Catena 172 (2019) 179–189

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

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

ARTICLE INFO

Keywords:
Spoil heaps
Rock fragment
Hydrological process
Soil detachment
Controlled flume experiment
Multiple rainfall events

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.

https://doi.org/10.1016/j.catena.2018.08.024
Received 9 May 2018; Received in revised form 13 August 2018; Accepted 23 August 2018
Available online 01 September 2018
0341-8162/

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.

Fig. 1. Experiment flume setup, the three observation sections were separated by the white lines (white arrow).

The slope of the soil flume (Fig. 1) for simulated spoil heaps was adjusted to 64.9% considering that field surveys of spoil heaps indicated the angle of repose centering in 48.8–70.0% (Zhao et al., 2012) and the prevalence of moderately large steepness (Zhang et al., 2015). In the flume, a 10-cm-thick layer of coarse sand was packed at first to let the infiltrated water drain naturally. The prepared spoil heap materials were then uniformly mixed with rock fragments and the sieved soil according to the designed rock fragment contents, after which the soil flume was filled with the mixture to a depth of 40 cm. To ensure consistency, the lower 10 cm of the mixture was tamped, giving a bulk weight of the soil of around 1.5 g cm^{-3}. Additionally, the upper 30 cm was filled with the mixture without compaction to simulate the loose structure of field spoil heaps and a board was lightly run across the surface to ensure it was flat. After flume preparation, it was covered with plastic sheeting and untouched for the following 24 h to allow natural settling.

Prior to the experiment, rainfall intensity was calibrated to 1.5 mm min^{-1} and was measured three times to ensure the error < 5%. When the rainfall intensity was calibrated sufficiently, the plastic sheeting was removed. Using a timer with a precision of 0.01 s to record the test time, the time at which runoff flowed out the outlet was recorded as the runoff generation time (Seeger, 2007), after which the timer was reset and the experiment was launched. The duration of each rainfall event was 45 min, during which time the runoff and sediment samples were taken every min for the initial 3 min and then every 3 min for the rest of each rainfall event. During the test, three 1-m-long observation sections were set from upslope (0.25 m) to downslope (3.25 m), each of which was photographed before and after the rainfall event, and the rock fragment cover was obtained through image processing by Adobe Photoshop CC (the percentage of pixels in the photo taken by the rock fragments). The average of the three slope sections was the rock fragment cover of the slope.

A rainfall event was followed by 24 h of sheeting and natural air-drying without altering the soil surface, after which the above steps were repeated until completion of the three rainfall events. After the test was completed, the sediments were oven-dried at 105 °C for > 24 h to calculate sediment yields.

2.3. Data analysis

The runoff rate I_r was calculated by:

$$I_r = (M - m)/1000\rho T \tag{1}$$

where I_r is the runoff rate (L min^{-1}); M (g) is the weight of each sample; m (g) is the relevant soil loss weight of the sample; ρ (g cm^{-3}) is the density of water, being 1 g cm^{-3}; T (min) is the sampling duration.

The runoff coefficient α, which was the ratio of the depth of produced runoff during any time period to the depth of precipitation that corresponded to the runoff resulting from this period of time, was given by:

$$\alpha = I_r T/(bL\cos 33^{\circ})IT \tag{2}$$

where α is the runoff coefficient; b (m) is the width of the flume; L (m) is the length of the flume; I (mm min^{-1}) is the rainfall intensity.

The soil detachment rate D_r was calculated by:

$$D_r = m/bLT \tag{3}$$

where D_r (g m^{-2} s^{-1}) is the soil detachment rate.

The analysis of variance (ANOVA) was used to statistically assess the relationship between each factor and runoff, detachment and surface cover based on the level of significance. The percentage contribution of each factor, ρ_F, was calculated as follows (Sadeghi et al., 2012):

$$\rho_F = \frac{SS_F - (DOF_F V_{Er})}{SS_T} \times 100\% \tag{4}$$

where SS_F represents the factorial sum of square; DOF_F is the degree of freedom for each factor; V_{Er} represents the variance of error; SS_T is the total sum of squares.

3. Results

3.1. Runoff and infiltration

3.1.1. General runoff and infiltration characteristics

Infiltration refers to the process of moisture entering the soil which determines the amount of precipitation that becomes the surface flow and soil reservoir. The infiltration rate was calculated as the difference between rainfall intensity and the corresponding runoff intensity. As shown in Table 1, the accumulative runoff yield of the bare soil spoil heaps was 560.324 L. The produced runoff accounted for 94.3% of the total rainfall, with runoff coefficients 0.055–0.221 higher and accumulated infiltration levels 4.298–44.838 mm lower than those of spoil heaps containing rock fragments. The presence of rock fragments significantly enhanced the infiltration capacity of the spoil heaps and reduced the runoff on the slope. The difference in runoff rates between different rock fragment content and size were both significant (Table 2).

The final infiltration rate of each rainfall event was plotted in Fig. 2. For a given rock fragment content, the final infiltration rate was largest for size class 4–7 cm, followed by that of the 1–4 cm size class and the 7–10 cm size class, which were 0.201–0.335, 0.151–0.323, and 0.099–0.277 mm min^{-1}, respectively. As the soil became saturated, the

Table 1
Runoff, infiltration and sediment production characteristics of each treatment.

Treatment		Average runoff rate (L min^{-1})			Accumulated total runoff (L)	Runoff coefficient	Accumulated total infiltration (mm)	Accumulated total soil loss amount (kg)	Increment of the rock fragment cover (%)
		Rainfall event							
Content (%)	Size (cm)	1	2	3					
Bare soil		4.126	4.163	4.163	560.324	0.943	11.611	33.397	–
20	1–4	3.810	3.846	3.883	519.281	0.874	25.593	17.143	12.04
20	4–7	3.626	3.643	3.622	490.112	0.825	35.530	13.553	11.36
20	7–10	3.998	4.073	4.094	547.413	0.921	16.010	21.712	12.75
40	1–4	3.702	3.731	3.753	503.382	0.847	31.009	11.294	14.35
40	4–7	3.485	3.519	3.524	473.774	0.797	41.095	10.755	10.98
40	7–10	3.903	3.906	3.919	527.724	0.888	22.717	15.208	15.83
60	1–4	3.331	3.323	3.335	448.620	0.755	49.178	7.765	40.52
60	4–7	3.185	3.176	3.166	428.705	0.721	56.371	8.892	22.85
60	7–10	3.549	3.549	3.516	477.627	0.804	39.783	10.080	31.18

Table 2
Effects of rock fragment size, content and their interaction on runoff, rock fragment cover and soil detachment based on ANOVA, and percentage contribution of each factor (P — probability, SS_F — fractional sum of squares, ρ_F — percentage contribution).

