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Research Article

Influence of infiltration on soil erosion in green infrastructures

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Rainwater-induced erosion in green geotechnical infrastructures such as a multilayered landfill cover system (MLCS) is a severe concern in the current era. Although vegetation is a proven measure to control erosion in the MLCS, there are other factors such as infiltration rate which influence the control of the phenomenon. Most of the existing studies are limited to understand influence of vegetation on erosion control or infiltration rate alone. In this study, an attempt is made to incorporate infiltration measurements alongside vegetation cover to understand erosion in surface layer of the MLCS. For this purpose, a pilot MLCS was constructed, and erosion of its surface soil was temporally evaluated through soil loss depth of eroded cover surface under the influence of natural as well as simulated rainfall conditions. Alongside erosion, the amount of vegetated cover was evaluated through photographic image analyses and infiltration rate was measured by mini disk infiltrometer. From the observed results, it is understood that soil erosion and infiltration rate depict a contrasting behaviour with growing vegetation. Antecedent moisture contents were observed to show greater influence on such erosion behaviour which was observed during the testing period. Such studies may be helpful to researchers and practicing engineers for understanding performance of various green geotechnical infrastructures and scheduling the maintenance services to increase the longevity of their layered soil systems.

Keywords: erosion, vegetation, infiltration, surface soil, multilayered landfill cover system

1 Introduction

Rainfall-induced erosion is one of the most important concerns involved with layered soil system of different geotechnical green infrastructures such as a multilayered landfill cover system (MLCS) (Xue et al., 2016). It needs prime attention particularly if environmental influence of uncovered waste is considered (Shaikh et al., 2019a; Yamsani et al., 2017). Shaikh et al. (2021) investigated seepage characteristics of MLCSs under an extreme ponding condition through detailed laboratory column tests and finite-element seepage analyses. Their study suggested that erosion can be controlled by managing surface-water runoff, minimizing seepage flow, and selecting a surface layer material that can withstand anticipated erosive stresses. Swope (1975) studied 24 landfill cover systems in the USA and found that 33% had slight erosion, 40% had moderate erosion, and more than 20% had severe erosion. In the United States of America, most landfill cover system top decks are designed to have an inclination in the range of 2 to 5%, after accounting for settlement, to promote surface runoff (Nyhan, 2005). Based on the literature, slopes flatter than 2% may cause water to be ponded on the surface (Anderson & Stormont, 1997). Slopes greater than 5% likely promote erosion, unless preventive measures are taken (Gross et al., 2002). Excessive erosion or slope instability rises as the cover system inclination increases (Morris & Stormont, 1998). The soil surface should be uniformly graded and sloped at about 3% to prevent ponding of rainwater (Koerner & Daniel, 1997). According to Sherard et al. (1976), erosion potential of soil is primarily a function of the size of soil particles, inter-particle cohesive forces, and velocity of transporting fluid (air or water). Erosion-resistant materials such as soil-gravel mixtures, gravel, riprap,

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and geo-synthetic erosion control materials, may be utilized to help in reducing erosion (Gray & Sotir, 1996). In addition to these, use of asphalt concrete, articulated block systems, construction and demolition wastes, and lightweight manufactured aggregates can also be used (Barnswell & Dwyer, 2012).

