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ORIGINAL ARTICLE

Effectiveness of geotextiles for road slope protection under simulated rainfall

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Abstract Geotextiles are used to control soil losses in civil engineering. The effects of geotextiles on runoff and soil erosion have been documented; however, the conditions studied to date have been limited and are insufficient for the optimization of the selection and application of geotextiles for other sites. As a result, systematic studies of various rainfall intensities are still required. In this study, four geotextiles (coir blanket—CB, mixed coir and straw blanket—MCSB, straw blanket—SB and nonwoven fabric—NB) and a bare control group were examined under simulated rainfall events. Four rainfall intensities (24, 47, 71 and 93 mm h^{-1}) were simulated for 60 min. The plots used in this experiment were 200 cm long by 100 cm wide by 40 cm deep at a slope gradient of 70 %. The tested soil was sandy loam, which is a primary soil type in northern China. The results show that geotextiles are more effective for soil loss control than for runoff control, especially in the case of stronger rainfall events. The effectivenesses of the geotextiles at reducing runoff and soil erosion decrease with increasing rainfall intensity; the geotextiles are most effective under moderate rainfall intensity levels. NB is the most effective geotextile for reducing runoff, while it reduces soil loss only below a rainfall intensity level of 47 mm h^{-1}. The natural geotextiles can reduce both runoff and soil erosion. For runoff control, SBs are more effective than MCSB, followed by CBs. For soil erosion control, CBs are the most effective, followed by MCSBs and then SBs.

Keywords Geotextile · Rainfall simulation · Runoff generation · Soil erosion · Sediment concentration

Introduction

Civil engineering projects can produce many steep slopes with exposed and disturbed surface soils that are hypersensitive to erosion agents (Alvarez-Mozos et al. 2014a; Krenitsky et al. 1998). To consolidate side slopes produced through civil engineering activities, various measures have been designed and applied for side-slope protection, including engineering and vegetation methods. Vegetation measures have been shown to be effective for soil loss control on steep slopes (Cammeraat et al. 2005; Fan et al. 2013; Xu et al. 2006). Pan et al. (2016) showed that revegetation on steep slopes significantly increases soil resistance to concentrated flows. Even so, the levels of soil and water loss remain high immediately after engineering projects are completed, and vegetation fails to provide sufficient coverage. Cerda (2007) demonstrated that bare road embankments result in 30 times more soil loss than vegetated ones and recommended that restoration works should be undertaken immediately after road construction

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to reduce soil erosion, protect roads and prevent traffic accidents. Moreover, seeds can be washed away by runoff flows when no other measures are adopted (Smets et al. 2009). Therefore, geotextiles are recommended and widely used to support vegetation as a supplementary means of controlling soil erosion (Alvarez-Mozos et al. 2014b; Ghosh et al. 2016). Geotextiles are blankets, mats or nets made from woven or nonwoven natural (jute, coir, straw, etc.) or synthetic (polypropylene, polyester, etc.) materials for slope protection (Rickson 2006).

Geotextiles have been found to be effective for runoff and erosion control (Alvarez-Mozos et al. 2014a; Bhattacharyya et al. 2008; Saengrungruang and Boyd 2014; Smets and Poesen 2009). Geotextiles adhere to the soil surface after installation due to their drapability (Sutherland and Ziegler 1995). Wet geotextiles expand, enhancing the drapability levels. Countless micro-depressions form after geotextiles applied. At the same time, geotextiles can store runoff and trap sediment (Krenitsky et al. 1998; Mitchell et al. 2003) by reducing runoff flow velocities (Ziegler and Sutherland 1998). As their primary function, geotextiles reduce the kinetic energy of raindrops and prevent surface soil particles from being splashed away (Ziegler et al. 1997) or from undergoing interrill erosion (Ziegler and Sutherland 1998). Mitchell et al. (2003) reported that fine sediment particles become visibly trapped by palm mats in their field study.

The effectiveness of geotextiles for runoff and erosion control depends on rainfall intensity levels to a great extent. However, systematic studies that have covered wide ranges of rainfall intensity levels in combination with various geotextiles have been limited. Won et al. (2012) compared three geotextiles and a control group on two slopes (10 and 20 %) under two rainfall intensity levels (30 and 60 mm h^{-1}). The results showed that geotextiles are more effective under low rainfall intensity levels (30 mm h^{-1}) than under high rainfall intensity levels (60 mm h^{-1}). Shao et al. (2014) examined the effectiveness of three geotextiles under three rainfall intensities (10, 30 and 50 mm h^{-1}) and found that geotextiles are more effective at reducing runoff at lower rainfall intensity levels, whereas they are more effective at erosion control at higher rainfall intensity levels. Both of these studies show that the effectivenesses of geotextiles vary with rainfall intensity. However, the maximum rainfall intensities adopted in the tests were not high enough, and the range of rainfall intensity studied was limited in comparison with that of natural rainfall. To explore the relationships between the effectiveness of a geotextile and the rainfall intensity, experiments under higher rainfall intensities and larger ranges must be conducted. Moreover, rill erosion has been observed after stronger rainfall events even when nonwoven fabrics were adopted, which contradicts the common understanding of geotextiles. Thus, it is essential to test the effectiveness of geotextiles over the course of full rainfall events and to document the dominant period during which geotextiles function well or fail to function. There are no directly related national or professional standards on the production and application of natural geotextiles, and these standards are urgently needed for the use of natural geotextiles. As one purpose of this funding project is to develop professional standards of natural geotextiles, the objectives of this study are as follows: (1) to evaluate the effectiveness of selected geotextiles on runoff generation and soil erosion and to identify the differences between those geotextiles; (2) to assess the influence of rainfall intensity on the effectiveness of geotextiles and to identify the related trends; and (3) to contribute to the ongoing application of geotextiles and to the development of professional standards on the production and application of natural geotextiles.