Variables	Factor	P	SS_F	ρ_F (%)
Runoff rate (L min^{-1})	Size	0.000**	4.264	27.57
	Content	0.000**	6.748	43.86
	Size × content	0.898 ns	–	–
	Error		4.211	28.90
Rock fragment cover (%)	Size	0.000**	1500.836	14.22
	Content	0.000**	5650.665	56.55
	Size × content	0.001**	1682.963	14.98
	Error		967.343	14.26
Soil detachment rate (g m^{-2} s^{-1})	Size	0.000**	0.825	22.67
	Content	0.000**	2.244	61.84
	Size × content	0.000**	0.221	5.88
	Error		0.332	8.39

** indicates the significant effect of the treatment on variables at $P < 0.01$.

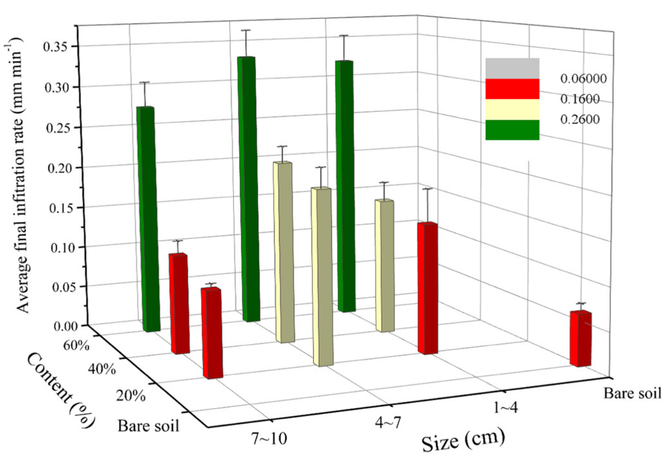

Fig. 2. Average final infiltration rate of each treatment.

final infiltration depended on the structural features of the soil-rock fragment mixture and corresponded to its saturated hydraulic conductivity. The smaller the rock fragment size was, the more soil-rock fragment interferences existed, which led to increased macropores promoting the infiltration; however, the tortuosity of the influent path increased at the same time, impeding the infiltration (Zhou et al., 2011). The final infiltration rate was the result of both positive and negative effects, and our results indicated that size class 4–7 cm contributed to the optimum infiltration capacity of spoil heaps under the three contents.

However, for a given size class, the final infiltration rate increased with the increasing rock fragment content without a certain content when relationship changed (Fig. 2), which indicates the absolute advantageous effect of infiltration promotion because of increasing rock fragment content. When the rock fragment content increased from 0 to 20%, 20 to 40%, and 40 to 60%, the average decreases in the average runoff rates were 0.307, 0.128, and 0.370 L min^{-1}, respectively (Table 1). The decrease in runoff rate was smallest when the rock fragment content increased from 20 to 40%, which showed that the advantage of infiltration promotion effect of the added rock fragments part over inhibition effect was not very large. But runoff rates dropped the most significantly when the content reached 60%. This finding indicated that much more continuous preferential flow paths developed because of the increasing rock-to-rock connections (Nasri et al., 2015) when the content increased to 60%, which greatly increased the infiltration of the spoil heaps.

3.1.2. Runoff rate changing process

The instant runoff rates of bare soil spoil heaps varied from 3.885–4.223 L min^{-1}, while those of spoil heaps containing rock fragments were 2.366–4.159 L min^{-1}. There was no significant difference in the runoff rates under the three rainfall events for each treatment. As shown in Fig. 3, for a definite treatment, the runoff rate of the spoil heaps tended to increase first, after which they stabilized with the extension of rainfall duration in each rainfall event. The lower rate at the beginning was because the smaller initial soil moisture content and the higher infiltration rate in the early stages. Therefore, the much smaller initial runoff rate of the first rainfall event than those of the last two rainfall events was because of the relatively much lower initial moisture content of the soil compared to the soil that had already experienced precipitation in the last two rainfall events. With the water content of the spoil heaps gradually becoming saturated a steady infiltration rate was reached and the runoff rate became relatively constant.

For a given rock fragment content, runoff rate process curves were arranged between size classes as 4–7 < 1–4 < 7–10 cm for the spoil heaps as a whole. But at the beginning (1–10 min) of the first rainfall event the runoff rate was lowest for size class 1–4 cm (Fig. 3). This phenomenon can be explained as follows. The surface fine earth tended to develop soil crust under the raindrop impact to reduce infiltration at the beginning of the first rainfall event (Chamizo et al., 2012; Neave and Rayburg, 2007). At the same time some raindrops splashed rock fragments to coat them with a layer of water film, and the contact between the rock fragments and the surrounding soil then became the preferred infiltration point compared to the bare soil area. Hence, smaller rock fragment size was associated with a larger exposed area (rock fragment cover) and more infiltration points for size class 1–4 cm, resulting in a lower runoff rate at the beginning. As the surface soil became saturated the infiltration no longer depended on the infiltration

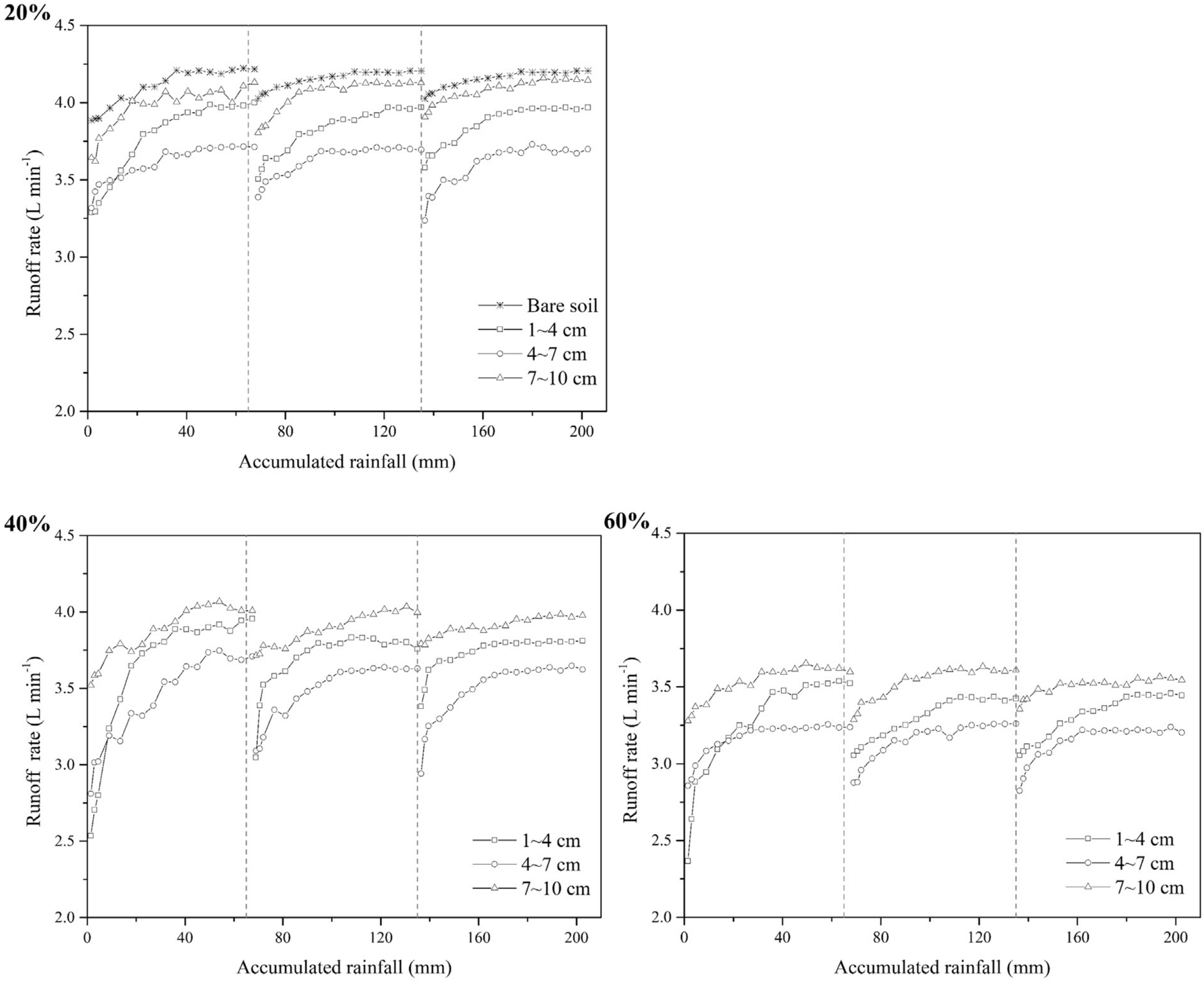

Fig. 3. Change in runoff rate with accumulated rainfall under different rock fragment contents and sizes.

points, thus during the subsequent rainfall, the rock fragment cover did not show any effect on infiltration and runoff.