Landreth et al. (1991) recommends a minimum cover soil thickness of 900 mm or greater for a few specific types of MLCSs such as evapotranspiration or capillary barrier cover system. The minimum thickness of surface layer is established based on consideration of rooting depth of surface vegetation, anticipated erosion rate, and construction tolerances (Øygarden et al., 1997). For shallow-rooted plants such as certain grasses, a 150 mm thick layer of soil usually provides adequate rooting depth (Zhan et al., 2007). Thus, the minimum thickness of a vegetated surface layer is generally 150 mm (USEPA, 1989). If plants with deeper roots are considered, thickness of topsoil should be increased to accommodate the excess root growth (Blight, 2009). The most common material used to construct the surface layer is locally available topsoil which contains adequate organic matter and plant nutrients (Hoor and Rowe, 2013). It helps to promote growth of vegetation (Khapre et al., 2017). Thus, previous researchers (Schnabel et al., 2012; Song et al., 2017) have had diverse opinions on the relation between erosion and infiltration in vegetated soils. Climatic factors affect the types of vegetation that grow on MLCS surface layers (Bonaparte et al., 2002). Climatic criteria for designing MLCSs may include quantity and seasonal distribution of precipitation, intensity and duration of specific storm events, seasonal temperature variations, depth of frost penetration, quantity of snow melt, wind speed and direction, solar radiation, and humidity (Jarvis et al., 2011). Heavy rainfall for a prolonged period leads to increase in rainwater infiltration and erosion of MLCS (Maqsoud et al., 2011). Drier climate results in shrinkage and desiccation cracks in MLCS surface layer (Landreth et al., 1991). Cracks may also develop due to the effects of freeze-thaw cycles in cold regions (Dune et al., 2011). Repeated cycles of wetting and drying can induce fatigue stress in the geomaterials, thereby deteriorating its performance (Nyhan et al., 1990). As a result, hydraulic conductivity may increase in surface layers because of cracks and root growth (Sinnathamby et al., 2014). The effect of climate change on functioning of MLCS has been rarely investigated from the purview of geotechnical engineering. Most of the existing studies solely discuss the influence of rainfall on surface erosion of vegetated cover soil (Shaikh et al., 2019b) without much emphasis on the infiltration happening simultaneously. Some studies (Gadi et al., 2017; Ghosh et al., 2019) attempted for understanding the infiltration rate through vegetated soils without considering the erosion. Limited studies (Zhang et al., 2014) attempted for evaluating the combined effects of infiltration and vegetation on rain induced erosion of surface soils of the MLCS.

This study attempts to address this issue by monitoring the infiltration of surface soils alongside the vegetation and erosion due to rainfall activity. The prime objective of the study is to access the temporal variation in erosion, infiltration, and vegetation characteristics of surface layer in a pilot Multilayered landfill cover system (MLCS) under natural and controlled rainfall simulation events.

2 Materials and methods

2.1 Study area

As understood from the above-mentioned literature, field monitoring programmes might solve such problems involving MLCS erosion. Hence for this study, a pilot MLCS was constructed in the backyard of the civil engineering department, Indian Institute of Technology Guwahati, India. Configuration and individual layer material of field model were selected in accordance with the

Table 1 Basic characteristics of soils used in the study

Properties	Clayey silt (ML)
Specific gravity	2.65
Hygroscopic water content (%)	5
Saturated hydraulic conductivity (m.s^{-1})	2.9E-8
Specific surface area (m^2.g^{-1})	55
Linear shrinkage (%)	2
Free swell index (%)	10
% mass of gravel (>4.75 mm)	0
% mass of coarse sand (2.0–4.75 mm)	17
% mass of medium sand (0.425–2.0 mm)	16
% mass of fine sand (0.075–0.425 mm)	16
% mass of silt (0.002–0.075 mm)	19
% mass of clay (<0.002mm)	32
Liquid limit (% mass)	42
Plastic limit (% mass)	22
Shrinkage limit (% mass)	21
Plasticity index (%)	20
Optimum moisture content (% mass)	20
Maximum dry density (g.cm^{-3})	1.73
Soil pH value with water (at 28.5 °C)	6.85
Organic content (% mass)	0.48
Cation exchange capacity (meq.100 g^{-1})	8

recommendations of the United States Environmental Protection Agency (USEPA, 1989). Soils used for the MLCS model were locally collected from a nearby hill. The MLCS is made of the conventional layers: hydraulic barrier, drainage system, and surface protection layer along with various geosynthetic inclusions as additional barrier, drainage, and filter layers for superior performance. Locally available hill soil, reddish in colour, was selected for its use as a surface protection layer. Geotechnical characterization of this surface soil was evaluated using standard procedures in the ASTM guidelines (ASTM standard D422-63 (2007); ASTM standard D854 (2014); ASTM standard D5084 (2014); ASTM standard D4318 (2017)), and corresponding results are summarized in Table 1. It was low plastic clayey silt soil (ML according to the Unified soil classification system (ASTM standard D2487, 2017)). This soil would depict moderate infiltration and good resistance to erosion as understood from its plasticity and density characteristics. However, a detailed study would show an exact performance of the surface soil with growing vegetation.