Materials and methods

Geotextiles tested

There are no national or professional standards directly related to the production, application and evaluation of natural geotextiles. As one of our goals is to develop such a professional standard, we examined the natural geotextiles that are popular in the trading market and that are already being used in several engineering projects. Three natural geotextiles (coir blanket, mixed coir and straw blanket, and straw blanket) and a synthetic geotextile of nonwoven fabric (polypropylene) were selected to evaluate the effectiveness of soil loss and runoff control on steep slopes. The nonwoven fabric (NF) was designed in accordance with the related professional standards (FZT 64004-1993). The natural geotextiles examined were produced by the Beijing Land Company. The structures of the natural geotextiles were nonwoven natural fibers enhanced by PP Twine on both the upper and lower surfaces. The coir blanket (CB) was composed of 100 % coir that was 350 g m^{-2} and 6 mm thick; the mixed coir and straw blanket (MCSB) was composed of 50 % coir and 50 % rice straw that was 230 g m^{-2} and 3.5 mm thick; the straw blanket (SB) was composed of 100 % rice straw that was 260 g m^{-2} and 3.5 mm thick; and the nonwoven fabric (NF) was 60 g m^{-2} and 0.3 mm thick.

Soil properties and experimental plot setup

The soil used was sandy loam according to the International Standard for Soil Texture Classification. The soil texture was as follows: 65 % sand (2–0.02 mm), 24 % silt (0.02–0.002 mm) and 11 % clay (<0.002 mm). The organic matter content was 0.37 %. The selected soil is the primary soil type in northern China, where applications of natural geotextiles have been performed. One bare control group was established as the background value to evaluate the effectiveness of the geotextiles. Prior to the experiments, the tested soil was sieved through a 1-cm screen, and then screened block masses were scraped and re-sieved. The sieved soil was air-dried at open-air temperatures to achieve an initial gravimetric water content level of 6 ± 0.5 %. A rectangular experimental plot (200 cm long by 100 cm wide by 40 cm deep) with a movable foundation was used to conduct the experiments. Each plot was filled with the prepared test soil in two layers, including a top layer and a sublayer. The top layer was 20 cm thick with a bulk density of 1.3 g cm^{-3}, which is in accordance with the natural state of the sampled soil, and the sublayer was 15 cm thick with a compacted bulk density of 1.7 g cm^{-3}. This two-layered structure was designed to simulate common slopes with a relatively loose surface layer and a compacted sublayer. Geotextiles were then placed on the plot to prepare the plots for simulated rainfall. The plot gradient was set to 70 % according to field conditions of highway base slopes in China. Cloths were placed on the perforated base of the experimental plot to facilitate infiltration and to prevent soil materials from leaking through. At the downslope end of the experimental plot, a trough was installed to collect runoff and sediment.

Rainfall simulation experiments

Rainfall simulation was conducted using Meyer rainfall simulators fitted with Veejet 80150 nozzles in the rainfall simulation laboratory of Beijing Normal University, China. The simulators were installed 6 m from the ground to ensure the uniformity of the simulated rainfall, as the erosion plot was approximately 2 m high when positioned at a gradient of 70 %, and a vertical distance of no less than 2.5 m from the plot was required to establish the rainfall simulation system. The water pressure level was set to 0.04 MPa. The rainfall simulation system had a 95 % uniformity coefficient. The rainfall intensity level was designed based on local rainfall data to cover the range of maximum 30-min rainfall intensities found in northern China, as rainfall erosivity is closely related to the maximum 30-min rainfall intensity level. At the same time, soil erosion is mostly attributed to more significant rainfall events, and thus, the following four rainfall intensities were selected: 24, 47, 71 and 93 mm h^{-1}. The rainfall duration for each rainfall intensity setting was 60 min. All experiments were conducted in the same position relative to the rainfall simulators to maintain consistency. All runoff was collected over 5-min intervals from the beginning of the simulated rainfall through the 60-min duration, resulting in a total of 12 time intervals. Runoff volumes were measured, and samples were then oven-dried at 105 °C for 48 h to measure the sediment yields. The laboratory test apparatus used is shown in Fig. 1, and the photographs of the experiment are shown in Fig. 2.

Data derivation

The degrees of reduction of runoff and soil loss are used to evaluate the effectiveness of the four tested geotextiles for slope protection, which are presented as Eqs. 1 (Sutherland 1998) and 2, respectively.

$$\text{RRE} = \frac{R_{\text{BS}} - R_i}{R_{\text{BS}}} \times 100 \tag{1}$$

where R_{BS} is the runoff depth of the bare soil (BS) plot and R_i is the runoff depth of the specified geotextile.

$$\text{SLRE} = \frac{\text{SL}_{\text{BS}} - \text{SL}_i}{\text{SL}_{\text{BS}}} \times 100 \tag{2}$$

where SL_{BS} is the soil loss of the BS plot and SL_i is the soil loss of the specified geotextile. Positive or negative signs indicate whether there was a reduction or increase, respectively, and the absolute values denote the magnitudes of the reduction or increase.

Paired sample *t* tests for comparison of the meanings were performed using SPSS 18.0.

