



Analyzing the effects of eco-DRR practices on slope stability in a landslide-prone transport corridor in the Western Ghats, India

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Abstract

Landslides pose a significant threat to infrastructure and human life, especially in mountainous roads that have poorly protected slopes. This study focuses on the Kallar-Ponmudi road corridor in the Western Ghats of Kerala, India, which is susceptible to rainfall-induced shallow landslides. To assess slope stability, we used the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability (TRIGRS) model, a physics-based, GIS-integrated FORTRAN program that simulates the timing and distribution of shallow landslides triggered by rainfall. Using this model, high susceptibility regions were selected to evaluate the effectiveness of different ecosystem-based disaster risk reduction (eco-DRR) measures in stabilizing the slopes. Initially, geotechnical parameters were derived from soil samples collected from these selected unstable slopes and used in the laboratory to recreate (simulate) real-field conditions. Five different slope conditions were tested under artificial rainfall: natural (unprotected), jute mesh, synthetic mesh, shallow-rooted grass, and deep-rooted vegetation. Jute mesh is selected for its affordability, biodegradability, and excellent soil contact, which supports vegetation growth and regulates surface erosion whereas synthetic mesh is included for its durability, adaptability, and effectiveness in reinforcing soil and improving drainage. Vegetative solutions using shallow- and deep-rooted species are considered due to their ability to strengthen soil through root reinforcement. Additionally, shallow roots reduce surface erosion whereas deep roots facilitate improved shear strength and subsurface stability, while also being readily available and low-cost. The results show that vegetative measures, particularly deep-rooted plants like vetiver grass, significantly enhanced slope stability compared to other reinforcements. Thus, this study highlights the importance of site-specific ecological interventions in improving road resilience in landslide-prone terrains, giving much impetus to eco-DRR measures.

Keywords: Landslides, Western Ghats, Slope stability, Slope protection, eco-DRR, TRIGRS

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1 Introduction

Landslide refers to the downhill movement of a mass of rock, debris or earth down a slope (Cruden, 1991; Cruden and Varnes, 1996). The occurrences of landslide are mainly conditioned by slope and soil whereas the trigger is rainfall. Shallow landslides, the usual type in terrain covered by thin

veneer of soil (usually 1–3 m depth), occur at boundaries between the debris and the underlying more solid parent rock (Salciarini et al., 2008). The sudden movement of earth materials caused by landslides, including this type of shallow one, result in fatalities and substantial damage to physical assets (Rotaru et al., 2007; Das et al., 2010; Froude and Petley, 2018; Weidner et al., 2018). One of the most

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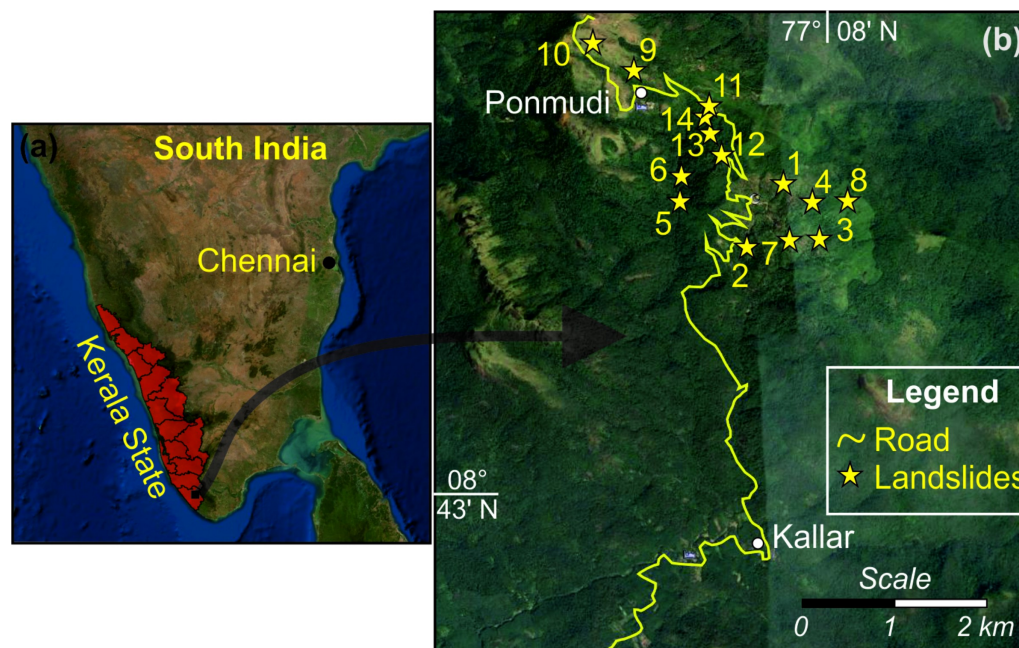


Fig. 1. (a) Location map of the study area (b) 12.7 km road stretch from Kallar to Ponmudi with landslide locations marked (landslide locations are detailed in Table 1).

Table 1. List of landslides along the road stretch from Kallar to Ponmudi between 1988 and 2019.

No	Location	Year	Dimension*	Type of landslide
1	Merchiston Estate 8°44'55.5"N, 77°07'50.6"E	1988	15 × 15 × 3 m	Debris slide
2	Merchiston Estate 8°44'35.3"N, 77°07'39.7"E	1992	35 × 10 × 2 m	Debris flow
3	Merchiston Estate 8°44'33.9"N, 77°08'03.3"E	1992	200 × 10 × 2 m	Debris flow
4	Ponmudi 8°44'49.4"N, 77°07'58.6"E	1992	2 × 1 × 1 m	Rock fall
5	Merchiston Estate 8°44'51.1"N, 77°07'39.9"E	1992	800 × 40 × 3 m	Debris flow
6	Idinjar 8°45'06.8"N, 77°04'15.6"E	1992	3000 × 300 × 5 m	Debris flow
7	Merchiston Estate 8°44'34.6"N, 77°07'55.9"E	1992	600 × 35 × 5 m	Debris flow
8	Ponmudi 8°44'49.4"N, 77°07'59"E	1992	500 × 20 × 2 m	Debris flow
9	Hairpin 22 8°45'32.3"N, 77°06'53.7"E	2002	5 × 40 × 3 m	Debris slide
10	Upper Sanatorium 8°45'48"N, 77°06'34.4"E	22.07.2010	12 × 20 × 1 m	Debris slide
11	Between 21 & 22 hairpin 8°45'17.1"N, 77°07'31.4"E	22.07.2010	15 × 10 × 1 m	Debris slide
12	Hairpin 17 8°45'6.9"N, 77°07'29.28"E	01.08.2014	5 × 2 × 2 m	Debris slide
13	Hairpin 19 8°45'15.1"N, 77°07'30.4"E	14.08.2018	5 × 15 × 2 m	Debris slide
14	Hairpin 19 and 20 8°45'16.5"N, 77°07'31.2"E	17.10. 2019	10 × 5 × 2 m	Debris slide

*indicates length × width × thickness.

important physical assets is the roads. Roads form an important infrastructural asset in mountainous regions that links different places as well as being a livelihood link for the population living uphill (Sudmeier-Rieux et al., 2019). Poorly constructed roads, i.e., the one without proper slope protection measures and surface/sub-surface drainage measures, exacerbate landslide occurrence. Such roads are quite common in developing countries like India.