2.2 Experimental set-up

The construction of the pilot cover system, filling up with materials, compacting every layer, erecting rainfall simulator, and installation of weather monitoring systems have been done with extreme care to avoid any kind of experimental errors. The coefficient of uniformity for 100 mm rainfall was found to be around 90% (Shaikh et al., 2019a). About 8,000 kilograms of soils were used for preparing the setup. The usual recommendation of cover slope angle is 3 to 7°, however, to understand the worst probable performance a slope of 10° is adopted in this study. The photograph of operational field set-up under simulated rainfall is presented in Fig. 1. The properties of rainfall simulator are in accordance with Shaikh et al. (2019b). A micro weather station equipped with rain gauge (ECRN 100 high-resolution double-spoon tipping bucket type rain gauge, Meter Group Inc. (2019a)) is installed in the vicinity of field pilot MLCS. The weather monitoring during the test period is summarized in Fig. 2. The rainfall simulation experiments are started after finishing the regular monsoon for understanding the maximum possible erosion scenario.

The surface area is categorized into small grids for quantifying spatial heterogeneity in vegetation growth, infiltration, and soil loss depth. The grid size was selected based on the initial measurements of vegetation and infiltration. Fig. 3. illustrates the layout of 81 locations, where the vegetation percentage, infiltration rate, and eroded depth of soil surface are measured on surface protection layer of MLCS. The vegetation density was measured in accordance with procedures detailed in Gadi et al. (2017) by collecting photographic images of vegetated surface with varying time and processing them with a freeware Image analysis program (Image-J) similar to methods followed by Shaikh et al. (2019b). The infiltration rate was attained through sequential measurements of 150 ml Mini disk infiltrometer (MDI, Meter Group Inc. (2019b)) at every location as mentioned



