Investigating the Slope Stability and Factor of Safety Properties of Soil Reinforced with Natural Jute Fibers under Different Rainfall Conditions

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ABSTRACT

Heavy rainfall is often responsible for embankment failures. During intense rainfall, the embankment slope inclination is vital for slope stability. Some failures occur in the slope due to heavy rainfall and sudden change in the matric suction. Jute fiber is a reinforcing material that is added to improve soil strength. In this research, in order to explore the effects of slope inclination on soil stability, soil samples were collected and exposed to artificial rainfalls. This study presented various tests performed on the soil samples. Different tests like sieve analysis, permeability test, Direct Shear Test (DST), liquid limit, plasticity limit, and numerical modeling were conducted in the laboratory. The study's findings revealed that the failure is caused by a soil suction loss when the inclination of the slope is higher than the soil friction angle and the collapse is caused by the positive water pressure at the slope's toe when it is lower than the soil's friction angle. Furthermore, when the slope angle increases, the slopes are becoming increasingly vulnerable to rapid collapse. After that, jute fibers were combined with the soil to improve its performance. Samples of 2, 3, and 4 rows of jute fibers were tested. These jute fiber samples performed better than the ones without fibers under different rainfall conditions. The distribution of jute fibers had a favorable influence on both strength measurements and safety aspects. Utilizing the factor of safety and matric suction, the performance of jute fiber samples is superior to those without jute fibers. Consequently, by adding jute fibers the stabilization of the soil is significantly improved along with its factor of safety.

Keywords-soil samples; slope stability, reinforced material; jute fibers; sieve analysis; factor of safety; matric suction; deformation

I. INTRODUCTION

Every year, thousands of landslides occur around the world, causing financial losses and even deaths. Soil stabilization is very important for slope embankment. To assure the ground soil's stability during construction, embankments are usually built in several phases. In order to quantify the gain in shear strength effectively, the foundation soil's undrained shear strength normally rises with consolidation [1]. The soil's top layer in an embankment slope is more sensitive to erosion during rainstorms. It provides the least erosion resistance and rapidly loses strength [2]. The undrained condition of soil stability analysis was calculated by First Order Reliability Method (FORM), and Monte Carlo Simulation (MCS) method to calculate the Factor of Safety (FoS) in [3]. Ground water samples obtained from the river side embankment to check the drinking water quality and 12 parameters, namely, pH, EC, TDS, Ca, Mg, Na, F, SO4, K, Cl, and HCO3 were used to compute the water quality based on the water quality index method [4]. The bearing capacity of a stone column is highly related to the diameter of the column, the properties of the soil, and its bearing capacity. It was found that when the diameter of the stone column increases, the bearing capacity of the soil increases exceptionally [5]. Rainfall infiltration reduces the soil matric suction and shear power and increases the soil loss susceptibility [6]. Displacements in the vertical and lateral planes were reduced and the bearing capacity was increased by reinforced embankments [7]. To suit engineering requirements, soil stabilization is a technique of enhancing the physical, chemical, or biological qualities of natural soil. Shear strength quality, cohesiveness, and friction angle are determined utilizing a laboratory direct shear test [8]. The finite difference approach was utilized to perform numerical modeling and in the numerical modeling, the model scale was used to replicate the centrifuge tests [9].