Kerala, a state in India, is characterized by a linear escarpment throughout its entire length, called the Western Ghats (Fig. 1a). Several hamlets as well as tourist destinations nestle in this escarpment. The sole lifeline to these hamlets is roads. From the road density map of this hilly state, created from Open Street Map (OSM), the density is 853 km/100 km² when compared to the country level road density of 142.7 km/100 km². Ponmudi, a popular hill station 53 km NE of Thiruvananthapuram, Kerala's capital, is reached by a winding mountain road with a series of hair-pin bends. (Fig. 1b). The stretch of 12.7 km road

from Kallar to Ponmudi has 22 hairpin turns through an elevation between 300 m and 1,100 m, which shows the geomorphic dissection of this terrain. The cut slopes along the road are mostly unprotected and have witnessed several shallow landslides (mainly debris flow) as well as a few rock falls (Table 1). All the landslides were triggered during monsoon season, spanning from June to October.

To enhance the stability of these roads, this study aims to analyze the effects of various ecosystem-based disaster risk reduction (eco-DRR) measures on the hydrological and mechanical properties that determine the factor of safety (FoS), using a catchment-scale dynamic hydrological and slope stability model called Transient Rainfall Infiltration and Grid-based Regional Slope-stability (TRIGRS). Eco-DRR, as defined by the International Union for Conservation of Nature (IUCN), refers to 'the sustainable management, conservation, and restoration of ecosystems to provide services that reduce disaster risk by mitigating hazards and increasing livelihood resilience' (Joseph et al., 2024).

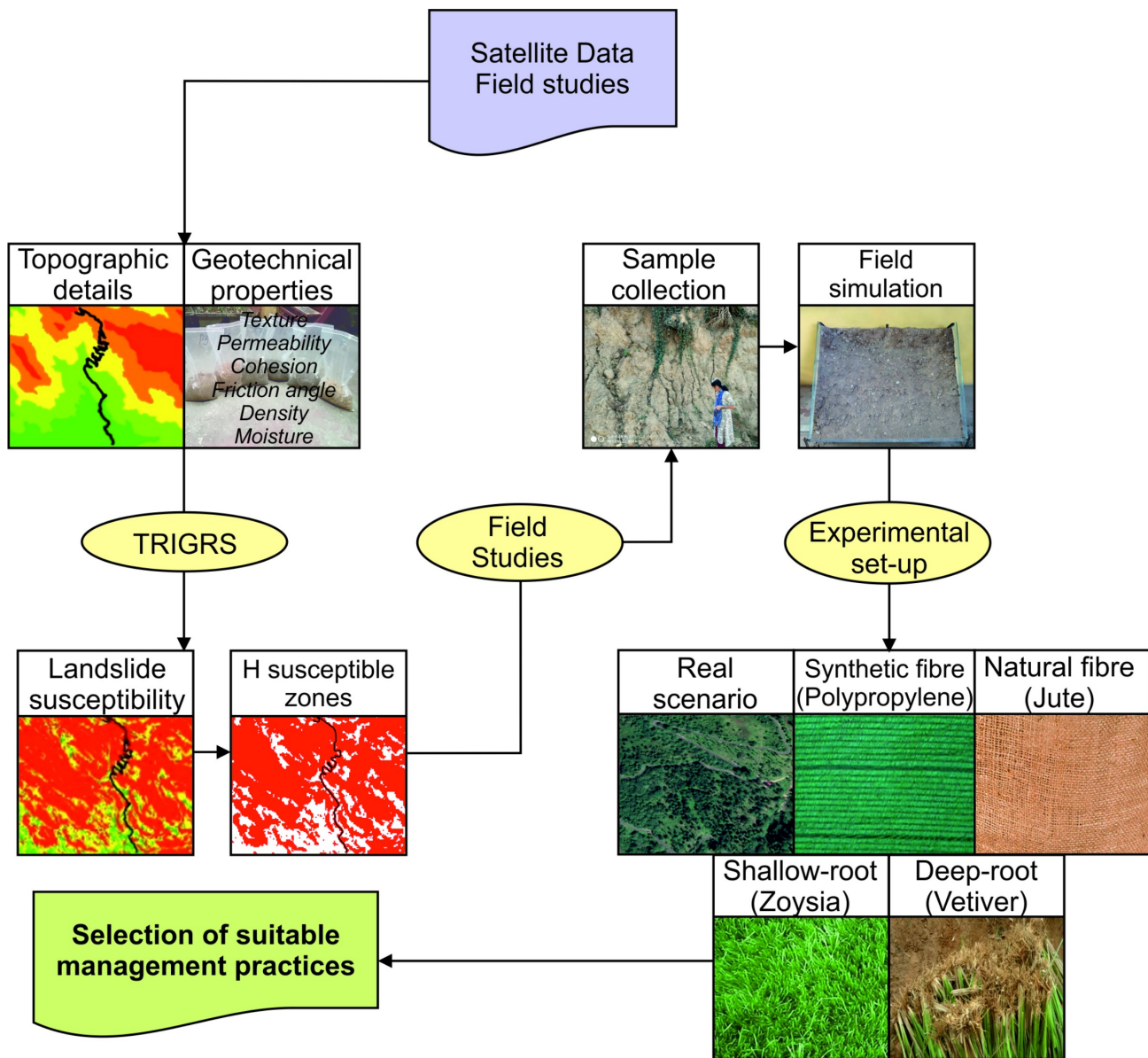


Fig. 2. Flow chart of the methodology adopted for the study (H = High).

The importance of such nature-based solutions in disaster risk reduction has been widely recognized (Renaud et al., 2013; Joseph et al., 2017, 2024).

The unstable slopes were subjected to detailed studies. Representative soil samples from the unstable slopes were collected and analyzed in the laboratory by simulating the real-field conditions. These were used as input for the model. The model was tested with four different stabilization methods, apart from the natural existing condition, artificial rain was created to identify which method is well-suited for this hilly road and under what precipitation conditions. The four different stabilization methods used are (i) jute mesh, (ii) synthetic mesh, (iii) shallow-rooted grass, and (iv) deep-rooted plants.