Overall, the rock fragment content had a greater influence on the runoff of spoil heaps than rock fragment size, with percentage contributions of 43.86% and 27.57%, respectively (Table 2). In addition, there was no obvious interaction effect.

3.2. Rock fragment cover and soil loss amount

Both rock fragment content and size had significant effects on the rock fragment cover (Table 2). The initial rock fragment cover increased with increasing content and the coefficient of partial correlation was 0.810 ($^{**}P < 0.01$). Conversely, the cover decreased as the mean rock fragment diameter decreased (the mean diameter of the rock fragments for size class 1–4, 4–7, 7–10 cm was 2.5, 5.5, 8.5 cm, respectively), with a partial correlation coefficient of −0.687 ($^{*}P < 0.05$). In general, rock fragment cover was mainly controlled by the rock fragment content with a percentage contribution of 56.55%, and the interaction between content and size also had a significant effect (Table 2).

An increasing number of rock fragments were exposed as the topsoil was detached during the rainfall events. Fig. 4 presents the evolution of the rock fragment cover visually as the rainfall events went on. As shown in Fig. 5, as the accumulated rainfall increased, the rock fragment cover showed first rapid increase, then continued to increase at a slower rate. The growth rate was fastest during the first rainfall period, then slower during the latter two rainfall events. These findings indicate that soil was primarily eroded in the first rainfall event, after which the amount of soil loss caused by subsequent rainfall events was reduced; thus, the newly added rock fragment cover was smaller.

The initial rock fragment cover ranged from 2.71% to 41.12, and after three rainfall events, the final rock fragment cover range increased to 14.65%–81.64%. The expansion of the rock fragment cover reflected, to some extent, the amount of soil erosion that had occurred. As Table 1 shows, the total soil loss amount among the three classes occurred in the order 7–10 > 1–4 > 4–7 cm, which was in accordance with the increase in rock fragment cover under 20 and 40% content. However, when the content was 60%, although the increase in rock fragment cover was largest for the 1–4 cm size class, the total soil loss amount was smallest. This is because there was less topsoil when the initial rock fragment cover of the spoil heap containing 60% rock fragments reached 41.12%, which was 5–15 times that of other treatments. As shown in Fig. 6, the cumulative amount of soil loss had a significant power function relationship with the rock fragment cover for each treatment.

3.3. Sediment production

3.3.1. Sediment yield and impacting factors

The average soil detachment rates of the bare soil spoil heaps were 1.107–1.315 $g\,m^{-2}\,s^{-1}$, while those of the spoil heaps containing rock fragments were 0.208–1.028 $g\,m^{-2}\,s^{-1}$ which were reduced by 21.78–81.26% (Fig. 7). It can be concluded that the existence of the rock fragments in the spoil heaps had obvious benefits on erosion

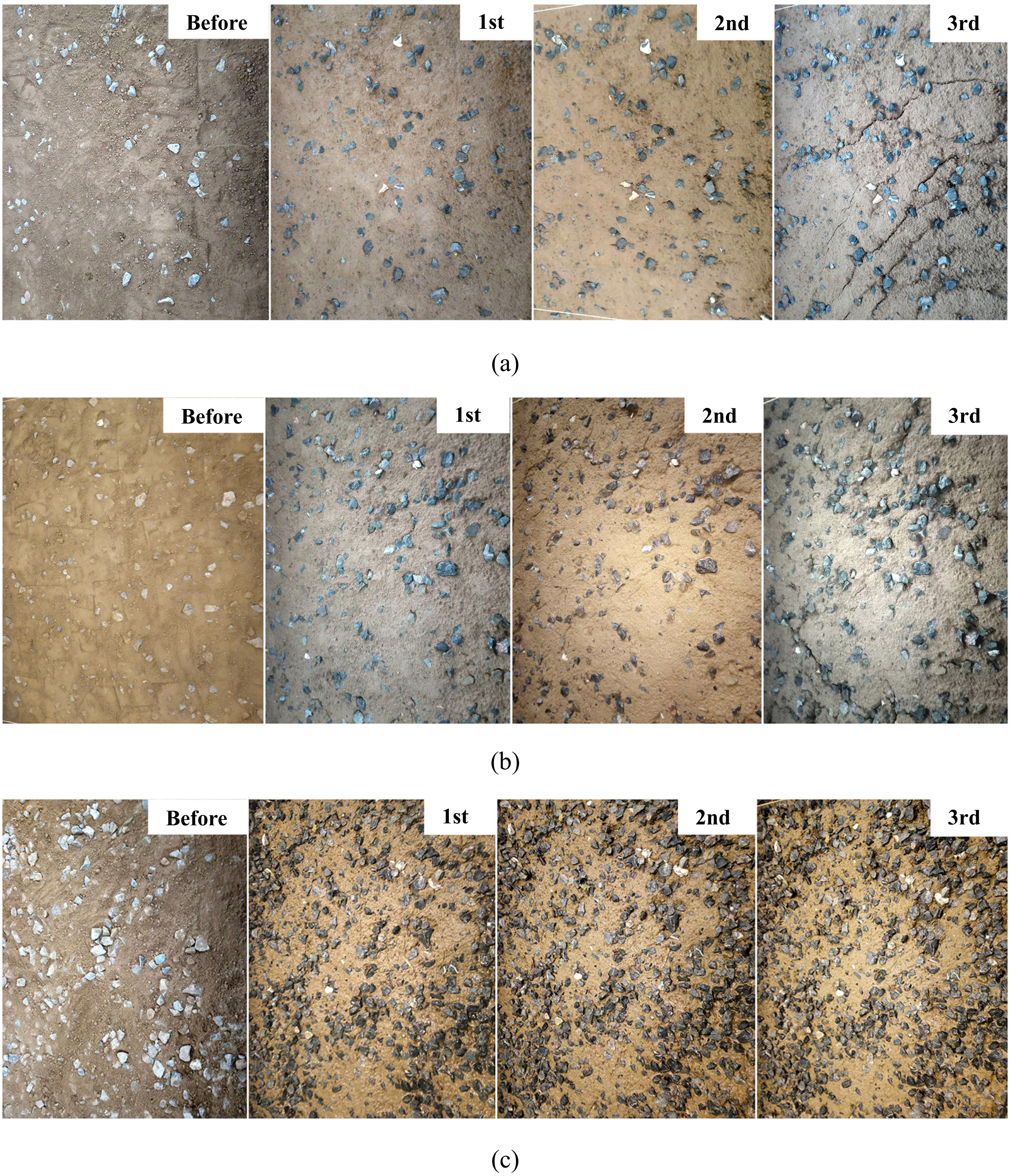

Fig. 4. Photographs of the first section observed on the slope of spoil heaps containing 20% (a), 40% (b), 60% (c) rock fragments with a diameter of 4–7 cm (before: photographed before the first rainfall event; 1st: photographed after the first rainfall event; 2nd: photographed after the second rainfall event; 3rd: photographed after the third rainfall event).

reduction. Among these benefits, the content of rock fragment played a dominant role, with a percentage contribution of 61.84%, while the effects of rock fragment size and their interaction were smaller, contributing 22.67 and 5.88%, respectively (Table 2).