Due to the high cost of creating and transporting free-draining coarse-grained materials, slope failure along highways is frequently repaired or restored using locally available soil with significant amounts of fines present (clay and silt) [10]. Due to the three-dimensional nature of the reinforcement, a geocell-reinforced slope acts as a beam in the soil. Furthermore, the moment of inertia is taken into consideration due to its bending features, resulting in enhanced bending strength, the reinforcement lowers slope displacement, and the slope's FoS is raised [11]. Jute fibers of predefined length and content are mixed extensively by hand with expansive soil until a fairly uniform distribution of jute fibers in the soil is achieved [12]. Fibers improve the soil composite mechanical properties. The normal pressures acting on the soil composite mobilize tensile resistance in the fibers, giving the soil higher shear strength [13]. The reinforcing effect location on the failure and deformation behavior of soil slope and superstructure by evaluating various geogrid layers is explored in [14]. Jute fiber is excellent for enhancing soil qualities since it is inexpensive, readily available, biodegradable, and environmentally friendly [15, 16]. A moisture barrier and altered recycled plastic pins were utilized to stabilize the pavement distresses and the rainfall-induced slope failure in [17]. The slopes' FoS or chance of failure were displayed in ASCII format in [18]. The matric suction losses caused by rainfall infiltration had only a minor impact on the reinforced sand slope's global and local FoS. The tensile reinforcement strengths are necessary to sustain FoS on reinforced clay and silt slopes [19].

Under relatively modest stress conditions, from a geotechnical standpoint, problematic soils are those that can disperse, collapse, have an excessive settlement, expand, or even fail. There is erosion or cracking in the soil, and consequently the soil may not be stable for the embankment. Due to this problem, the current paper presents various tests for testing slope soil stability. Here, rainfall intensity is set up to test the soil stability, because it generates cracks and slope failure may occur and reinforcing material like jute fibers is added, to strengthen the soil and increase the slope stability. This study is based on the reinforced soil stabilization process. It investigates various researches for slope stability. Authors in [20] proved the embankment slope stability for roads erected on soft terrain using Prefabricated Vertical Drains (PVDs). The slope stability was investigated using numerical analysis and modeling based on the FoS with an artificial neural network. A novel approach is proposed in [21], where the soil strength follows the nonlinear yield criterion to determine the FoS of soil slopes. First, the magnitude and coordinates of minor primary stress are determined using numerical simulation. The freeze-thaw cycles were investigated by the effect on the embankment slope stability of polypropylene fibers using a numerical analytic method [22]. The DST was built to measure 9 sets of specimens, shear strength metrics such as binding force and internal friction angle were considered along with 3 components (freeze-thaw cycle, fiber content, and fiber length). Authors in [23] investigated the failure and deformation behaviors of reinforced slopes with various geotextile layouts utilizing a set of centrifuge model drawdown experiments. Under drawdown conditions, the geotextile reinforcement was found to considerably raise the ductility and safety limit, change the slope failure feature, and minimize displacement. The injection approach was used to produce one untreated embankment and 3 small-scale bio-treated sand embankments in [24]. To investigate the embankment's slope collapse, rainfall scouring experiments were used.

II. RESEARCH METHODOLOGY

Geotextile-reinforced model slopes are investigated with tests regarding the geotextiles' mechanism and the reinforcement effect. The soil's water content and dry density, and the slope's height and gradient, were kept constant throughout all of tests. The reinforced slopes' behavior influence is observed utilizing different geotextile layouts. Different centrifuge experiments were undertaken on unreinforced and reinforced slopes. For this experiment, disturbed and undisturbed soil samples were considered. During the sampling process, the soil's natural structure has been altered or destroyed, their structure is referred to as disturbed samples. The non-representative samples are soils from different mixed strata. The deadweight of the soil slope, which was applied to the entire slope, and the evenly distributed loading, which was applied to replicate the vehicle load are the two types of loadings that were used to the finite element model in the slope stability analysis. Using the proposed slope stability analysis approach, the maximum plastic strain and the slope's maximum horizontal displacement were respectively computed. The flow diagram of the proposed method is depicted in Figure 1.