2 Methodology

The methodology adopted is described below and illustrated in a flow chart (Fig. 2).

2.1 Creation of landslide susceptibility maps

TRIGRS, a Fortran-based program was adopted for the landslide susceptibility analysis based on the applicability of this method in similar terrain conditions (e.g. Weidner et al., 2018). All the input files for the TRIGRS model were created in the form of ASCII grid files. TRIGRS model calculates the FoS for each grid cell with respect to the created rainfall event of the southwest monsoon utilizing the parameters such as digital elevation model (DEM), slope and its aspect, flow accumulation, and flow direction in a GIS environment. TRIGRS is a raster and physics-based model that uses a time-dependent approach to predict the slope stability of landscapes during a rainfall event (Baum et al., 2002). It is created for measuring the timing and distribution of shallow rain-induced landslides. It incorporates a pressure head factor, $\Psi(Z, t)$, where Ψ represents the ground-water pressure head, t is time, and $Z = z/\cos(\delta)$. Here, Z is the vertical coordinate direction (positive downward)

and represents the depth below the ground surface, while z is the slope-normal coordinate direction (also positive downward), and δ is the slope angle (in degree). This factor is integrated into the resisting force, which varies with depth and time, thereby linking the geohydrologic and slope stability components of the model. TRIGRS also calculates runoff routing, distributing excess water above the infiltration capacity to adjacent cells.

The procedure for slope stability modelling using TRIGRS consists of different stages (Fig. 2): collection of DEM for the assessment of topography, collection of soil samples for deriving soil-geotechnical properties, and rainfall data, followed by preparation of parameters (e.g., slope, aspect, flow direction, flow accumulation) required for the execution of TRIGRS model. The topographic data, including slope, slope aspect, flow accumulation and direction values, were derived from the TanDEM-X 12 m elevation data. Geotechnical properties such as soil cohesion, unit weight, and friction angle were determined. Disturbed soil samples were collected from field for the analysis of change in the index properties. Physical and chemical characteristics of soil such as porosity, texture, soil mineral, and water content can be determined by Atterberg properties (Kitutu et al., 2009; Kuriakose et al., 2009; Heshmati et al., 2011). Soil Atterberg limits can characterize the liquid limits, plastic limits, and plasticity index, and helps in estimating water absorption capacity of soil's slope stability and soil susceptibility for landslides (Jegede, 2000; Boulanger and Idriss, 2006; Ramezanpour et al., 2010; Yalcin, 2011; Mugagga et al., 2012). Atterberg limits, natural moisture content (in %), percentage composition, permeability, specific gravity, and shear parameters of the soil samples were determined as per Indian Standard (IS) codes. Eight samples were collected from different regions of Ponmudi–Kallar route. Samples were collected from every 1–2 km stretch of the road. Soil thickness and water table depth (in m) were measured in the field; and rainfall rates (daily basis in mm) for each rainfall period were derived from the India Meteorological Department website (IMD; www.imd.gov.in).

2.2 Simulation of field conditions

The landslide susceptible zones along the 12.7 km Kallar–Ponmudi stretch were extracted using TRIGRS. The cut-slopes of each zone were measured and sufficient quantity of samples was collected for simulating the field conditions in the lab that was set-up in the Department of Geology, University of Kerala, India. This experimental model was created to analyze the failure under different conditions. To investigate the failure conditions of the slope, the experimental set-up was inclined to the slope condition of the study area. This was subjected to uniform rainfall intensity for the five different conditions, i.e., unprotected natural slope, slope protected with synthetic fiber (polypropylene), natural fiber (jute), short-root reinforcement (lawn grass), and deep-root reinforcement (vetiver). Initially the soil is compacted using a hand-held compactor to match with the field specific gravity. Specific gravity is determined on a trial and error basis, and continued till the same field conditions were obtained. The moisture con-

tent of the soil (%) was checked twice: prior to and after the experiment, to know the residual and saturated moisture content. Water is now sprinkled over the experimental container, mimicking rainfall. The quantity of water passing through the water meter was recorded. Sprinkling of water was continued till the soil failed. Video recording of the experiment was done through the side of the container, which is made of transparent glass. Water supply was stopped once crack develops and/or the soil fails. The amount of water and time of failure were recorded. The entire soil was sun dried and the experiments were continued for the eight different samples for the five different conditions. The experiments for short-root and deep-root plants were done after two weeks of its planting so as to get the soil cohesion due to the growth of root and subsequent binding. The schematic sketch of the experimental set-up is shown in Fig. 3a. Experiments were done with artificially-induced rainfall seepage to understand the pore-water pressure under different mitigation measures. The experiment model consisted of a tiltable metal container (1.0 m × 1.0 m × 0.5 m) (Fig. 3b), 0.5 hp motor pump (Fig. 3c), water (flow) meter (Fig. 3d), rain simulation using PVC pipes (nostrils) (Fig. 3e) and water sprinklers (Fig. 3f), a lever for tilting the soil container to the desired slope (Fig. 3g), and a Brunton compass to measure the slope (Fig. 3h). The soil in the experimental set-up was compacted using a hand compactor to achieve the field density conditions (Fig. 3i). Core samples were checked frequently for density calculation through the core cutter method (Fig. 3j). The entire process was monitored as well as recorded through a video camera (Fig. 3k).

Soil samples from the field were loaded in the metal container under the same slope and density conditions. The four sides of the container are made up of glass for facilitating video recording. Uniform rainfall intensity was provided for each test. The 0.5 hp motor pump was used to supply water uniformly to create rainfall shower under a regulated condition. The water (flow) meter is used to measure the amount of water (in liters) used during the simulation processes. This water passes through polyvinyl chloride (PVC) pipes and provides a rainfall effect through several nostrils that provides a sprinkling effect. The effects of rainwater infiltration on the soil column for the initiation of failure process and initial moisture content of the soil were investigated. The rainfall intensity of the failure process was investigated by the amount of water (in liters) that passed through the water meter. The residual and saturated water content and rainfall intensity of each test were collected and FoS was calculated by analytical solutions.