As shown in Fig. 7, for the definite rock fragment size class, the average soil detachment rate decreased as the rock fragment content increased. Specifically, for a given content, the average detachment rate was 7–10 > 1–4 > 4–7 cm among size classes, except for 60% content, for which it was 7–10 > 4–7 > 1–4 cm.

Soil erosion is related to erosion dynamics and underlying surface

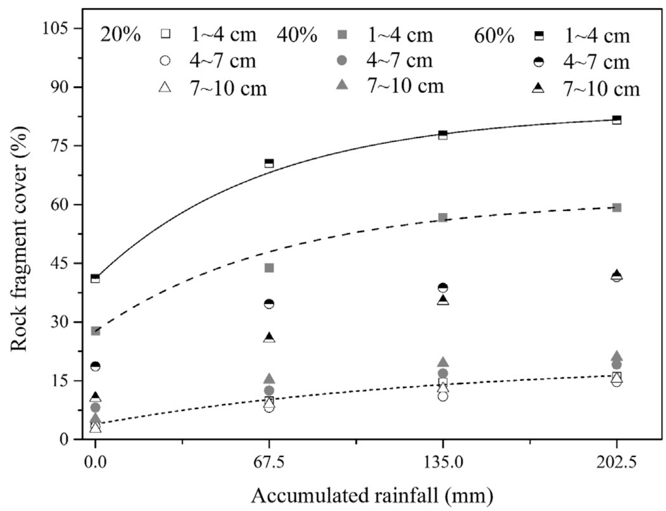

Fig. 5. Change in rock fragment cover with accumulated rainfall under different rock fragment content and size.

conditions. The average detachment rate varied almost consistently between the different rock fragment content and size with runoff rate. Runoff is not only the driving force of soil erosion, but also the carrier of sediment transport; therefore, it had important influences on soil erosion on spoil heaps. The rock fragment cover was also a nonnegligible underlying factor. Rock fragments exposed to the surface were able to dissipate the raindrop energy and enhance the resistance of topsoil (Zavala et al., 2010). The rock fragment cover also caused an increase in surface roughness. Specifically, the impervious rock fragments protruded from the surface and divided the runoff into multiple flow paths, increasing the wetted perimeter, which caused an increase in frictional resistance to reduce the sedimentation capacity of runoff (Lawrence, 1997).

The multiple regression analysis indicated that the average soil detachment rate had the following relationship with average runoff rate and median rock fragment cover:

$$\overline{Dr} = e^{-1.092}\overline{I_r}^{1.058}R_m^{-0.392}\ (R^2 = 0.664, F = 23.715, P < 0.001) \tag{5}$$

where $\overline{Dr}$ ($\text{g m}^{-2}\,\text{s}^{-1}$) is the average soil detachment rate of each rainfall event; $\overline{I_r}$ (L min^{-1}) is the relevant average runoff rate; R_m (%) is the relevant median rock fragment cover.

The exponents of $\overline{I_r}$ and R_m indicate that runoff rate has a greater effect on soil detachment rate than rock fragment cover.

3.3.2. Soil detachment processes

The change processes of soil detachment rates under each treatment were plotted in Fig. 8, the soil detachment rates of the bare soil spoil heaps were 0.814–1.402 $\text{g m}^{-2}\,\text{s}^{-1}$, while those of the spoil heaps containing rock fragments were 0.179–1.205 $\text{g m}^{-2}\,\text{s}^{-1}$. From the perspective of the overall change process of detachment rate under each treatment, as the accumulated rainfall increased, the soil detachment rates of the bare soil spoil heaps decreased slightly, and no significant

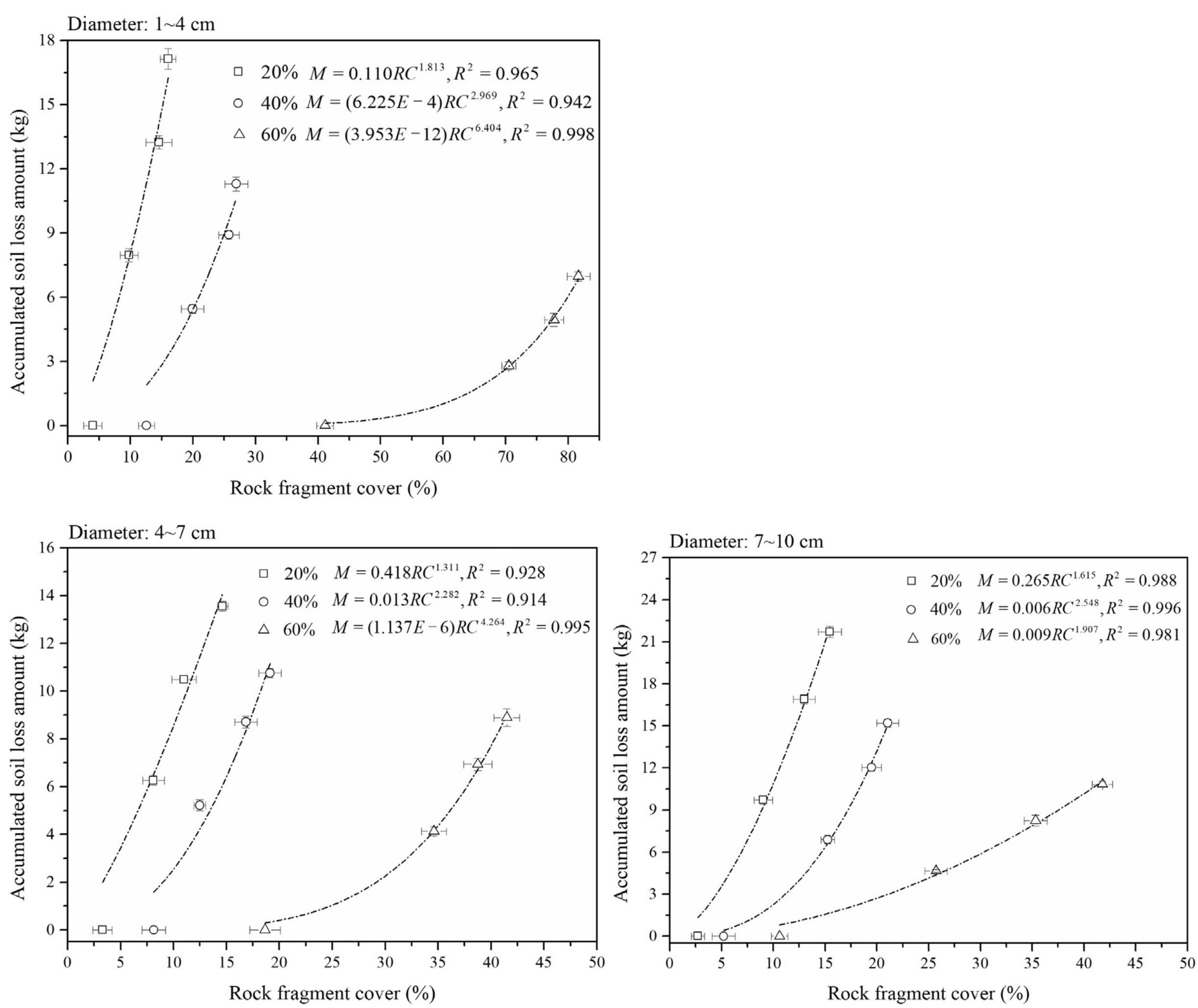

Fig. 6. Accumulated soil loss amount as a function of rock fragment cover (*M*, accumulated soil loss amount, kg; *RC*, the rock fragment cover, %).