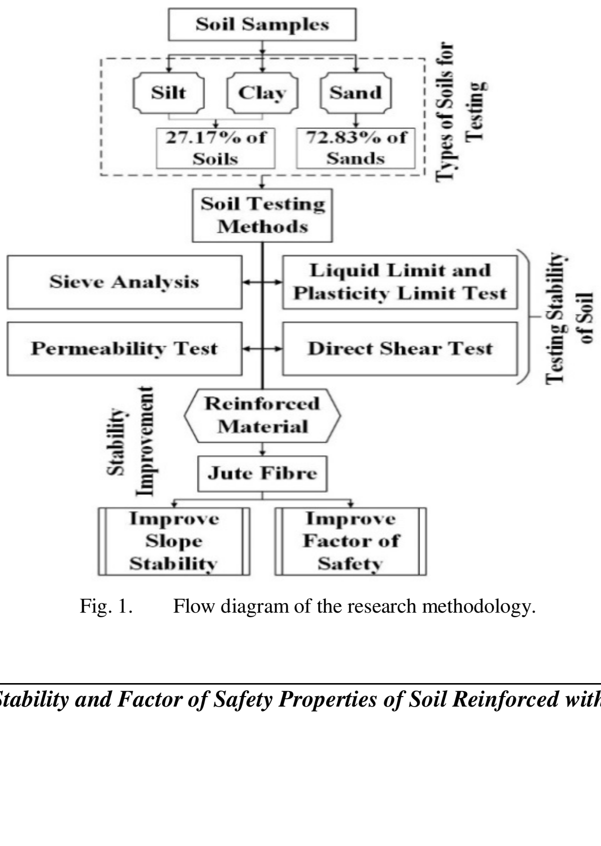

Fig. 1. Flow diagram of the research methodology.

A. Material Collection

This study studies soil samples to determine the soil embankment stability. The soil samples taken for this study have 27.17% silt and clay soil and 72.83% sand. Multiple, smaller samples known as cores, compose an accurate soil sample. The majority of their nutrients are derived from plants or grasses that individual cores contain from the soil surface. In a variety of locations throughout the area, a minimum of 10 soil cores was taken. Several tests were used to measure the stability of the soil slope. Soil samples were powdered, sieved, and dried before being analyzed. For analysis, a homogenous mixture was ensured by grinding and sifting steps. Soil samples were dried in cardboard boxes at 50°C. The soil was ground in a mechanical mortar and pestle and passed via a 12-mesh, roughly 2mm screen.

Mineral particles, water, air, and organic matter are present in the samples. Chemistry, color, structure, porosity, and soil texture are determined by combinations of these factors. Table I illustrates the plastic limit, liquid limit, plasticity index, coefficient of permeability, dry unit weight, saturated unit weight, cohesion, angle of internal friction, Poisson's ratio, and Young's modulus of elasticity. These are the soil properties utilized in the experiment. To test the soil stability, various soil testing methods were utilized. Specified analytical equipment is utilized for the analysis. Sample preparation included sample cleaning up, sample pre-concentration, alkali or acid-based chemical digestion, sample extraction, crushing and dissolution. In Table I, the coefficient of permeability (K_{Sat}) was obtained by the constant head permeability test and the modulus of elasticity (E) and the coefficient of internal friction (ϕ) were obtained by direct shear test in the laboratory.

TABLE I. SOIL SAMPLE PROPERTIES

Soil properties	Values
Plastic limit W_p	15%
Liquid limit W_L	21%
Plasticity Index PI	6%
Soil classification	SM-SC
Coefficient of permeability K_{Sat}	8.27×10^{-4}cm/sec
Dry unit weight γ_{dry}	14.5kN/m^3
Saturated unit weight γ_{sat}	18.67kN/m^3
Cohesion C	5kPa
The angle of internal friction ϕ	26.8°
Young's modulus of elasticity E	5110kPa
Poisson's ratio υ	0.25