2.3 Quantifying the geotechnical parameters

Slope of the terrain (°) and moisture content (%) were measured on site. Slope angle was calculated using a Brunton Compass whereas soil moisture content was determined using a rapid moisture meter as per the ASTM standards (D4643-00). Textural analysis, Atterberg limits, shear parameters, specific gravity, and permeability were obtained through laboratory tests. Soil texture was obtained through sieve analysis, accordingly the percentage of gravel, sand

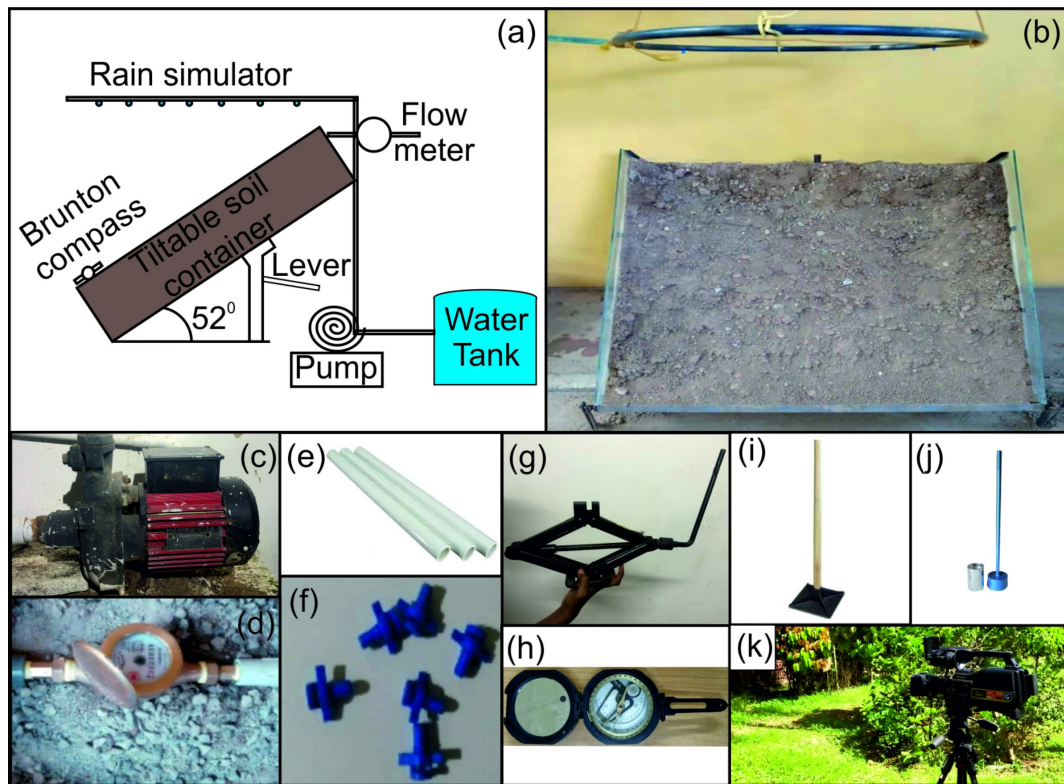


Fig. 3. Experimental model simulating the field condition. (a) Schematic model of the set-up (b) tiltable soil container (c) 0.5 hp motor pump (d) water meter (e) nozzle providing rain effect (f) water sprinklers (g) lever for tilting the container (h) Brunton compass to measure the tilting of the container (i) hand-held coil compactor (j) soil core-cutter for density checking, and (k) video camera for continuous monitoring and recording of the experiment.

and silt were calculated. Textural analysis provides the information about the soil grain size distribution to better understand the amount of soil required for filling the experimental container. Direct shear test was performed to calculate the shear strength parameters. Specific gravity of soil was determined using pycnometer method, which involves measuring the weight of a known volume of dry soil and comparing it to the weight of an equal volume of water. This was done to measure the moisture content (in %) of the soil prior (initial moisture) and after (saturated moisture) the experiment. Permeability was quantified in the field using a permeameter. FoS was measured from the shear strength parameters.

2.4 Use of different protective measures

Experiments were conducted under five different conditions: (i) natural condition (Fig. 4a), (ii) reinforced with synthetic mesh (Fig. 4b), (iii) reinforced with jute mesh (Fig. 4c), (iv) reinforced with shallow-rooted grass (Fig. 4d), and (v) reinforced with deep-rooted plants (Fig. 4e). These five different conditions were experimented for eight different soil samples, collected along the entire road stretch with equal interval sampling.

2.4.1 Unprotected natural slope condition

This was implemented using the same field conditions i.e., same slope angle ($^{\circ}$), soil texture, and soil moisture (%).

2.4.2 Synthetic mesh (Polypropylene)

Green house shade net, made with polypropylene fiber were used as synthetic protective measures. This material is strong and robust. The polypropylene fiber is a common soil reinforcement material that is used to prevent the slope failure and soil erosion (Tang et al., 2007; Bao et al., 2022). The fiber used is having a woven space of $1 \text{ mm} \times 2 \text{ mm}$ (Fig. 5a).

2.4.3 Natural mesh (jute)

Jute is a natural product that is used to offer slope stabilization and erosion control in low to moderate slope (Ghosh et al., 2015). It is a woven mesh that provides a large effect to hold the soil from erosion. The jute meshes are available in different mesh size. $1 \text{ mm} \times 1 \text{ mm}$ section fiber was used in this study (Fig. 5b). Jute mesh provides a provision for planting and establishing vegetation. This helps to prevent further erosion of slope. Jute is an eco-friendly and biodegradable fiber constructed from jute yarns. It has high tensile strength and high water absorption capacity.

2.4.4 Short-root reinforcement

The roots of plants provide a strong interlocking network to hold the soil minerals together and prevent erosion. The shallow rooted grass species are quick to establish, are versatile, and are cheap, with a high range of tolerance (Shahriar et al., 2016; Vannoppen et al., 2017; Capilleri et al., 2019). Short-root has higher tensile strengths and