Results and discussion

Effects on runoff generation

The runoff depths of various combinations of rainfall intensity and coverage are presented in Table 1. Runoff depths increased with rainfall intensity from 0.80 to

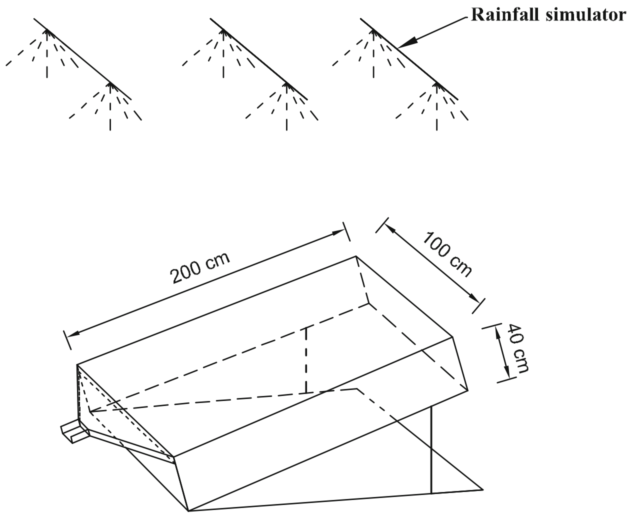


Fig. 1 Schematic diagram of the laboratory test apparatus

Fig. 2 Photographs of the experiments

45.64 mm, and both the smallest and highest runoff depths were derived from the bare control groups. The increase in runoff levels varied with different types of geotextiles. The bare soil sample presented the greatest increase in runoff depth of 44.84 mm followed by the MCSB, CB, SB and NF plots with the increased runoff depths of 34.89, 33.91, 32.92 and 22.32 mm, respectively.

Figure 3 shows that geotextiles were effective at reducing runoff relative to the bare control group except when the rainfall intensity was 24 mm h^{-1}. For the 24 mm h^{-1} rainfall case, the RRE values of all four geotextiles were negative ranging from −67.24 (CB) to −9.27 (MCSB), indicating that geotextiles can increase runoff levels under low levels of rainfall intensity. This result is in agreement with Smets et al.'s (2011) observations of minor runoff events (<1 mm). In our study, when the rainfall intensity was 24 mm h^{-1}, geotextile runoff depths remained greater than those of the control plot (Table 1). This increment occurred because the geotextile fibers contributed to the direct runoff that flowed downslope along the geotextile surface, leading to an increase in runoff under light rainfall conditions. In fact, this effect

Table 1 Runoff depths of various combinations of rainfall intensity and coverage

Rainfall intensity (mm h^{-1})	Runoff depth (mm)				
	CB	MCSB	SB	NF	BS
24	1.34	0.88	1.32	1.18	0.80
47	7.94	1.70	2.82	1.99	14.49
71	25.15	25.71	16.56	19.59	34.36
93	35.25	35.77	34.24	23.50	45.64

CB, MCSB, SB, NF and BS denote coir blanket, mixed coir and straw blanket, straw blanket, nonwoven fabric and bare soil, respectively

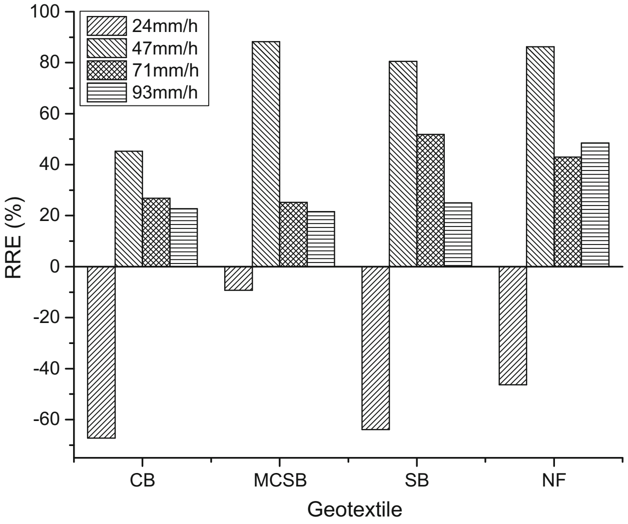


Fig. 3 Runoff reduction effectivenesses of the tested geotextiles under various rainfall intensity levels. *RRE* represents runoff reduction effectiveness. *CB*, *MCSB*, *SB* and *NF* denote coir blanket, mixed coir and straw blanket, straw blanket and nonwoven fabric, respectively

still existed under more significant rainfall and runoff conditions, but the relative contributions of direct runoff to the total runoff depth were less significant.

Under the three higher rainfall intensity conditions, geotextiles were found to be clearly capable of reducing the total runoff. The values of RRE ranged from 21.62 to 88.26 with an average value of 47.08, suggesting that approximately half of the runoff was reduced by geotextiles relative to the bare plot. This result is consistent with the results of previous studies (Bhattacharyya et al. 2009; Krenitsky et al. 1998; Luo et al. 2013; Shao et al. 2014; Smets et al. 2007). Geotextiles can absorb water during rainfall events, and they expand, adhere to the soil surface and enhance the drapability as they become saturated with water (Sutherland and Ziegler 1995). This drapability facilitates the formation of micro-dams and micro-depressions in the soil/geotextile interface (Krenitsky et al. 1998; Mitchell et al. 2003) and increases surface roughness (Bhattacharyya et al. 2011a; Rickson 2006; Sutherland and Ziegler 2007). Hence, the application of geotextiles can delay the initiation of runoff, slow the runoff flow velocity, increase the flow depth, and impound and store runoff in small depressions, thereby inducing more water infiltration and runoff reduction (Bhattacharyya et al. 2011b; Krenitsky et al. 1998; Shao et al. 2014; Sutherland and Ziegler 2007). The water-holding capacity is considered to be an important property of geotextiles. Geotextiles become heavier when they become wet, enhancing their drapability on soil (Rickson 2006). Geotextiles reduce the direct effects of raindrops on surface soils and dissipate the kinetic energy of the raindrops, thus weakening surface sealing and crusting (Sutherland and Ziegler 2007). This process increases the infiltration rates of the covered surfaces relative to bare soil, thereby decreasing runoff levels.