B. Reinforced Slope with Jute Fibers for Slope Stability

By adding a surface cover, slopes can be stabilized. The slope reinforcement and the geometry of the slope can be modified with support structures. Continuous fibers are woven, stitched, braided, or knitted into the fabric from twisted and plied yarn to create multidirectional reinforcements. Almost any reinforcing fiber can be utilized to make fabrics. To enhance its resiliency and strength, incorporating reinforced material into the soil is involved in the method of soil stabilization. Jute fibers are widely known for their ability to be spun into coarse and strong threads. Jute fibers are noted for their glossy, long, and soft nature. Jute fibers can be utilized to strengthen soil to improve its engineering qualities. To endure rot and heat, jute fibers are utilized because of their high tensile strength, superior durability, and excellent drainage and filtration provided by its porous texture. Jute fibers are also inexpensive, readily available, biodegradable, and environmentally beneficial. Lateral deformation prevention, settlement, ductility, bearing capacity, and strength are improved by the soil reinforcement. Jute fibers have the highest tensile strength among all natural fibers and can withstand rolling and heat. The fibers provide a high level of fineness and flexibility. Jute fibers were utilized for the slope stability improvement (Figure 2). In terms of fatigue and mechanical qualities, woven jute hybrids were found to be environmentally benign, cost-effective, and lightweight.

Fig. 2. Jute fibers.

TABLE II. JUTE FIBERS MECHANICAL PROPERTIES

Characteristics	Values
Density ρ	1.35gm/cc
Young's Modulus E	20GPa
Poisson's ratio υ	0.38
Shear Modulus G	7.24GPa
Tensile Strength T	393MPa

III. EXPERIMENTATION AND RESULT DISCUSSION

All slope models were created in a specially designed chamber. The initial ratio of the slope is 2:1, and it contains rainfall nozzle, frame, inlet pipe, outlet pipe, rain gauge, and a digital tensiometer. Initially, the soil samples are set up in slope format. Here, the rainfall intensity is fixed in the experiment to test the slope soil stability. The rainfall nozzle, inlet pipe, and outlet pipe are utilized for rainfall intensity. After the rainfall intensity, cracks are appearing on the soil and slope failure occurs.

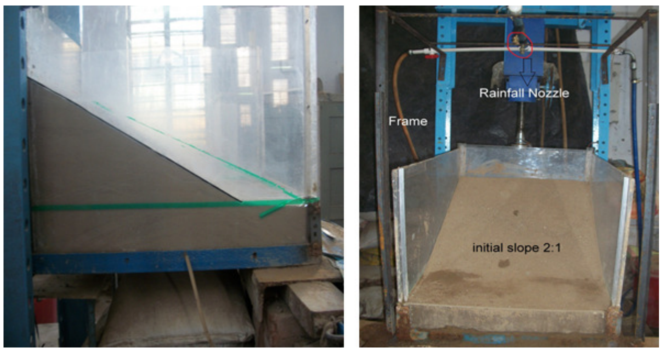

Fig. 3. Experimental setup.

For the rainfall measurement, a standard rain gauge instrument was used. This is a fundamentally 203mm diameter circular funnel that collects rain into a calibrated and graduated cylinder. Precipitation up to 25mm can be recorded by the measuring cylinder. The free energy shifts in a unit volume of water, known as matric suction. The digital tensiometer was used to measure the matric suction of the soil. Figure 5 represents the experimental results of saturated slope deformation without utilizing jute fibers. This depicts the original slope as 2.25:1, whereas the embankment slopes are 2:1, 1.5:1, and 1.25:1.

Fig. 4. Measurement of matric suction, rainfall, and slope failures.

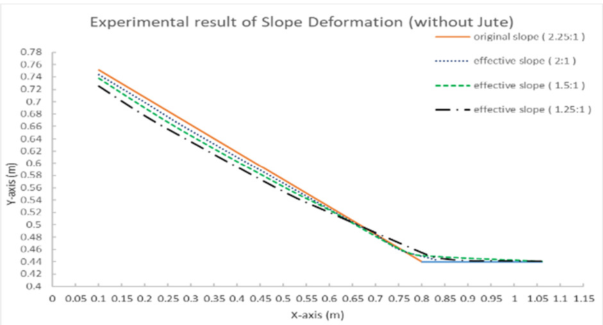

Fig. 5. Experimental results of saturated slope deformation without jute reinforcement.