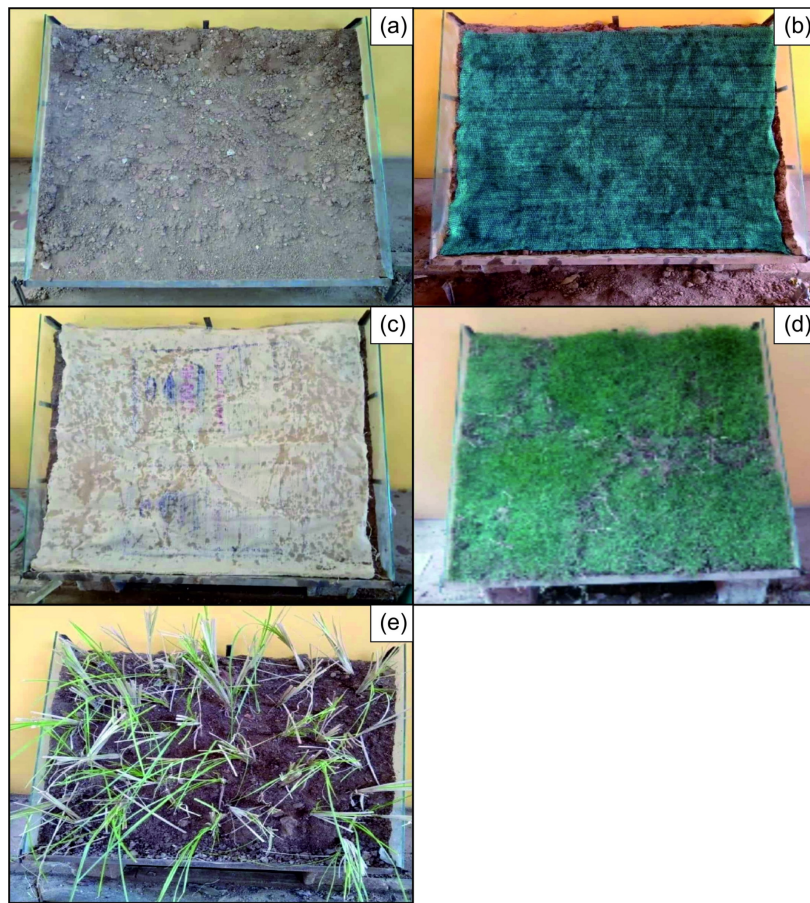


Fig. 4. Experimental setup under five different slope conditions. (a) natural (unreinforced) condition (b) slope reinforced with synthetic mesh (c) slope reinforced with jute mesh (d) slope reinforced with shallow-rooted vegetation (*Zoysia japonica*) and (e) slope reinforced with deep-rooted vegetation (*Chrysopogon zizanioides*).

Table 2. Geotechnical properties of soil collected from the study area.

Samp No	Slope (°) of the terrain	Moisture Content (%)	Texture (%)				Atterberg Limits			Soil type*	Shear Parameters		Specific Gravity	Permeability (cm/s)	Factor of safety
			Gravel	Sand	Silt	Clay	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)		Cohesion (kN/cm ²)	Friction Angle (°)			
1	40	18.25	7	42	20	31	48	34.7	13.3	MI	4.8	30	2.40	1.02×10^{-3}	1–1.2
2	25	22.00	9	30	21	41	44	24.5	19.5	CI	14.0	20	2.90	1.172×10^{-3}	>1.2
3	48	23.45	6.4	46	35.6	12.1	38	25.6	12.4	MI	4.6	15	2.47	1.099×10^{-3}	1–1.2
4	50	19.48	7	36	25	32	43	34.3	8.7	MI	4.6	26	3.30	9.77×10^{-3}	1–1.2
5	52	20.12	8	49	38	5	41	23.5	17.5	MI	4.0	30	2.40	1.17×10^{-3}	<1
6	40	17.25	6	48	22	24	30	23.7	6.3	MI	4.4	30	2.84	1.099×10^{-3}	1–1.2
7	38	9.43	5.7	40.3	25	29	36	31	5	MI	4.8	30	2.63	1.005×10^{-3}	1–1.2
8	30	12.59	9	27.4	25.6	38	43	23.69	19.31	CI	8.4	20	2.70	1.099×10^{-3}	>1.2

*Soil classification as per Indian Standards (IS): MI-silt of intermediate plasticity; CI-clay of intermediate plasticity.

is effective at stabilizing the upper soil layers (Ali and Osman, 2008; Capilleri et al., 2019). Lawn grass, scientifically known as *Zoysia* (*Zoysia japonica*), was used in this study as short root plant (Fig. 5c).

2.4.5 Deep-root reinforcement

Deep-rooted plants demand little care but need more time to develop functional root systems. Deep-roots extend to greater depths of the soil and protect large volume of soil from failure. In this study vetiver (*Chrysopogon zizanioides*) was used as deep root plant (Fig. 5d). Vetiver is a perennial grass, the roots of which spread over a large area of soil system.

2.5 Experiments using different protective measures

The artificially constructed slope was subjected to experiments using the five different conditions for the eight soil types using the model as shown in Fig. 3. The quantity of water was plotted against time throughout the experiment till the slope gets failed.

3 Results

3.1 Geotechnical properties of soil samples

The geotechnical characterization of eight soil samples, collected from the high landslide susceptible terrain slopes in the study area, revealed a diverse range of physical and mechanical properties (Table 2). The slope angles varied