The maximum RRE of geotextiles appeared under 47 mm h^{-1} rainfall conditions and then decreased with increasing rainfall intensity (Fig. 3). The average RRE values of the four tested geotextiles at rainfall intensities of 47, 71 and 93 mm h^{-1} were 75.07, 36.7 and 29.47, respectively. These data show that geotextiles are effective at reducing runoff under moderate to heavy rainfall intensity levels; however, this effectiveness decreased with an increase in rainfall intensity. Similar phenomena have been reported by Shao et al. (2014) and Won et al. (2012). As the rainfall intensity level increases, geotextiles reach their respective maximum water absorbance capacities, and micro-depressions are gradually filled with runoff as rainfall continues. This increased flow depth results in an increase in the infiltration rate as the infiltration rate of soil gradually reaches its steady infiltration rate. The values of RRE thus decrease with time, and the higher the rainfall intensity becomes, the faster the RRE values decrease.

Though geotextiles have been widely confirmed to reduce runoff, their effectiveness is variable among the different types (Fig. 3). Under the three higher rainfall intensity conditions, the average RRE of NFs was the highest (59.26) followed by those of SBs (52.44), MCSBs (45.02) and CBs (31.59), which indicates that NF was the most effective geotextile for controlling runoff. As NF becomes wet, it adheres to the soil surface more compactly than the three natural geotextiles as it is thinner and more flexible, thus causing more runoff to reach the soil surface and resulting in a reduction in the direct runoff. Meanwhile, upon impacting the geotextiles, cracked raindrops pass through the NF more easily due to the presence of evenly distributed micropores. This behavior thus resulted in less direct runoff in the NF plot compared to that found in the natural geotextiles plots.

Runoff reduction levels also varied among the three natural geotextiles (Fig. 3). Straw blanket was found to be

66 % more effective at reducing runoff than CB on average. Furthermore, at a rainfall intensity of 71 mm h^{-1}, straw blanket was the only natural material that reduced runoff by more than half relative to the bare plot. The mixed coir and straw blanket and the coir blanket reduced the runoff by approximately one quarter. When rainfall reached maximum levels, the three natural geotextiles exhibited similar effectiveness levels of approximately one quarter, only accounting for half that of the NF. The varying effectivenesses of the natural geotextiles can be attributed to their different properties (e.g., the percentage of open area and the thickness) (Bhattacharyya et al. 2009). Coir blanket was the densest and thickest of the three geotextiles, and this property resulted in higher levels of direct runoff and thus the lowest RRE value. Straw blanket was the loosest and thinnest, producing less direct runoff and thus the highest RRE.

Figure 4 illustrates the temporal change in effectiveness that occurred during the experiments. Geotextiles exhibited continually decreasing runoff levels throughout almost the entire 60-min simulated rainfall period except for a few negative data points that resulted from the rainfall events of 24 mm h^{-1} (Fig. 4). At the beginning of the 5-min interval, the runoff reduction effectiveness of NF was −17,300, meaning that the runoff depth of the NF plot was 174 times of that of the bare plot during the first time interval (Fig. 4a). As raindrops impacted the NF surface, they moved downslope and formed sheet flow immediately. This portion of the runoff was not significant in volume; however, it affected RRE greatly when the runoff depth was low. This phenomenon was also observed during the first period at higher rainfall intensity levels (Fig. 4b–d), explaining why RRE values were typically low and even negative when rainfall started. During the three higher rainfall intensities, the maximum runoff depth of the bare plot was 1.15 mm over the time period as the geotextiles increased the runoff levels. That is, all of these runoff-increasing cases occurred during minor runoff events (<1.15 mm). Runoff reduction effectiveness increased quickly during the first period and then gradually decreased after peak values were reached, indicating that the RRE of geotextiles changed over time after rainfall began. The period during which RRE began to decrease shortened as the rainfall intensity increased. Furthermore, the evaluated RRE values may be affected by the duration of the rainfall simulations. Short durations (e.g., less than 10 min) may lead to low and even negative RRE values. Maximum RRE values are obtained from moderate periods. Longer periods resulted in lower RRE values. When comparing natural and synthetic geotextiles, the average runoff reduction effectiveness of the three natural geotextiles was significantly lower than that of NF at a significance level of 0.1. However, despite being less effective than NF in terms of runoff control, the three natural geotextiles performed well in reducing soil loss.