Figure 1 MLCS test setup during a rainfall simulation event

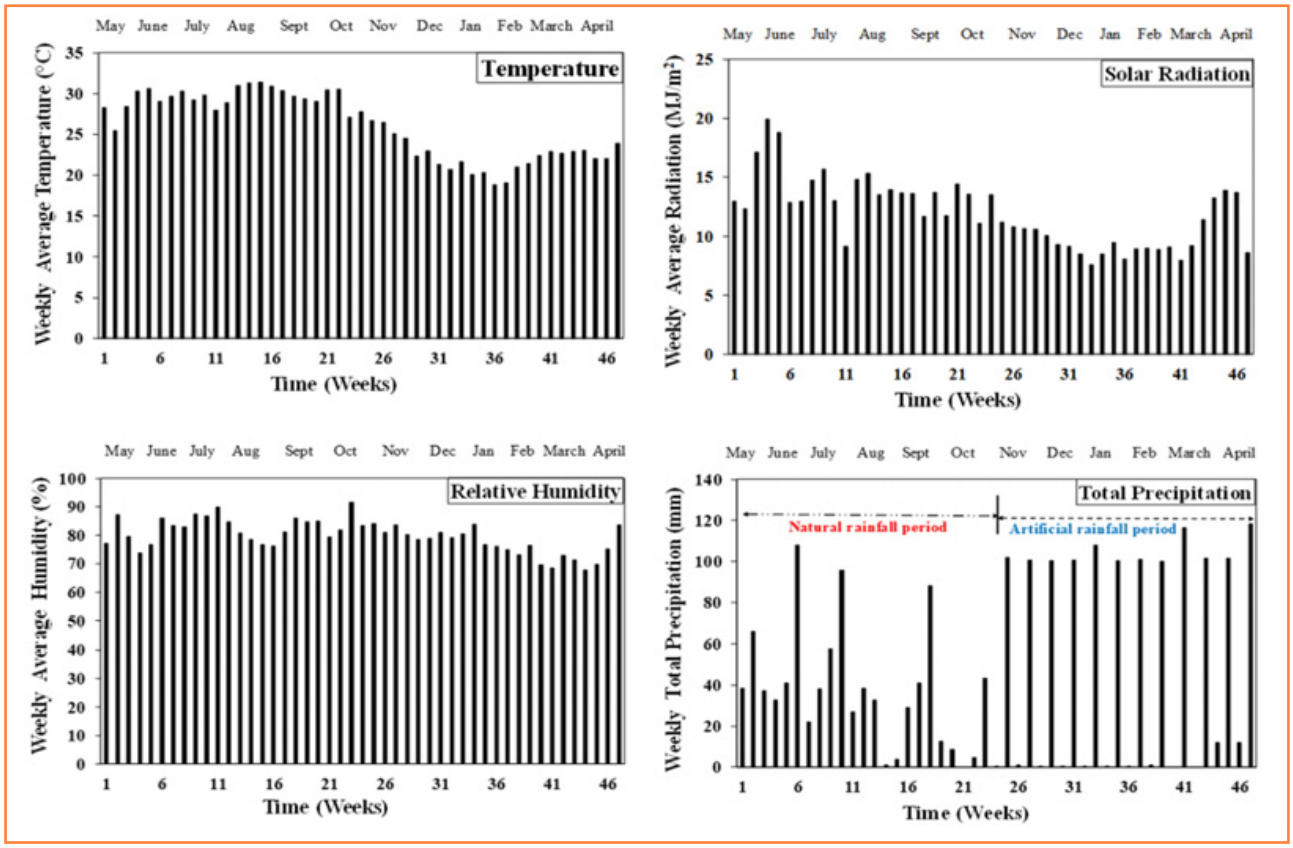


Figure 2 Weather monitoring during the test period monitored using ECRN 100

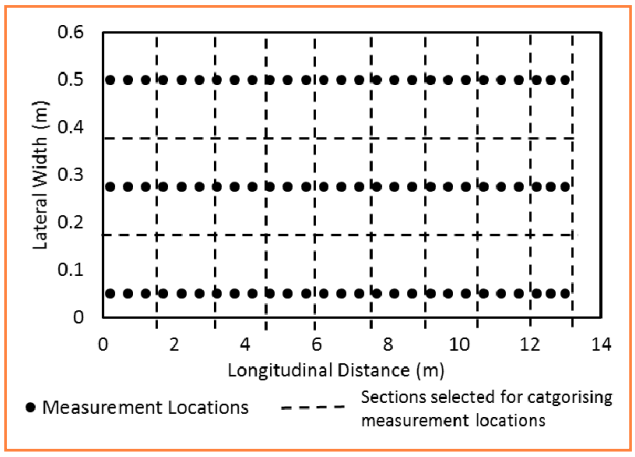


Figure 3 Schematic layout of measurement locations involved in evaluating surface layer



Figure 4 Repeated infiltration measurements around desiccation cracks on surface soil

in the grid. Measurements were repeated in locations with desiccation cracks and increased grass cover, to account for all real field conditions as depicted in Fig. 4. Further, the varying depth of surface is measured using Vernier calipers at different points, to attain a spatial soil loss profile on temporal basis throughout the study period.

3 Results and discussion

3.1 Temporal variation of infiltration, vegetation, and erosion

Fig. 5 depicts the contours describing the temporal variation of infiltration rate, vegetation density, and eroded depth of surface layer of the pilot MLCS under above-shown weather conditions. Though the study was conducted for one year and the data were evaluated