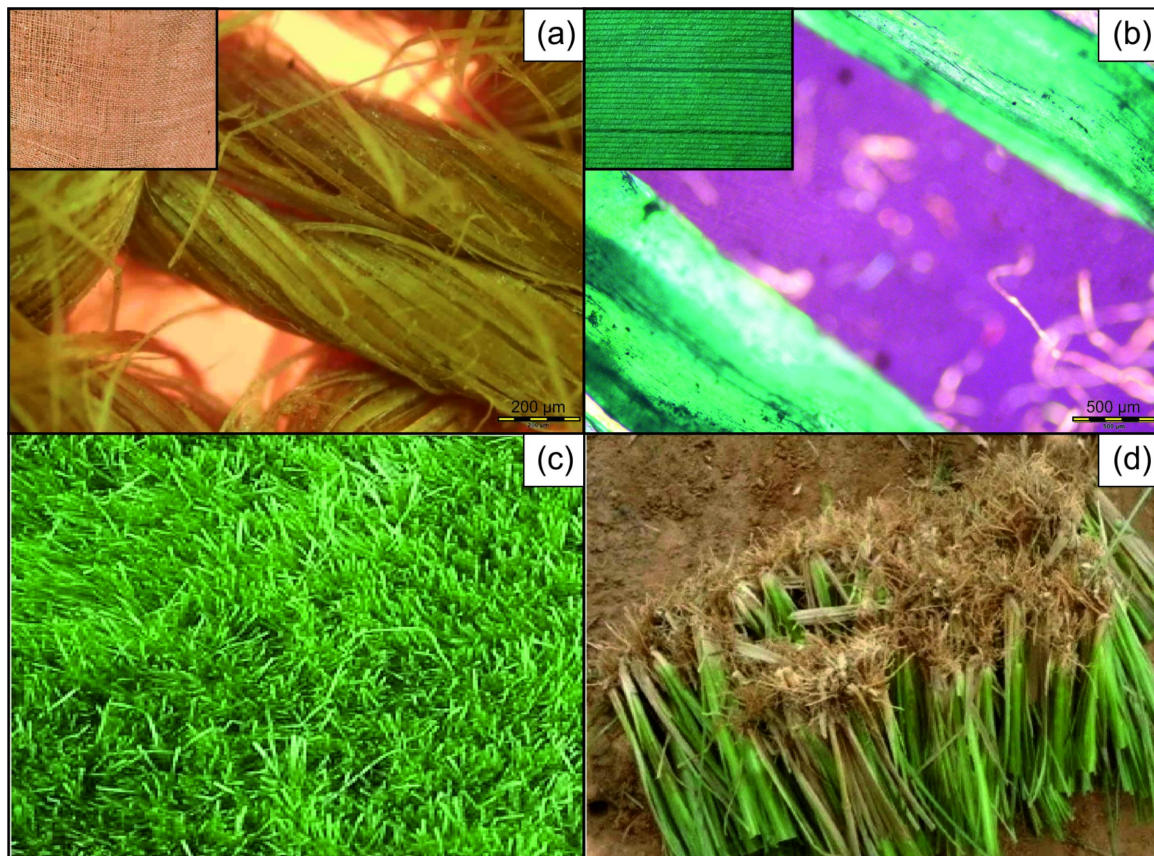


Fig. 5. Types of slope reinforcement materials used in the experimental study. (a) synthetic mesh made of polypropylene fiber (greenhouse shade net) with a woven space of 1 mm × 2 mm (b) natural jute mesh with 1 mm × 1 mm spacing, which is eco-friendly and biodegradable (c) short-rooted grass species *Zoysia japonica* used for shallow-root reinforcement, and (d) deep-rooted grass species vetiver (*Chrysopogon zizanioides*) used for deep-root reinforcement.

from 25° to 52°, covering a representative range of both moderately steep and very steep terrain prone to instability. Moisture content ranged between 9.43% and 23.45%, with higher values generally associated with samples from steeper slopes, such as Sample 3 (48°) and Sample 5 (52°), indicating increased water retention due to finer soil fractions. Soil texture analysis showed a dominance of sand (27.4%–49%), followed by variable amounts of clay (5%–38%) and silt (20%–35.6%). The soils were classified as either MI (silt of intermediate plasticity) or CI (clay of intermediate plasticity), according to the Indian Standard Soil Classification System. The Atterberg limits such as liquid limits ranging from 30% to 48% and plastic limits varying from 23.5% to 34.7%, with plasticity indices (PI) spanning from 5% (Sample 7) to 19.5% (Sample 2) points towards the possibility of deformation of these soils. These values signify moderate to high plasticity, particularly in clay-rich samples. The shear strength parameters exhibited a wide variation in cohesion (4.0–14.0 kN/cm²) and friction angles (15°–30°). CI-classified samples (2 and 8) displayed notably higher cohesion values, corresponding with greater plasticity and finer particles. The MI-classified soils generally exhibited lower cohesion, except for Sample 1 and Sample 7, which maintained relatively high shear resistance due to balanced sand-silt proportions and good inter-particle friction. Specific gravity values ranged from 2.40 to 3.30, typical for silty and clayey soils. Permeability values remained rela-

tively consistent across the samples ($\sim 10^{-3}$ cm/s), with the highest observed in Sample 4 (9.77×10^{-3} cm/s), indicative of relatively better drainage conditions.

The calculated FoS values varied from <1.0 to >1.2. Sample 5 exhibited a FoS value <1.0, pointing to a potentially unstable condition, likely due to its steep slope (52°), high moisture content, and relatively lower cohesion. However, Samples 2 and 8 showed FoS values >1.2, indicating comparatively stable conditions, supported by higher cohesion and moderate slope angles. The geotechnical data suggests that slopes with higher clay content, lower cohesion, and high moisture retention exhibit reduced stability, particularly when coupled with steeper gradients. These findings are critical for landslide susceptibility assessments and slope stability analysis in the study area.

3.2 Creation of landslide susceptibility map

The landslide susceptibility map of the study area was developed using TRIGRS, and was categorized into three zones based on FoS values:

- (a) Highly unstable zone with low FoS (<1), assigned to areas where large landslides may reactivate or are active.
- (b) Unstable zone with moderate FoS (1–1.2), corresponding to areas where either frequent landslides of small

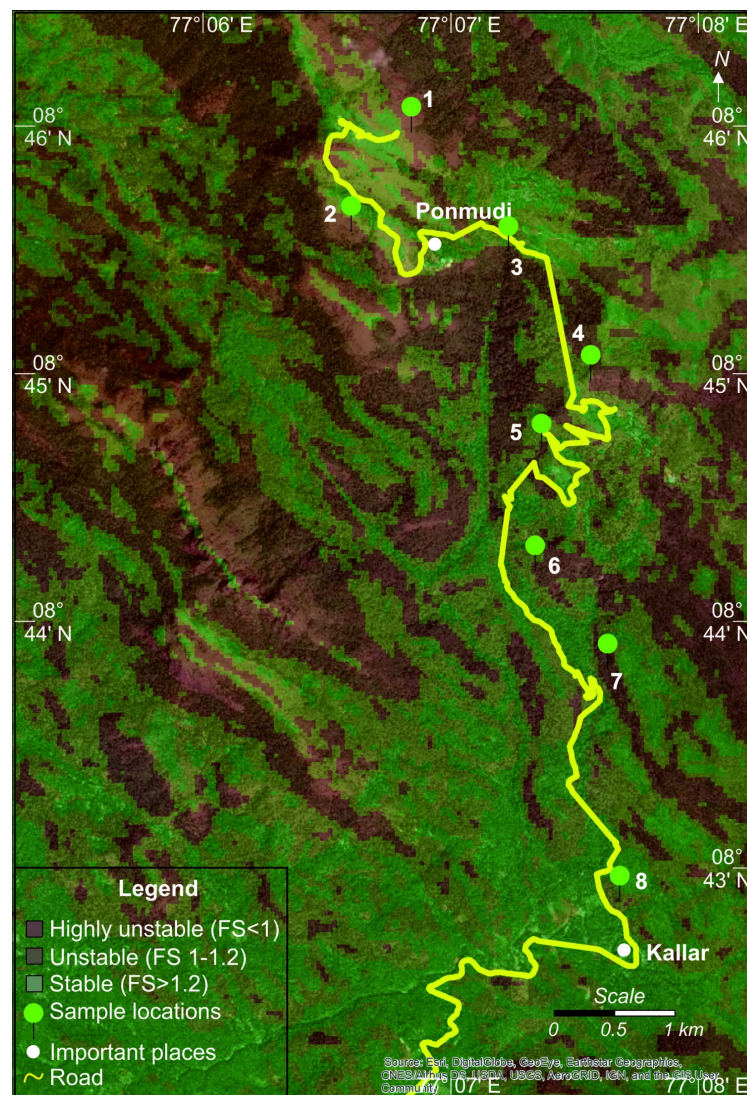


Fig. 6. Landslide susceptibility map of the study area developed using TRIGRS and locations of eight samples collected from the high susceptibility zones along the Ponmudi–Kallar route with approximately 1–2 km interval.

magnitude or large landslides with low frequency may take place.