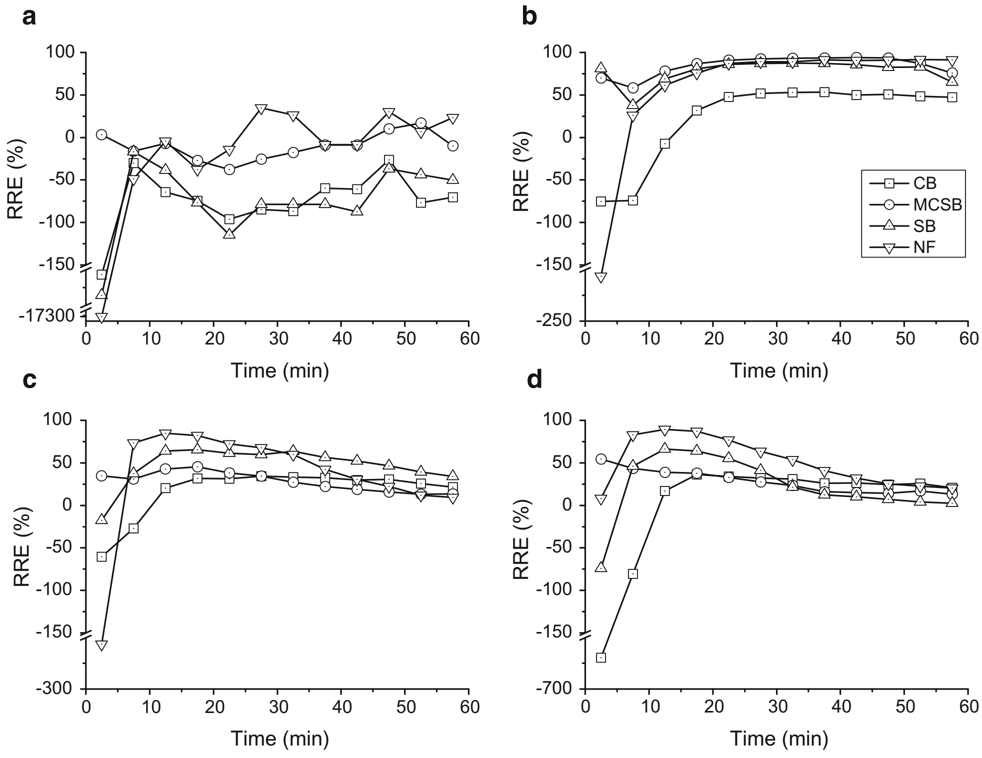


Fig. 4 Runoff reduction effectivenesses over 60 min of rainfall for various geotextiles and rainfall intensities. *RRE* denotes runoff reduction effectiveness. *CB*, *MCSB*, *SB* and *NF* denote coir blanket, mixed coir and straw blanket, straw blanket and nonwoven fabric, respectively. **a**, **b**, **c** and **d** denote rainfall intensities of 24, 47, 71 and 93 mm h^{-1}, respectively

Effects on soil erosion

The soil erosion rates (SERs) of different combinations of rainfall intensity and coverage are presented in Table 2. The SERs ranged from 7.28 t km^{-2} in SB at a rainfall intensity of 24 mm h^{-1} to 4332.77 t km^{-2} in BS at a rainfall intensity of 93 mm h^{-1}. The average SER was 856.44 t km^{-2}.

Geotextiles limited soil losses except when the rainfall intensity was 24 mm h^{-1} and for the case of NF at 71 mm h^{-1} (Fig. 5). For the three higher rainfall intensity levels, the average soil loss reduction effectiveness (SLRE) of the four tested geotextiles was 74.5, representing a nearly three-quarter soil loss reduction. Similar results have been reported previously. Bhattacharyya et al. (2012) indicated that erosion rates have significantly decreased by 15–20 % in Lithuania and by 67–98 % in Southeast Asia relative to plots with no geotextile cover. Davies et al. (2006) tested the effectiveness of palm-mat geotextiles and found that geotextiles reduce soil losses by roughly two-thirds relative to bare control plots. Kalibova et al. (2016) found that all of their tested geotextiles reduced soil losses by more than 90 %. Raindrops with high levels of kinetic energy can disperse soil aggregates into particles that are easily transported by runoff. Geotextiles can limit raindrop splash erosion by dissipating the kinetic energy of the raindrops (Ziegler et al. 1997). In addition, under intense rainfall conditions, fine particles are visibly trapped by palm mats (Mitchell et al. 2003). In Collins et al. (2015), field embankment tests showed that geotextiles can hold the soil together to prevent soil erosion. The effects of geotextiles on runoff described above affect soil losses. For example, slowed flow velocities decrease the shear stress of the overland flow (Rickson 2006; Ziegler and Sutherland 1998) and decrease the soil detachment rate (Smets et al. 2009), causing fewer soil particles to become detached by the flows. This decrease in runoff velocity also reduces the sediment carrying capacity of runoff, causing more soil particles to become deposited and stored in the micro-depressions.

At a rainfall intensity of 24 mm h^{-1}, soil losses from geotextile-covered plots were greater than those from the bare plot with the exception of a slight decline in the SB (Fig. 5). The pattern of effectiveness was recorded as follows: SB > MCSB > CB > NF. Generally, higher levels of runoff resulted in greater sediment yields. When the experimental plots were prepared, the surface soil particles were loose. The surface soil became more easily detached and transported and more sensitive to runoff depth in comparison to compacted soil. As runoff depths were increased at a rainfall intensity of 24 mm h^{-1}, more soil materials were carried away, leading to higher erosion levels compared to those of the bare plot.

The maximum SLRE of all geotextiles appeared at a rainfall intensity of 47 mm h^{-1} with an average of 96.28, denoting high erosion control effectiveness. As the rainfall intensity increased, the three natural geotextiles effectively controlled erosion, and the minimal SLRE value reached 64.79, which appeared in SB at a rainfall intensity of 93 mm h^{-1}. The SLRE of the CB was high and stable under the three higher rainfall intensity levels at a minimal value of 91.32 and was primarily due to its dense and thick structure relative to the other materials that were considered.