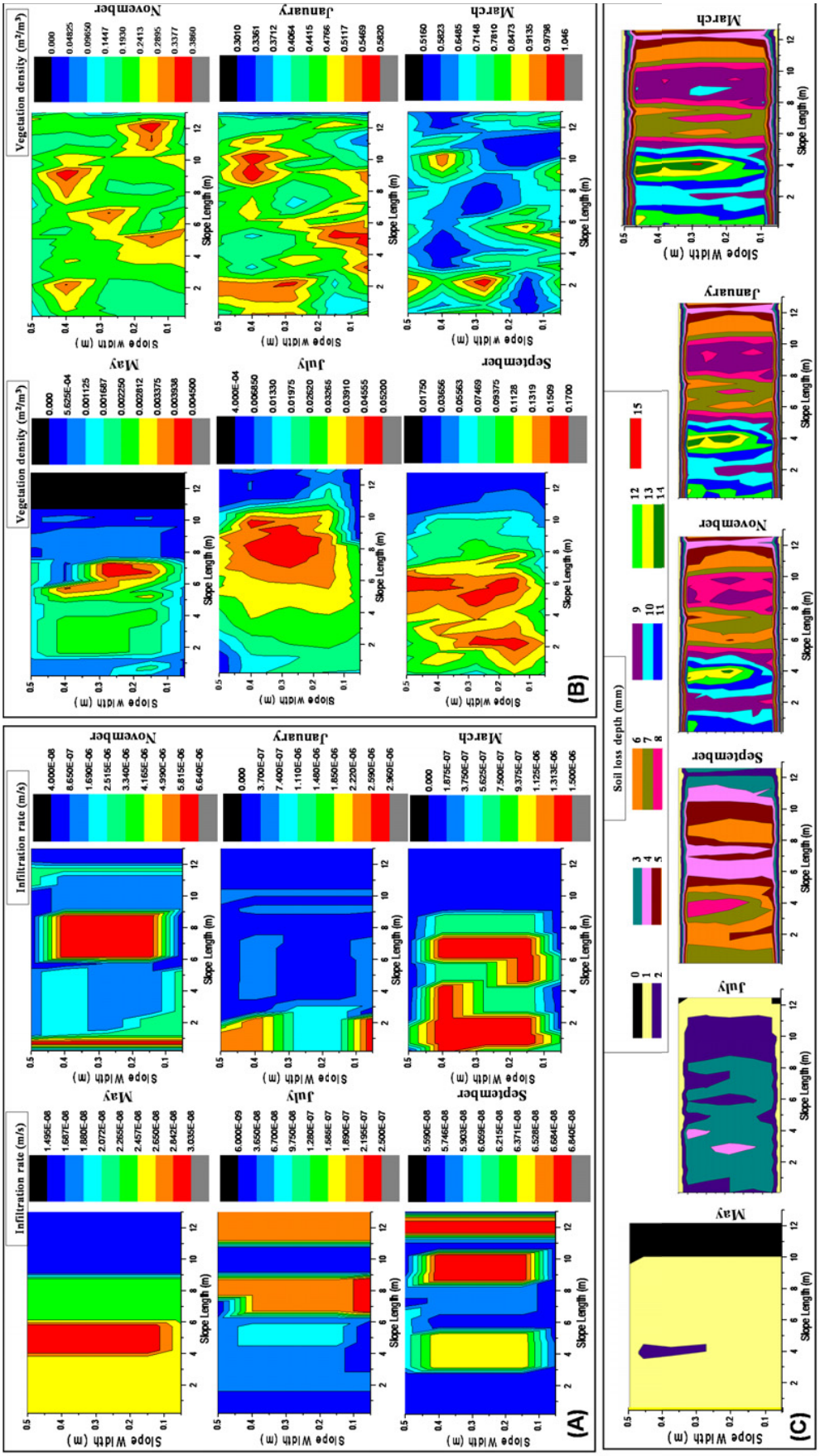


Figure 5 Temporal and spatial variation of infiltration, vegetation, and erosion

on weekly basis, every two-month average results were considered in describing the contours to reduce the number of figures and have a representative picture. From the depicted results it can be observed that within the initial days the amount of infiltration, vegetation density, and eroded depth are relatively low indicating the effect of newly compacted surface layer. Similar results are observed by Shrestha et al. (2005); Bhave and Sreeja (2013); Adams and Smith (2014); Yamsani et al. (2017). The infiltration was observed to vary 6E-09 to 1.5E-06 throughout the study period. The least infiltration was observed in months of July on the surface subjected to intense drying; such a behaviour is expected in general. The variation in infiltration rate for a particular period of time is about tenfold within the considered area of study. Greater degree of variation is observed with growing vegetation. Variation was also observed around the mild cracks generated during the dry spell. However, it was also noted that these mild cracks were found to be closed with high intensity rainfall simulations in the months of November and December. As a result, there is a decrease in corresponding infiltration rate for that particular time.