- (c) Stable zone with high FoS (>1.2), in which no hazard has been observed.

Eight samples were collected from the high susceptibility zones along the Ponmudi–Kallar route with approximately 1–2 km interval (Fig. 6).

3.3 Experimental investigation

The results of the experiment show that the unprotected natural slope with less amount of water failed frequently when compared to protected slopes. The quantity of water required to destabilize the slope for protected slope also varied with the type of material used. Our experimental set-up shows that more water is needed to destabilize the slope (in an aggravated manner) for synthetic fiber, natural fiber, short-root grass species, and deep-root grass species reinforced soil slope. The quantity of water increased to 189 percent when the slope was protected with the deep-root grass species (6.725 liter (l)) when compared to unprotected

slope (3.563 l). And hence, the time required for destabilizing the soil also increased. The correlation between time and quantity of water required to destabilize the slope is shown in Fig. 7a and the data is shown in Table 3. Moreover, the moisture content at the end of the experiment also shows an increase from unprotected slope to deep-root reinforced slope. The correlation between the moisture content at failure (i.e., the difference in moisture between saturated and residual moisture), and the amount of water required to destabilize the slope is shown in Fig. 7b and the data is shown in Table 3.

4 Discussion

The soil samples collected from the highly unstable slopes of Kallar–Ponmudi transportation corridor was used to create an experimental model to investigate which protective measure performs well to stabilize the slope. Five different scenarios were assessed in which the first one being the real field conditions whereas the rest four represents the real field conditions with protection measures such as synthetic fiber, natural fiber, short-root reinforcement, and

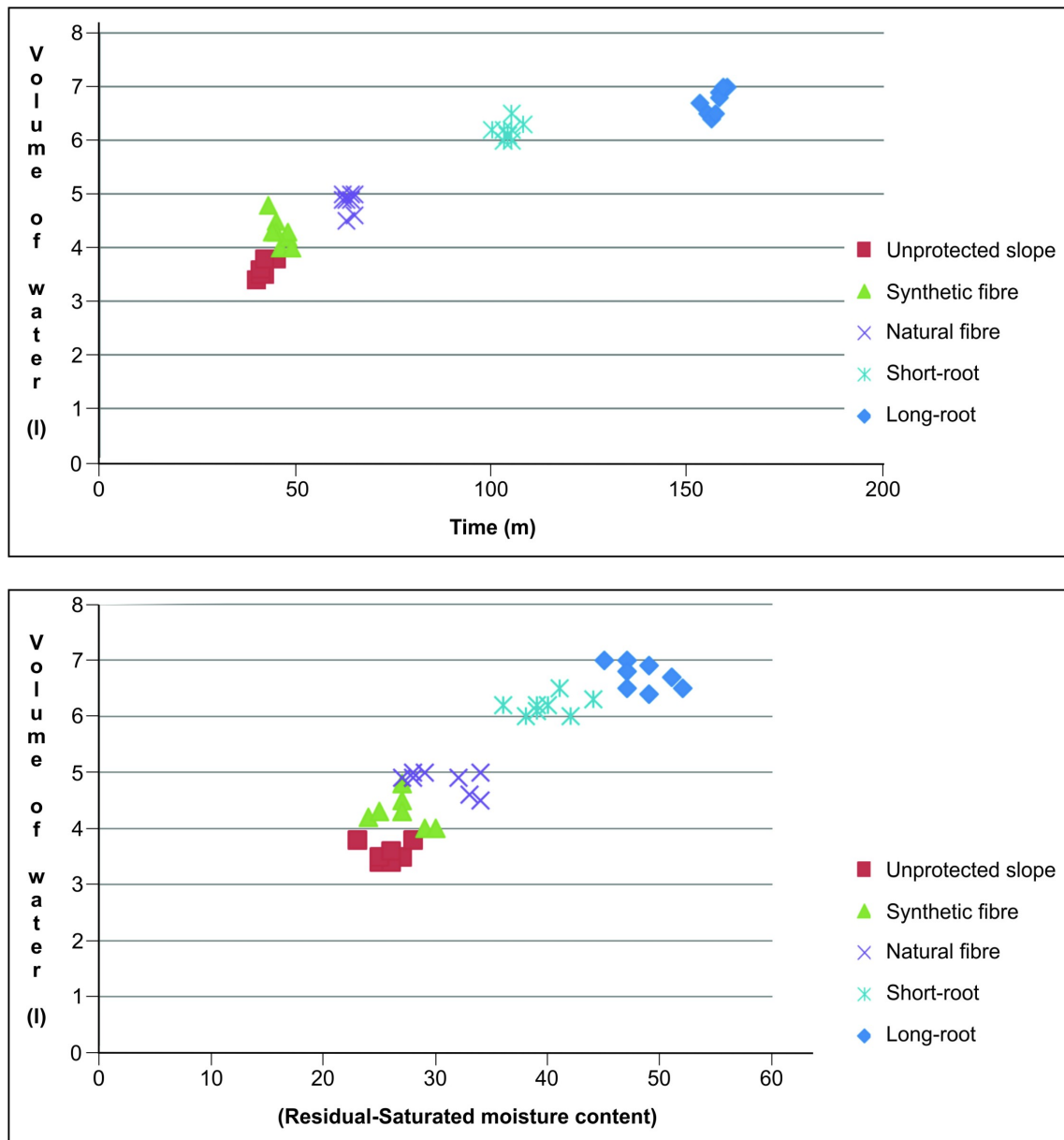


Fig. 7. (a) Graph showing the correlation between time and volume of water required to destabilize the slope under five different slope conditions (b) correlation between the moisture content at failure (i.e., the difference in moisture between saturated and residual moisture) and volume of water required to destabilize the slope under five different slope conditions.

deep-root reinforcement.

As the model started to run, especially from the unprotected natural slope, the first noteworthy phenomena noted was the development of rills and ravines, followed by the development of minor curvilinear cracks that subsequently developed into a crown of a landslide. The development of rill and ravines unequivocally point to the flow path of the landslide. These are usually known as geomorphic hollows in real field scenario, the one in which the landslide is usually confined. The surface of the container provided a glide plane for the failure that is unique in translational failures. Translational failures are the ubiquitous type of landslide seen throughout this tropical area. But the present study area experienced numerous debris slides rather than translational failure due to the road-cut. The present model has the great advantage of having the lower part that acts as

a cut-slope. Hence, this model was ideal for studying both the landslide types.