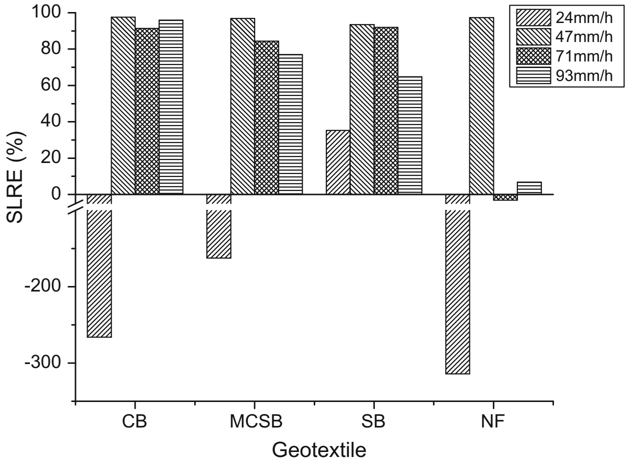


Fig. 5 Soil loss reduction effectivenesses of the tested geotextiles under various rainfall intensities. *SLRE* denotes soil loss reduction effectiveness. *CB*, *MCSB*, *SB* and *NF* denote coir blanket, mixed coir and straw blanket, straw blanket and nonwoven fabric, respectively

Table 2 Soil erosion rates of various combinations of rainfall intensity and coverage

Rainfall intensity (mm h^{-1})	Soil erosion rate (t km^{-2})				
	CB	MCSB	SB	NF	BS
24	41.19	29.54	7.28	46.62	11.25
47	20.72	26.84	54.64	22.91	840.56
71	182.72	329.10	169.25	2170.44	2104.88
93	178.05	996.58	1525.67	4037.81	4332.77

CB, MCSB, SB, NF and BS denote coir blanket, mixed coir and straw blanket, straw blanket, nonwoven fabric and bare soil, respectively

Although NF was the most effective in terms of runoff control, its performance in regard to erosion control was not as good as those of the natural geotextiles, especially under the two highest rainfall intensity levels. The average soil loss reduction effectiveness of the three natural geotextiles was significantly higher than that of nonwoven fabric at a significance level of 0.1. The SLRE values of NF for rainfall intensities of 71 and 93 mm h^{-1} were −3.11 and 6.81, respectively, meaning that the erosion intensity of the NF plot was similar to that of the BS plot. Rills were observed on the NF plot for rainfall intensities of 71 and 93 mm h^{-1}. The occurrence of rill erosion can distinctly enhance erosion intensity relative to sheet erosion. After installation, nonwoven fabric simply adheres to the soil surface with little integration, while the fibers of natural geotextiles become integrated with the surface soil to form a steadier structure. This integration can better resist runoff. Nonwoven fabric was found to be more effective at reducing runoff, resulting in more infiltration and higher soil water content, and the soil became more erodible relative to the other plots. This weaker protective structure with soil and increased susceptibility to runoff caused the NF to fail to conserve soil.

Ziegler and Sutherland (1998) found that geotextiles offer enhanced drapability when integrated with the soil surface. Differences between natural geotextiles when integrated with soil result in different runoff control performances. Coir is better able to integrate with surface soil than straw; therefore, coir blanket presents the highest degree of drapability and the highest SLRE value followed by MCSB and then SB. Shao et al. (2014) found that the erosion control effects are more obvious under high rainfall intensities. However, their experiments were carried out under three rainfall intensity conditions of 10, 30 and 50 mm h^{-1}, and the highest rainfall intensity level used in Shao et al.'s (2014) experiments is close to the 47 mm h^{-1} condition used in this study, under which the highest SLRE was found. Therefore, the wider and higher range of rainfall intensities examined in this study facilitates a more comprehensive understanding of the effects of geotextiles on runoff and erosion control under various rainfall intensity conditions.

Soil loss reduction effectiveness levels under the simulated rainfall conditions are presented in Fig. 6. Generally, soil loss reduction effectiveness increased quickly during the first and second time intervals. This observation is in accordance with the RRE results. At a rainfall intensity of 24 mm h^{-1}, the soil loss reduction effectiveness values fluctuated considerably, and most remained negative throughout the entire process, indicating that sediment levels increased to some extent. The erosion enhancing effect of NF can be clearly observed in Fig. 6c, d. From 40 to 45 min under a rainfall intensity of 71 mm h^{-1} and from 35 to 40 min under a rainfall intensity of 93 mm h^{-1}, the SLRE of NF decreased dramatically over the remaining time period, which increased erosion. The SLRE values of NF in the last 5-min interval under rainfall intensities of 71 and 93 mm h^{-1} were −194 and −43, respectively. The former SLRE was nearly five times that of the latter. Nonwoven fabric effectively controlled erosion only before these sharp declines occurred, appearing approximately 35 min after rainfall started. This suggests that the NF can be effective at reducing soil losses during heavy rainfall periods for a restricted duration of approximately half an hour, and it enhances the soil erosion process thereafter.

For the three natural geotextiles, the duration also influences the estimation of SLRE, although to a limited extent, and their performances vary with rainfall intensity. Generally, short durations result in smaller SLRE values during the first period, and long durations resulted in lower SLRE values because the effectiveness levels became less significant with time. Moderate durations contributed to the highest SLRE.

