragments and hydrological and sediment yielding processes under different experiment conditions (Rieke-Zapp et al., 2007; Shi et al., 2012; Urbanek and Shakesby, 2009). Some researchers have shared the view that there is a content threshold for the influence of rock fragment content on hydrological characteristics. For example, Zhou et al. (2009) observed the critical rock fragment content to be 40% where the saturated hydraulic conductivity was smallest though a clay loam penetration test using Mariotte bottles, which is similar to the results reported by Novák et al. (2011), indicating that the saturated hydraulic conductivity (4 soils, texture from sandy to clay) decreased as the content increased from 0 to 31.4% using numerical method. However, Shi et al. (2012) found that steady effluent reached its maximum at the volumetric content of 15% to a forest soil depth of 60 cm on the Loess Plateau in China. Nevertheless, in some studies the influence of rock fragment content on hydrology is monotonic. For example, Urbanek and Shakesby (2009) indicated that infiltration increased with increasing rock fragment content by using a flow chamber to test the sand-stone mix, which is consistent with the results of Chow and Rees (1995) which indicated that runoff generation and soil loss decreased when rock fragment content increased from 7 to 25% by volume in a potato-forage rotation sandy loam field. The conclusion of Rieke-Zapp et al. (2007) also suggested that rock fragments dissipate the energy in the flow path on a 5 mm-deep V-shaped flume surface thus soil loss exhibits a linear reduction with increasing rock fragment content (0–40%).

Some studies have shown that infiltration was reduced when rock fragment size increased. For example, Guo et al. (2010) found that solute transport was higher in soil with small rock fragments (the bottom face of a stone was a square of 7.6 × 7.6 cm) than in soil with large rock fragments (18.4 × 18.4 cm) in a loess slope land. Novák et al. (2011) also reported that saturated hydraulic conductivities slowly decreased with increasing rock fragment diameter (10–80 cm) in the numeric simulation. However, Chow and Rees (1995) found that when rock fragment size was 1.9–5.1 cm, the runoff generation and soil loss amount were less than those under smaller or larger size. Zhou et al. (2011) found that for a given rock fragment content in a column of clay loam soil, saturated hydraulic conductivity decreased when rock fragment size increased from 0.2 to 3 cm and then increased for the size of 3–5 cm.

Rock fragment cover is also a key factor affecting hydraulic characteristics and soil loss process. Most studies have implied a negative correlation between soil loss and rock fragment cover under laboratory (Abrahams et al., 2015; Cerdà, 2001; Zavala et al., 2010) or field conditions (Mandal et al., 2005; Simanton et al., 1994; X. Wang et al., 2012), because rock fragments resting on the soil surface protect topsoil from detachment and the impact of raindrops, and reduce physical degradation of the soil surface based on the increase in water flow resistance and friction factor (Guo et al., 2010; Nyssen et al., 2001; Poesen and Lavee, 1994; Rieke-Zapp et al., 2007). However, positive associations between rock fragment cover and sediment yield and hydrological processes have also been observed. For example, Poesen et al. (1990) showed that when rock fragments were embedded in the top layer, an increasing rock fragment cover would lead to a larger runoff volume because of the sealing effect of the rock fragments, which increased impermeabilized area of top soil. However, for the rock fragments placed on top of the soil surface, the opposite trend was shown.

Therefore, rock fragments can affect soil hydrological and erosion processes differently because of their multiple roles, and it need to be explained properly what effect of rock fragments prevail under a certain condition for the high heterogeneity of soil-rock mixture (Tetegan et al., 2012).

Although several researchers have addressed the problem of soil erosion of spoil heaps in recent years (Peng et al., 2014; Zhang et al., 2015), few have focused on the rock fragments contained, even though their effects on hydrological and sediment yielding processes in spoil heaps still require clarification. Peng et al. (2014) suggested that rock fragment content affected erosion forms in disturbed soils, which resulted in heterogenous runoff generation and sediment yield; however, the specific role of rock fragments needed further clarification. Moreover, rock fragment cover is not only a factor that affects soil erosion, but also has the potential to serve as a reference for measuring the soil loss amount in the field. Because the soil is detached, increasing amounts of rock fragments are exposed on the surface, and the changes in coverage area reflect the soil loss amount to some extent. At present, the relationship between rock fragment cover and soil erosion on spoil heaps remains unstudied.

Therefore, in this paper, a laboratory experiment was conducted with the goal of observing and quantifying hydrological and sediment yielding characteristics affected by different rock fragment contents and sizes, the changes in rock fragment cover before and after multiple rainfall events and their correlation with soil loss are examined, too. The results presented herein provide references for clarification of the role of rock fragments in soil erosion processes of the spoil heaps, which will facilitate accurate soil loss prediction and reasonable conservation measurement allocation on disturbed land surfaces.

2. Materials and methods

2.1. Experimental materials

The simulated rainfall experiment was conducted in the rainfall simulation laboratory at the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling, China. In the simulator, artificial raindrops produced by a rotating sprinkler rainfall simulator with a uniformity of > 80% fall from a height of 18 m. The disturbed soil used in this study was collected from an urbanization construction site in Yangling, Shanxi Province, China that developed from the loess parent material on the Loess Plateau. The disturbed soil was air-dried to a 12–14% water content and the rock fragments (> 10 mm) were then separated. The spoil materials smaller than 10 mm were evenly distributed along the slope, so no separation was required in the simulation (Zhao et al., 2012). The selected finer soil in the spoil materials (< 2 mm) is a Urbic Technosol according to IUSS Working Group WRB (2015). The percentages of particles distributed according to diameters of < 0.002, 0.002–0.02, and 0.02–2 mm, were 27.6%, 48.2%, and 23.3%, and the organic matter accounted for 0.9%. The rock fragment samples used in this study were siliceous limestone taken from a quarry in Zhouzhi County, Shaanxi Province. This material is commonly used in engineering construction and has an irregular polyhedral shape with low water absorption permeability. Rock fragments were divided into 3 size classes of 1–4, 4–7, and 7–10 cm. The slope adjustable soil flume was made of steel, with dimensions of 3.5 m long, 1 m wide and 0.5 m deep. Permeable holes with a diameter of 5 mm were drilled into the bottom of the flume to enable free drainage of the infiltrated water.

2.2. Experiment methods

Experiments involved a combination of three rock fragment contents (20, 40, 60%, mass percentage) and three rock fragment size classes (1–4, 4–7, and 7–10 cm), as well as a control of bare soil. Ten treatments were conducted in three replicates for the sake of reducing random errors. The selected rainfall intensity of 1.5 mm min^{-1} is typical of intense storms on the Chinese Loess Plateau (Fang et al., 2015). Three simulated rainfalls events with a constant intensity of 1.5 mm min^{-1} were conducted on successive days for each treatment.