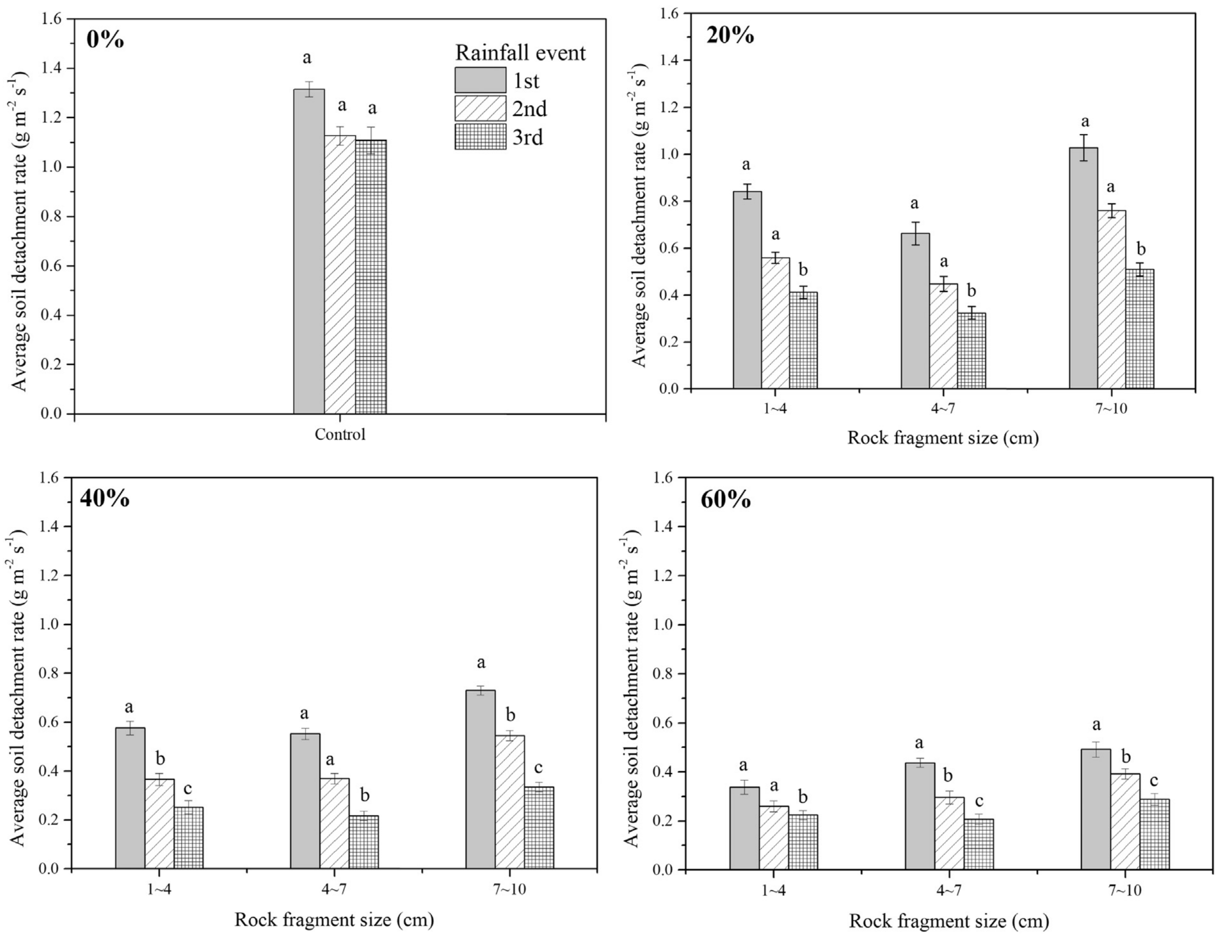

Fig. 7. Average soil detachment rates under different rock fragment contents and sizes.

difference in the detachment rate existed between the three rainfall events. However, the soil detachment rates of spoil heaps containing rock fragments decreased exponentially as the accumulated rainfall increased with significant difference between three rainfall events (**$P < 0.01$). From the point of erosion power source, the rainfall intensity was constant, and there was little change in runoff rate under the three rainfall events for a definite treatment (Fig. 2), the coefficient of variation of the average runoff rate under each treatment was 0.002–0.012. Therefore, the resistance factor, the increase in rock fragment cover, primarily led to the significant reduction in the detachment rate of the rocky spoil heaps.

During a single rainfall period, the detachment rate of bare soil spoil heaps showed a rapid increase followed by a tendency to be stable (Fig. 8). The initial detachment rate increased mainly because of the rapidly increasing initial runoff rate (Fig. 2), in addition, the loose soil flushed down to the slope led to the fastest increase of detachment rate in the first rainfall event. As rainfall continued, the amount of loose soil carried by runoff decreased, which may explain the relatively lower detachment in the later two rainfall events. During the third rainfall event, there was a peak on the detachment rate curve, which was caused by development of slender and shallow rills on the slope to gather the runoff, which in turn contributed to the higher erosivity of runoff (Shen et al., 2016). After the rill morphology had stabilized, the detachment rate became stable again. For treatments containing rock fragments, visual inspection showed there was no rill formation, and that raindrop and sheet detachment was the dominant erosion process.

For the rocky spoil heaps, the soil detachment rate showed a rapid increase followed by a gradual decrease during a single rainfall period. The initial increase of detachment rate is as explained above, in the later period of rainfall, the detachment rate gradually decreased mainly due to the expanding rock fragment cover. It is also because of the lack of protection of rock fragments that the detachment rate of bare soil spoil heaps showed a tendency to be stable rather than a reduction process after a rapid increase.

4. Discussion

Prior work has documented the effects of rock fragment features on soil hydrological and erosion dynamics; however, few studies have clarified the role of rock fragments in spoil heaps on the disturbed landforms. The results of laboratory simulated rainfall experiments in our study show that there are significant differences in runoff, sediment production, and rock fragment cover of the spoil heaps under different rock fragment content and size. The existence of rock fragments in spoil heaps significantly reduced the runoff and sediment production in virtually all cases.

Many studies specifically addressed the effects of rock fragment features on soil infiltration (Novák and Kňava, 2012; Urbanek and Shakesby, 2009; Zhou et al., 2011). Our results indicated that, as the rock fragment content increased from 0 to 60%, the steady infiltration rate increased, and the corresponding runoff rate decreased, which is similar to results of some previous studies (Chow and Rees, 1995; Urbanek and Shakesby, 2009). However, our results differed from those of Zhou et al. (2009) and Ma and Shao (2008), who found that infiltration decreased initially to a minimum value, then increased as rock fragment content increased. Our findings also differed from those of Novák et al. (2011), who showed decreasing saturated hydraulic conductivity as the volume content increased from 0 to 31.4%. These