Effects on sediment concentrations

Sediment concentrations constitute an important index that reflects interactions between runoff and surface soil. Table 3 presents the sediment concentrations of different rainfall intensities and treatments. The sediment concentration ranged from 2.6 g L^{-1} for CB at a rainfall intensity of 47 mm h^{-1} to 161.4 g L^{-1} for NF at a rainfall intensity of 93 mm h^{-1}. Generally, sediment concentrations increased with rainfall intensity. The global average sediment concentration of the five treatments for the three higher rainfall intensity levels increased from 21.1 g L^{-1} for 47 mm h^{-1} of rainfall to 39.3 g L^{-1} for 71 mm h^{-1} of rainfall and then to 65.9 g L^{-1} for 93 mm h^{-1} of rainfall. However, at a rainfall intensity of 24 mm h^{-1}, sediment concentrations for all treatments were higher (24.4 g L^{-1}) compared to those recorded at a rainfall intensity of 47 mm h^{-1} (21.1 g L^{-1}). This result was more conspicuous when the sediment concentration of the BS pot was removed from the two rainfall intensity cases: 27.0 g L^{-1} for 24 mm h^{-1} simulated rainfall against 12.2 g L^{-1} for 47 mm h^{-1} simulated rainfall. At low rainfall intensity levels, soil surfaces covered with geotextiles were even more sensitive to runoff than bare soil. Unexpectedly, the mean sediment concentration of the BS plot (69.4 g L^{-1}) for the three higher rainfall intensities was not the highest, being replaced by the NF plot (93.1 g L^{-1}), followed by SB (24.4 g L^{-1}), MCSB (18.7 g L^{-1}) and CB (4.9 g L^{-1}). This result shows that the coir blanket was the most effective at reducing soil sensitivity to runoff; by contrast, nonwoven fabric enhanced the interaction. Furthermore, at a rainfall intensity of 47 mm h^{-1}, nonwoven fabric

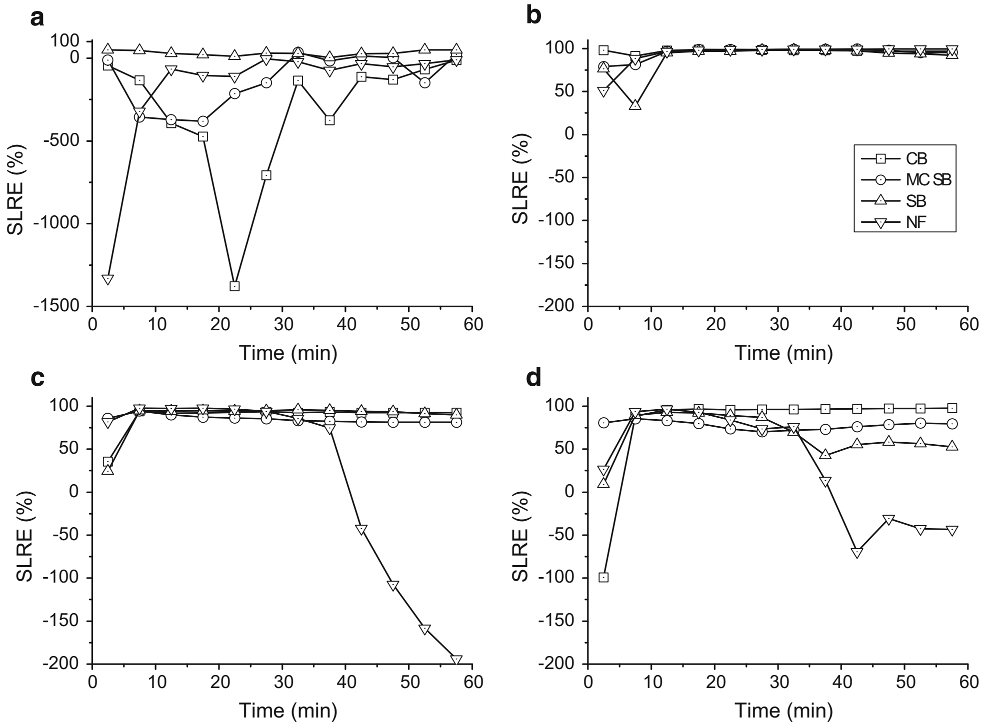


Fig. 6 Soil loss reduction effectivenesses over 60 min of rainfall for the tested geotextiles and rainfall intensities. *SLRE* denotes soil loss reduction effectiveness. *CB*, *MCSB*, *SB* and *NF* denote coir blanket, mixed coir and straw blanket, straw blanket and nonwoven fabric, respectively. **a**, **b**, **c** and **d** denote rainfall intensities of 24, 47, 71 and 93 mm h^{-1}, respectively

Table 3 Sediment concentrations of various combinations of intensity and coverage

Rainfall intensity (mm h^{-1})	Sediment concentration (g L^{-1})				
	CB	MCSB	SB	NF	BS
24	30.3	33.2	5.5	39.1	13.9
47	2.6	15.7	19.2	11.5	56.8
71	7.2	12.7	10.2	106.3	59.9
93	5.0	27.6	43.8	161.4	91.7