The eroded depth of soil was observed to vary from 0 to 15 mm within the considered study period accounting to about 5% of the surface soil thickness (300 mm as suggested in USEPA (1989)). Significant amount of erosion was noted during the rainfall simulation period nearly 12 mm, while during natural rainfall only about 6 mm of erosion was observed. The purpose of simulation experiments was to observe the worst possible behaviour of surface soil layer. Fig. 2 depicts only 3 weeks of about 100 mm cumulative precipitation during the natural monsoon, and there were only couple of cloud burst events accounting to about 70 mm rainfall during the natural cycle. Consecutive simulation of 12 cloud burst events has generated about 12 mm depth of soil loss. In this 12 mm of erosion depth, most of it was observed in the early months of July to November. Further, no significant variations in depth of erosion were noticed from months of November to March indicating nearly stable behaviour. Increased vegetation density and reduced climatic variations might be attributed for this stable behaviour which was similar to the observation made by Shaikh et al. (2019b).

3.2 Spatial variation of infiltration, vegetation, and erosion

Early results in Fig. 5, indicate that the infiltration increased with increasing the length of the slope. Infiltration in the toe regions was relatively high owing to the loose soil structure formed as a result of erosion from crest of the slope. In contrast, the vegetation density is relatively low towards the toe region. Thus, the interception (water retention on the plant leaves) was small. Hence, bigger proportion was distributed between infiltration and surface runoff. This significantly influences the variation in runoff as well as the settlement of eroded soil mass. The settled soil mass near the toe region even influenced the eroded depth to indicate a relatively lower value. However, all these variations are evident in initial stages of study, and in later stages, a uniform variation in observed parameters was noted. This could be likely due to the controlled rainfall condition in simulation experiments, relatively uniform weather conditions, and due to increased stability because of enhanced vegetation density in months of November to March. The all-time biggest soil loss depth was seen at the slope length of 4 m. This is likely due to lack of uniformity in compacting the soil of this region or the presence of some foreign loose matter in the soil of this region. The observed low soil loss towards the toe region is likely due to runoff sedimentation.

3.3 Influence of infiltration on erosion of vegetated soil

In general, the runoff and consecutive erosion are observed to be low when infiltration is high. However, the surface dryness was noted to increase infiltration and erosion in the months of July to November due to increased temperatures while the vegetation density was relatively low. And in the later stages of the study, as the vegetation density increased, the water holding capacity of surface soil was observed to increase. Hence, the average infiltration rate in both wet and dry weeks was observed to increase. Such findings were reported in Gadi et al. (2017) while studying hydraulic conductivity in green infrastructures. During this stage, the erosion rate is relatively low in comparison to early stages of study. In summary, this indicates the strong interplay between the infiltration and erosion behaviour of vegetated soil. For better understanding the relation between infiltration and erosion behaviour of vegetated soil, an integrated model that considers continuous changes of these parameters and resulting degradation needs to be developed. Such a study would bring a preliminary inference in developing effective soil loss models for surface soils used in MLCSs.

4 Conclusions

This article deals with the field evaluation of surface soil layer of a pilot MLCS in terms of its erosion and infiltration rate under the influence of natural and simulated rainfall for a period of a year. The study evidently presented the diverse reasons behind contrasting behaviour of erosion at higher rates of infiltration in vegetated and partially vegetated soil. Antecedent moisture contents have

greater influence on erosion and infiltration behaviour of surface soils. The rate of infiltration was observed to increase during days of no rainfall due to the formation of surface desiccation cracks and low in-situ water contents. Further, the infiltration was found to decrease with partial closure of desiccation cracks and increase in antecedent water contents owing to high intensity rainfall during simulated rainfall study. The high soil losses due to erosion during simulated rainfall events decreased significantly, as the vegetation increased. Vegetation was found to have significant effect on reducing the soil loss depth of surface soil layer of MLCSs. The study indicates the need of bioengineering for protecting the surface layer of MLCSs.

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