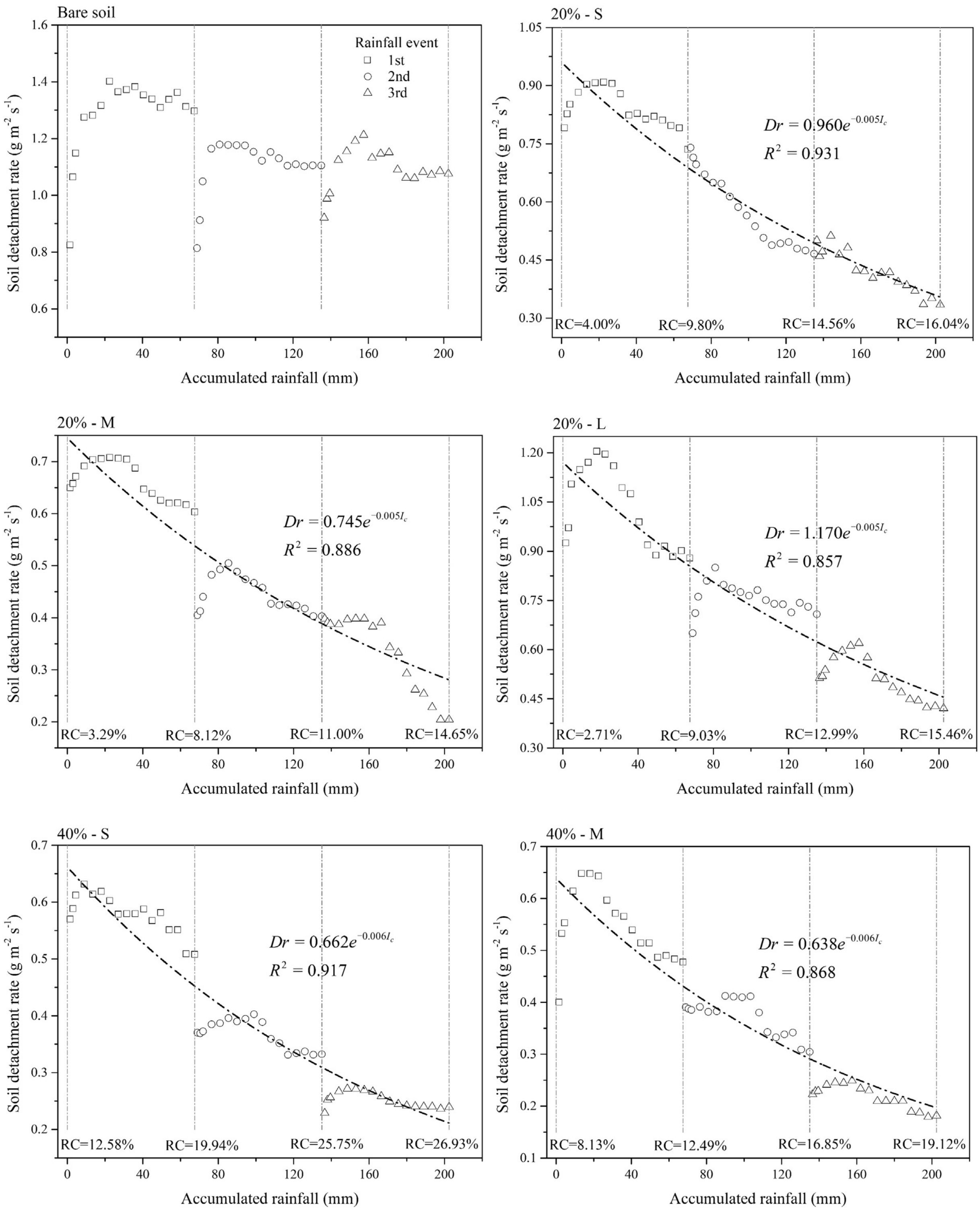

Fig. 8. Soil detachment rate as a function of accumulated rainfall under different rock fragment contents and sizes (S, 1–4 cm; M, 4–7 cm; L, 7–10 cm; D_r: soil detachment rate, g m^{-2} s^{-1}; I_c, accumulated rainfall, mm).

differences may have occurred for the following reasons. The spoil heaps are composed of disturbed surface materials whose original structure was completely destroyed. Therefore, the loose soil in the spaces between the rock fragments tended to become dense and pinched after being saturated. It is known that the interphase areas between rock fragments and the surrounding fine earth have high macroporosity with particularly distinct preferential flow features (Nasri et al., 2015; Urbanek and Shakesby, 2009). The spaces between rock fragments and the surrounding soil matrix were not completely filled in when the loose soil was saturated, which further increased the number of preferential flow channels, coupled with an increase in rock-to-rock connections with the addition of rock fragments, resulting in increased infiltration capacity with increasing rock fragment content.

In addition, the findings noted in our study showed that the infiltration rate increased first, then decreased as rock fragment size increased from 1 to 10 cm, which is comparable to the results of Chow

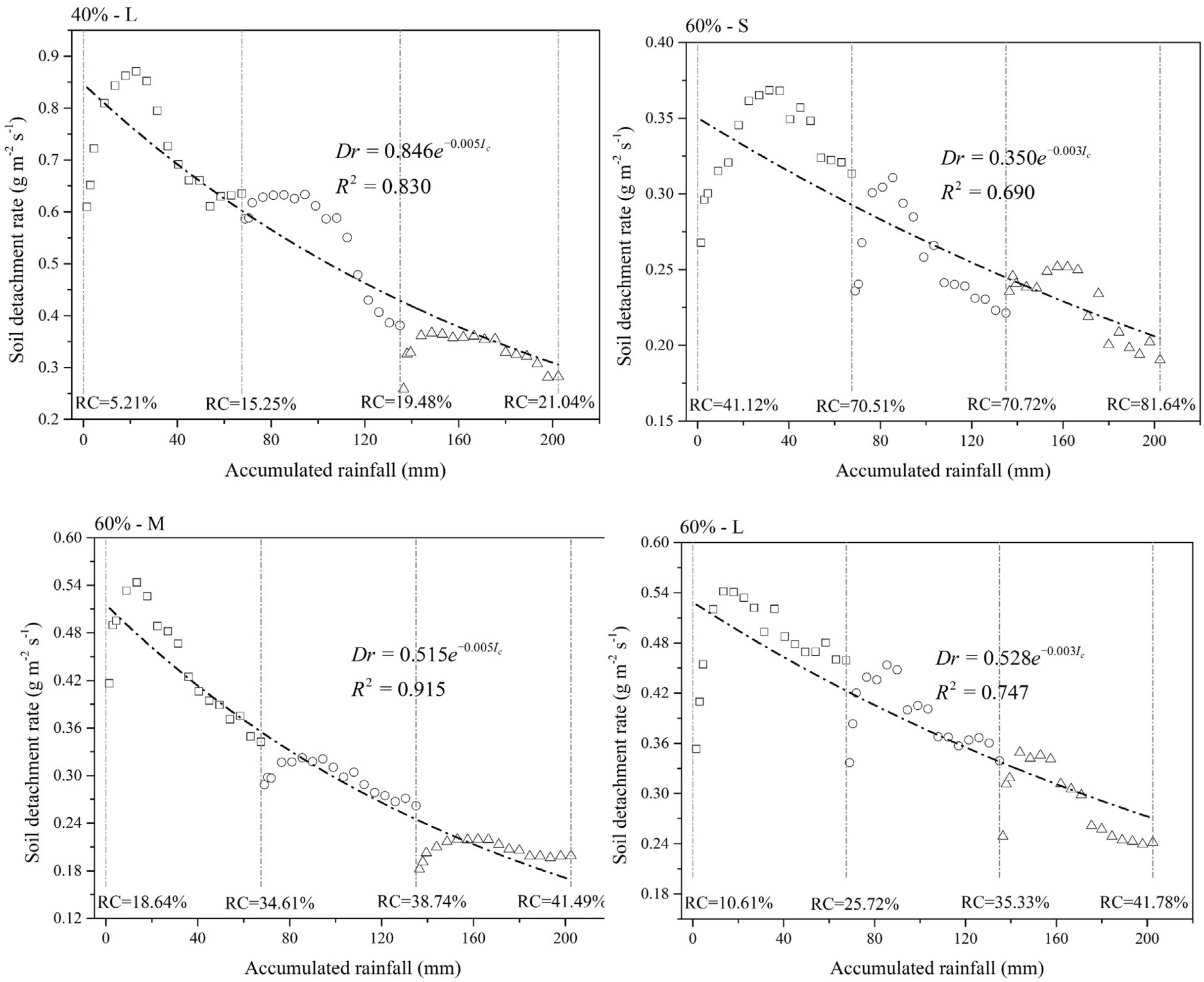

Fig. 8. (*continued*)