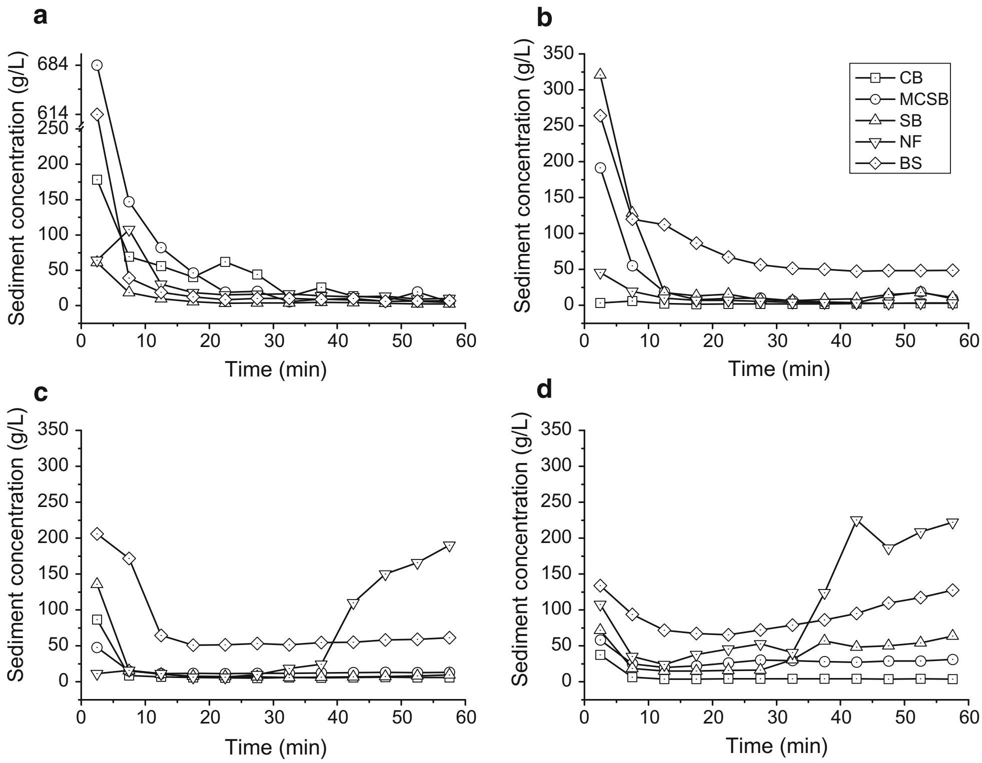
CB, MCSB, SB, NF and BS denote coir blanket, mixed coir and straw blanket, straw blanket, nonwoven fabric and bare soil, respectively

significantly reduced the sensitivity, while at rainfall intensities of 71 and 93 mm h^{-1}, nonwoven fabric enhanced the sediment concentrations. This result shows that the effectiveness of NF in terms of sediment concentrations was significantly influenced by the rainfall intensity levels.

Figure 7 shows the sediment concentration changing processes of the five treatments for the rainfall intensities examined. During the first few minutes, the sediment concentration of all treatments rapidly decreased before tapering off to a gradual decreasing trend, indicating that soil's sensitivity to runoff was high during this period. Although all treatments exhibited a gradual decreasing trend, the values varied. As the rainfall intensity level increased, sediment concentration variations became more obvious. After approximately 35 min under rainfall intensities of 71 and 93 mm h^{-1}, the sediment concentration of the NF plot increased rapidly and soon became higher than that of the BS plot. This behavior explains why the average sediment concentration of the NF plot was higher than that of the BS plot. This process is also in agreement with changes in soil loss found in the NF plot as discussed in "Effects on soil erosion" section.

Geotextiles are effective at reducing sediment concentrations relative to bare soils. Geotextiles limit raindrop splash and the soil detachment rate of runoff, resulting in lower surface sensitivity to unit runoff and thus lowering the sediment concentration. Sediment concentrations increased with rainfall intensity overall. However, at a rainfall intensity of 24 mm h^{-1}, sediment concentrations were higher than those recorded at the higher rainfall intensity level. As noted above, some loose soil particles were found on surfaces as a result of plot preparation. These particles were very sensitive to runoff, causing the sediment concentration to be higher under lower rainfall intensity conditions or at the start of a stronger storm. The difference between natural geotextiles is attributed to their properties. Coir blanket has a lower sediment concentration than MCSB and SB due to its denser and thicker structure. The sediment concentrations of NF at rainfall intensities of 71 and 93 mm h^{-1} were much higher than those of the bare plots. This is attributed to the development of rills during the erosion process as stated above. Luo et al. (2013) observed that over 20 min of rainfall at an intensity of 70.6 mm h^{-1}, the sediment concentration of NF was much

Fig. 7 Sediment concentration processes for each 60-min experiment for the tested rainfall intensities and coverage treatments. *CB*, *MCSB*, *SB*, *NF* and *BS* denote coir blanket, mixed coir and straw blanket, straw blanket, nonwoven fabric and bare soil, respectively. **a**, **b**, **c** and **d** denote rainfall intensities of 24, 47, 71 and 93 mm h^{-1}, respectively



lower than that of the bare plots. This result is consistent with what occurred over the first 30 min in our study, i.e., nonwoven fabric effectively reduced sediment concentrations over the first 30 min period.

Conclusions

The present study was conducted to determine the effectiveness of four geotextiles for sandy loam slope protection in northern China. Based on the results, our main findings are as follows:

Geotextiles effectively controlled runoff and soil erosion but not minor runoff events (<1.15 mm), and geotextiles were more effective at controlling soil erosion than runoff.

The reduction of runoff and soil erosion decreased with increasing rainfall intensity and was most successful under moderate rainfall intensity levels.

Nonwoven fabric was the most effective at reducing runoff and was effective at limiting soil erosion under a rainfall intensity of 47 mm h^{-1}. However, nonwoven fabric had marginal effects on (and at times even increased) the erosion intensity under high rainfall intensity conditions.

Natural geotextiles effectively controlled runoff and soil erosion, although the effectiveness of the three natural geotextiles varied. For runoff control, straw blanket performed better than MCSB followed by CB. For soil erosion control, coir blanket was the most effective followed by MCSB and then SB.

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