The results of the experiment showed that the quantity of water content required destabilizing the slope increased with the type of protective measures. The slope protected with synthetic fiber was 121 percent more stable than the natural slope whereas the natural fiber showed 136 percent. The bio-engineering technique of short-root reinforcement exhibited 174 percent stable than the natural slope, and the deep-root reinforcement, using vetiver, showed 189 percent stability. Moreover the time required for the slope to get destabilized also increased with the same type of protective measures. The main question to be addressed here is what made natural fiber superior to synthetic fiber? The natural fiber has more capacity to withhold moisture than the synthetic one as the latter is repellant to water. Also

Table 3. Experimental results for soil slope under five different slope conditions, showing values for time to failure (in minutes), water used (in liters), rate of flow (l/min), residual and saturated moisture content (%), and difference in moisture for eight soil samples.

Sample No	1	2	3	4	5	6	7	8	Average
Unprotected natural slope									
<i>Time</i> (in minutes)	42	40	41	45	40	41	41	42	41.5
<i>Water</i> (in liters)	3.5	3.4	3.5	3.8	3.4	3.5	3.6	3.8	3.563
<i>Rate of flow</i> (l/min)	0.083	0.085	0.085	0.084	0.085	0.085	0.088	0.090	0.086
<i>Residual moisture</i> (%)	21	20	21	22	20	21	21	28	21.75
<i>Saturated moisture</i> (%)	48	45	47	50	46	46	47	51	47.5
<i>Difference in moisture</i> (%)	27	25	26	28	26	25	26	23	25.75
Synthetic fibre (Polypropylene)									
<i>Time</i> (in minutes)	46	48	48	49	45	43	45	44	46
<i>Water</i> (in liters)	4	4.2	4.3	4	4.5	4.8	4.3	4.3	4.3
<i>Rate of flow</i> (l/min)	0.087	0.088	0.090	0.082	0.100	0.112	0.096	0.098	0.094
<i>Residual moisture</i> (%)	21	22	21	22	20	21	22	28	22.125
<i>Saturated moisture</i> (%)	50	46	48	52	47	48	47	55	49.125
<i>Difference in moisture</i> (%)	29	24	27	30	27	26	25	27	26.875
Natural fibre (Jute)									
<i>Time</i> (in minutes)	65	63	62	65	63	62	64	64	63.5
<i>Water</i> (in liters)	4.6	4.5	5	5	4.9	4.9	5	4.9	4.85
<i>Rate of flow</i> (l/min)	0.071	0.071	0.081	0.077	0.078	0.079	0.078	0.077	0.076
<i>Residual moisture</i> (%)	21	20	21	22	20	21	21	28	21.75
<i>Saturated moisture</i> (%)	54	54	55	50	48	48	50	60	52.375
<i>Difference in moisture</i> (%)	33	34	34	33	28	27	29	32	31.25
Short-root reinforcement (Garden lawn grass)									
<i>Time</i> (in minutes)	103	105	108	100	105	104	103	105	104.125
<i>Water</i> (in liters)	6	6.5	6.3	6.2	6	6.1	6.2	6.2	6.188
<i>Rate of flow</i> (l/min)	0.058	0.062	0.058	0.062	0.057	0.059	0.060	0.059	0.059
<i>Residual moisture</i> (%)	22	20	21	24	20	21	20	30	22.25
<i>Saturated moisture</i> (%)	60	61	65	63	62	60	60	66	62.125
<i>Difference in moisture</i> (%)	38	41	44	39	42	39	40	36	39.875
Deep-root reinforcement (Vetiver)									
<i>Time</i> (in minutes)	153	155	156	157	158	160	158	159	157
<i>Water</i> (in liters)	6.7	6.5	6.4	6.5	6.9	7	6.8	7	6.725
<i>Rate of flow</i> (l/min)	0.044	0.042	0.041	0.041	0.044	0.044	0.043	0.044	0.043
<i>Residual moisture</i> (%)	22	22	20	22	20	21	20	29	22
<i>Saturated moisture</i> (%)	73	74	69	69	69	68	67	74	70.375
<i>Difference in moisture</i> (%)	51	52	49	47	49	47	47	45	48.375

natural fiber provides ambience for cultivation or to have another layer of protection such as short-root or deep-root reinforcement. The bioengineering technique, which was experimented after two weeks of planting for the root cohesion to get established, has the capacity to withhold more moisture than the natural conditions. Moreover, the impact of raindrops will also be considerably reduced when a protective layer exists. Furthermore, the potential for the development of rills and ravines—which often serve as preferential flow paths facilitating landslide initiation—was substantially minimized.

Despite its usefulness, the model has certain limitations. The simplified setup cannot fully replicate the complex, heterogeneous subsurface and hydrological conditions of natural slopes. The short duration of root establishment (two weeks) may not reflect the long-term stabilization performance of bioengineering measures in real field scenarios. Additionally, rainfall simulation may not perfectly mimic the intensity and variability seen during actual monsoon events.

Future studies could extend the observation period for root development to better assess long-term effects of bio-reinforcement. Moreover, incorporating real-time field monitoring data and scaling up experiments to include heterogeneous soil profiles could improve the model's applicabil-

ity. Investigating the combined effects of multiple eco-DRR strategies over different land-use and rainfall conditions would also offer more comprehensive insights into sustainable slope stabilization.

5 Conclusions

Landslides are natural disasters that pose serious threats to human beings and property in many areas around the world. Roads in mountainous regions require more careful monitoring for landslide and related disasters. Rainfall-induced landslides may be serious hazards to human society, distorting natural landscapes, disturbing transportation and damaging social infrastructure. Other than the loss of life, the next most damaging effect is on the transportation corridor, especially mountainous roads that are cul-de-sac. The Kallar-Ponmudi road in Kerala, India, is one such cul-de-sac, which once affected by landslide will remain cut-off for several days. Hence, a study was devised to find out the best possible method to provide management practices.

The best way to mitigate the landslide disasters must rely on the ability to predict the locations that are more prone to landslides than providing for the entire stretch of the road. Thus, the landslide susceptibility map of this

transportation corridor was created using TRIGRS. Usually susceptible zones are the areas where management practices are to be adopted. But the use of coarse resolution imageries over-predicts the spatial extent of the landslide hazard. Hence, an experimental model was created and the rainfall effects on slope stability were analyzed with different slope stabilization methods. Though the model created is a miniature of the real field scenario, it really mimics the field conditions. Apart from the natural slope condition, the experiment was also done for the slope for four different protective measures such as synthetic fiber, natural fiber, short-root reinforcement and deep-root reinforcement. The analysis reveals that vegetative slopes are more stable than the fiber reinforced slopes, which is better than the unprotected slope. Thus, this study indicates that eco-DRR practices effectively improved the stability of slopes, especially vetiver grass cultivation, which can protect the slope for a longer period.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT statement

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