and Rees (1995). Moreover, the infiltration was smallest when the rock fragment size was 7–10 cm, indicating that large rock fragments hampered infiltration more than small rock fragments, which was in line with the viewpoint of Ma and Shao (2008). When the rock fragment content was given, the smaller size was associated with an increasing number of rock fragments, which caused higher resistance to flow. In contrast, the larger the rock fragment size was associated with fewer rock-soil interferences, which led to reduction of macropores (Novák and Kňava, 2012; Novák et al., 2011). Medium size of rock fragment led to the best infiltration capacity of spoil heaps, and correspondingly the smallest runoff rate.

The results of this study also indicated that the soil detachment rates were affected by changes in the rock fragment cover during multiple rainfall events. As the rock fragment cover increased, detachment rates showed a significant decreasing trend ($R^2 = 0.690$–0.931). These findings extend those of X. Wang et al. (2012) and Zavala et al. (2010), confirming that rock fragments not only protect the fine material from erosion (Abrahams et al., 2015; Cerdà, 2001), but also reduce the transporting capacity of runoff by increasing surface roughness (Cagnoli and Romano, 2012; Poesen et al., 1994; Rieke-Zapp et al., 2007).

Notably, our results showed that the accumulated soil loss under multiple rainfall events was well expressed by the power function of rock fragment cover ($R^2 = 0.914$–0.998), and the expanding rock fragment cover with the process of rainfall reflected the soil loss amount that had already occurred. This provides a reference to determine the amount of erosion of spoil heaps in the field.

In summary, rock fragments played a significant erosion-reduction role in spoil heaps by affecting the runoff and rock fragment cover. The runoff rate and rock fragment cover had positive and negative correlations with soil detachment rates, respectively, which were comparable to the results of Mandal et al. (2005), Rieke-Zapp et al. (2007) and Zavala et al. (2010). However, some limitations are worth noting. Although rock fragment cover evolution was considered in our study, it was not closely related to the process of soil erosion. Further work should be conducted to obtain more details regarding the microrelief information pertaining to the slope of spoil heaps to elucidate the runoff hydraulic properties and detachment characteristics.

5. Conclusion

A simulated rainfall experiment focusing on spoil heaps with four rock fragment contents (0, 20, 40, 60 mass percentage) and three rock fragment size classes (1–4, 4–7, 7–10 cm) was conducted to investigate the hydrological and erosion processes, as well as rock fragment cover evolution. The results showed that rock fragment content and size both significantly influenced runoff and soil loss processes, as well as rock fragment cover.

Rock fragments in spoil heaps reduce soil detachment rate by influencing runoff production and rock fragment cover. Runoff rates decrease with increasing rock fragment content under a given size class as follows 4–7 < 1–4 < 7–10 cm, but has little change in three rainfall events for a definite treatment. For rocky spoil heaps, rock fragment cover was obtained by processing images of three sections before and after rainfall. The initial rock fragment covers ranged from 2.71 to 41.12%, while the final cover was 14.65–81.64%, which increased fastest during the first rainfall period and the increase rate slowed down in the later two rainfall events. Average soil detachment rate can be expressed by a multiple regression equation of average runoff rate and median rock fragment cover. For a definite rock spoil heap, as accumulated rainfall increased in response to multiple rainfall events, the increasing rock fragment cover led to decreased soil detachment (R^2 = 0.690–0.931).

Acknowledgement

This work was supported by the Natural Science Foundation of China (41601300); the West Light Foundation of The Chinese Academy of Sciences (XAB2015B06); and the Fundamental Research Funds for the Central Universities (2452016107).

Conflict of interest statement

The authors declared that they have no conflicts of interest to this work.

References

Abrahams, A.D., Gao, P., Aebly, F.A., 2015. Relation of sediment transport capacity to stone cover and size in rain-impacted interrill flow. Earth Surf. Process. Landf. 25, 497–504. https://doi.org/10.1002/(SICI)1096-9837(200005)25:5<497::AID-ESP77>3.0.CO;2-P.

Bunte, K., Poesen, J., 1993. Effects of rock fragment covers on erosion and transport of noncohesive sediment by shallow overland flow. Water Resour. Res. 29, 1415–1424. https://doi.org/10.1029/92WR02706.

Cagnoli, B., Romano, G.P., 2012. Effects of flow volume and grain size on mobility of dry granular flows of angular rock fragments: a functional relationship of scaling parameters. J. Geophys. Res. Solid Earth 117. https://doi.org/10.1029/2011JB008926.

Cerdà, A., 2001. Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. Eur. J. Soil Sci. 52, 59–68. https://doi.org/10.1046/j.1365-2389.2001.00354.x.

Chamizo, S., Cantón, Y., Lázaro, R., Solé-Benet, A., Domingo, F., 2012. Crust composition and disturbance drive infiltration through biological soil crusts in semiarid ecosystems. Ecosystems 15, 148–161. https://doi.org/10.1007/s10021-011-9499-6.

Chow, T.L., Rees, H.W., 1995. Effects of coarse-fragment content and size on soil erosion under simulated rainfall. Can. J. Soil Sci. 75, 227–232. https://doi.org/10.4141/cjss95-031.

Cousin, I., Nicoullaud, B., Coutadeur, C., 2003. Influence of rock fragments on the water retention and water percolation in a calcareous soil. Catena 53, 97–114. https://doi.org/10.1016/S0341-8162(03)00037-7.

Fang, H., Sun, L., Tang, Z., 2015. Effects of rainfall and slope on runoff, soil erosion and rill development: an experimental study using two loess soils. Hydrol. Process. 29, 2649–2658. https://doi.org/10.1002/hyp.10392.

Guo, T.L., Wang, Q.J., Li, D.Q., Zhuang, J., 2010. Effect of surface stone cover on sediment and solute transport on the slope of fallow land in the semi-arid loess region of northwestern China. J. Soils Sediments 10, 1200–1208. https://doi.org/10.1007/s11368-010-0257-8.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. In: World Soil Resources Reports No. 106. FAO, Rome.

Jimenez, M.D., Ruiz-Capillas, P., Mola, I., Pérez-Corona, E., Casado, M.A., Balaguer, L., 2013. Soil development at the roadside: a case study of a novel ecosystem. Land Degrad. Dev. 24, 564–574. https://doi.org/10.1002/ldr.1157.

Lawrence, D.S.L., 1997. Macroscale surface roughness and frictional resistance in overland flow. Earth Surf. Process. Landf. 22, 365–382. https://doi.org/10.1002/(SICI)1096-9837(199704)22:4<365::AID-ESP693>3.0.CO;2-6.

Ma, D., Shao, M., 2008. Simulating infiltration into stony soils with a dual-porosity model. Eur. J. Soil Sci. 59, 950–959. https://doi.org/10.1111/j.1365-2389.2008.01055.x.

Mandal, U.K., Rao, K.V., Mishra, P.K., Kpr, V., Sharma, K.L., Narsimlu, B., Venkanna, K., 2005. Soil infiltration, runoff and sediment yield from a shallow soil with varied stone cover and intensity of rain. Eur. J. Soil Sci. 56, 435–443. https://doi.org/10.1111/j.1365-2389.2004.00687.x.

Nasri, B., Fouché, O., Torri, D., 2015. Coupling published pedotransfer functions for the estimation of bulk density and saturated hydraulic conductivity in stony soils. Catena 131, 99–108. https://doi.org/10.1016/j.catena.2015.03.018.

Nearing, M.A., Polyakov, V.O., Nichols, M.H., Hernandez, M., Li, L., Zhao, Y., Armendariz, G., 2017a. Slope-velocity equilibrium and evolution of surface roughness on a stony hillslope. Hydrol. Earth Syst. Sci. 21, 3221–3229. https://doi.org/10.1016/j.iswcr.2017.04.001.

Nearing, M.A., Xie, Y., Liu, B., Ye, Y., 2017b. Natural and anthropogenic rates of soil erosion. Int. Soil Water Conserv. Res. 5, 77–84. https://doi.org/10.1016/j.iswcr.2017.04.001.

Neave, M., Rayburg, S., 2007. A field investigation into the effects of progressive rainfall-induced soil seal and crust development on runoff and erosion rates: the impact of surface cover. Geomorphology 87, 378–390. https://doi.org/10.1016/j.geomorph.2006.10.007.

Novák, V., Kňava, K., 2012. The influence of stoniness and canopy properties on soil water content distribution: simulation of water movement in forest stony soil. Eur. J. For. Res. 131, 1727–1735. https://doi.org/10.1007/s10342-011-0589-y.

Novák, V., Kňava, K., Šimůnek, J., 2011. Determining the influence of stones on hydraulic conductivity of saturated soils using numerical method. Geoderma 161, 177–181. https://doi.org/10.1016/j.geoderma.2010.12.016.

Nyssen, J., Nyssen, J., Haile, M., Poesen, J., Deckers, J., Moeyersons, J., 2001. Removal of rock fragments and its effect on soil loss and crop yield, Tigray, Ethiopia. Soil Use Manag. 17, 179–187. https://doi.org/10.1079/sum200173.

Peng, X., Shi, D., Jiang, D., Wang, S., Li, Y., 2014. Runoff erosion process on different underlying surfaces from disturbed soils in the Three Gorges Reservoir Area, China. Catena 123, 215–224. https://doi.org/10.1016/j.catena.2014.08.012.

Poesen, J., Lavee, H., 1994. Rock fragments in top soils: significance and processes. Catena 23, 1–28. https://doi.org/10.1016/0341-8162(94)90050-7.

Poesen, J., Ingelmo-Sanchez, F., Mucher, H., 1990. The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. Earth Surf. Process. Landf. 15, 653–671. https://doi.org/10.1002/esp.3290150707.

Poesen, J.W., Torri, D., Bunte, K., 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena 23, 141–166.

Rieke-Zapp, D., Poesen, J., Nearing, M.A., 2007. Effects of rock fragments incorporated in the soil matrix on concentrated flow hydraulics and erosion. Earth Surf. Process. Landf. 32, 1063–1076. https://doi.org/10.1002/esp.1469.

Rodrigues, S.C., Silva, T.I., 2012. Dam construction and loss of geodiversity in the Araguari River basin, Brazil. Land Degrad. Dev. 23, 419–426. https://doi.org/10.1002/ldr.2157.

Sadeghi, S.H., Moosavi, V., Karami, A., Behnia, N., 2012. Soil erosion assessment and prioritization of affecting factors at plot scale using the Taguchi method. J. Hydrol. s448–449, 174–180. https://doi.org/10.1016/j.jhydrol.2012.04.038.

Seeger, M., 2007. Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulations. Catena 71, 56–67. https://doi.org/10.1016/j.catena.2006.10.005.

Shen, H., Zheng, F., Wen, L., Han, Y., Hu, W., 2016. Impacts of rainfall intensity and slope gradient on rill erosion processes at loessial hillslope. Soil Tillage Res. 155, 429–436. https://doi.org/10.1016/j.still.2015.09.011.

Shi, Z., Xu, L., Wang, Y., Yang, X., Jia, Z., Guo, H., Xiong, W., Yu, P., 2012. Effect of rock fragments on macropores and water effluent in a forest soil in the stony mountains of the Loess Plateau, China. Afr. J. Biotechnol. 11, 9350–9361. https://doi.org/10.5897/AJB12.145.

Shi, D., Wang, W., Jiang, G., Peng, X., Yu, Y., Li, Y., Ding, W., 2016. Effects of disturbed landforms on the soil water retention function during urbanization process in the Three Gorges Reservoir Region, China. Catena 144, 84–93. https://doi.org/10.1016/j.catena.2016.04.010.

Simanton, J.R., Renard, K.G., Christiansen, C.M., Lane, L.J., 1994. Spatial distribution of surface rock fragments along catenas in semiarid Arizona and Nevada, USA. Catena 23, 29–42. https://doi.org/10.1016/0341-8162(94)90051-5.

Tetegan, M., Pasquier, C., Besson, A., 2012. Field-scale estimation of the volume percentage of rock fragments in stony soils by electrical resistivity. Catena 92, 67–74. https://doi.org/10.1016/j.catena.2011.09.005.

Urbanek, E., Shakesby, R.A., 2009. Impact of stone content on water movement in water-repellent sand. Eur. J. Soil Sci. 60, 412–419. https://doi.org/10.1111/j.1365-2389.2009.01128.x.

Wang, G., Innes, J., Yang, Y., Chen, S., Krzyzanowski, J., Xie, J., Lin, W., 2012. Extent of soil erosion and surface runoff associated with large-scale infrastructure development in Fujian Province, China. Catena 89, 22–30. https://doi.org/10.1016/j.catena.2011.09.001.

Wang, X., Li, Z., Cai, C., Shi, Z., Xu, Q., Fu, Z., Guo, Z., 2012. Effects of rock fragment cover on hydrological response and soil loss from Regosols in a semi-humid environment in South-West China. Geomorphology 151, 234–242. https://doi.org/10.1016/j.geomorph.2012.02.008.

Zavala, L.M., Jordán, A., Bellinfante, N., Gil, J., 2010. Relationships between rock fragment cover and soil hydrological response in a Mediterranean environment. Soil Sci. Plant Nutr. 56, 95–104. https://doi.org/10.1111/j.1747-0765.2009.00429.x.

Zhang, L.T., Gao, Z.L., Yang, S.W., Li, Y.H., Tian, H.W., 2015. Dynamic processes of soil erosion by runoff on engineered landforms derived from expressway construction: a case study of typical steep spoil heap. Catena 128, 108–121. https://doi.org/10.1016/j.catena.2015.01.020.

Zhao, X., Xie, Y.S., Jing, M.X., Yang, Y.L., Wen-Hua, L.I., 2012. Standardization parameter for spoilbank underlying surface simulation of development construction project. J. Soil Water Conserv. 229–234, 26. https://doi.org/10.13870/j.cnki.stbcxb.2012.05.029. (in Chinese with English abstract).

Zhou, B.B., Shao, M.A., Shao, H.B., 2009. Effects of rock fragments on water movement and solute transport in a Loess Plateau soil. C. R. Géosci. 341, 462–472. https://doi.org/10.1016/j.crte.2009.03.009.

Zhou, B.B., Shao, M.A., Wang, Q.J., Yang, T., 2011. Effects of different rock fragment contents and sizes on solute transport in soil columns. Vadose Zone J. 10, 386. https://doi.org/10.2136/vzj2009.0195.