A. *Numerical Modeling using the Geo-Studio 2021 Software*

Geo-studio software is generally used for slope analysis, seepage analysis, and deformation analysis. It is based on the finite element method. By using this, the FoS of the slope can be determined at a different effective angle. By using SIGMA/W 2021, the maximum deformation of slope can be calculated and after that it can be compared with the experimental results. The FoS of the slope can be calculated using SLOPE/W 2021. Here, initially seepage analysis was done by using SEEP/W 2021 and after that, it is utilized as a parent analysis in SLOPE/W and SIGMA/W for calculating the deformation vector, the deformation mesh, and FoS.

$$\text{FoS} = \frac{\text{Ultimate Load (Strength)}}{\text{Allowable Load (Stress)}} \quad (1)$$

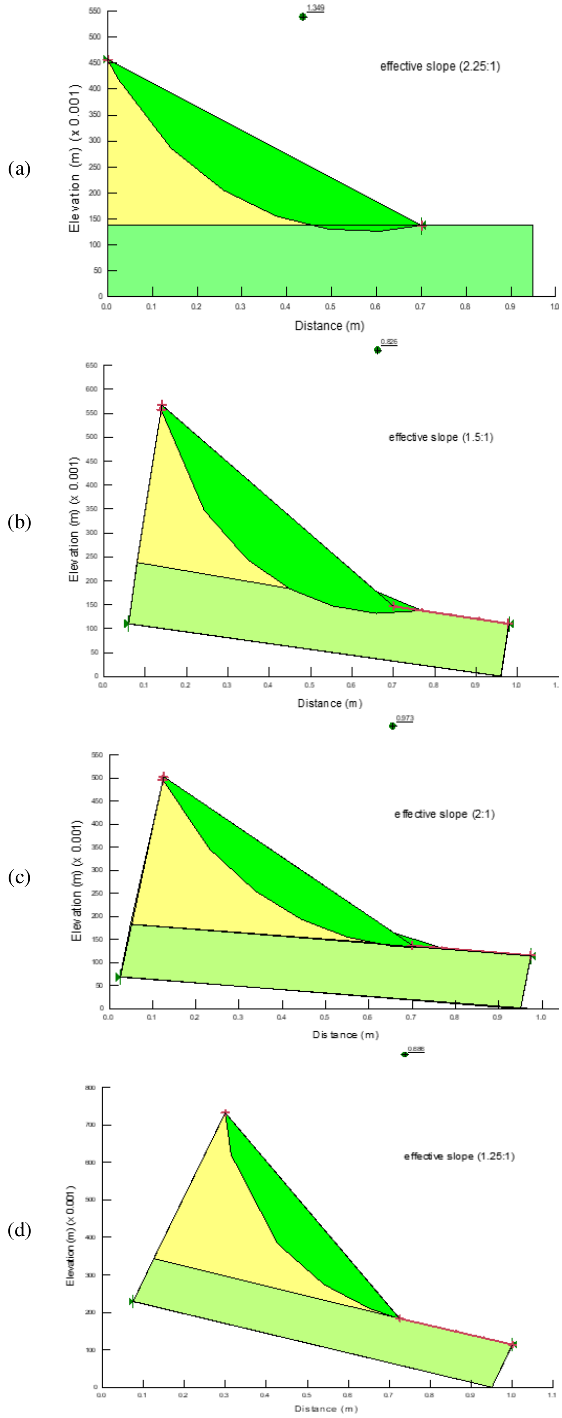

Fig. 6. FoS of original slope and different embankment slopes. (a) 2.25:1, (b) 1.5:1, (c) 2:1, (d) 1.25:1.

TABLE III. FOS AT DIFFERENT EMBANKMENT SLOPES

Embankment slope	FoS
2.25:1	1.349
2:1	0.973
1.5:1	0.826
1.25:1	0.686

Figure 6 exhibits the FoS of original and embankment slopes. The initial Figure depicts the original slopes of 2.25:1, next figure reveals the factor of safety for the embankment slopes of 2:1. Then the factor of safety for the embankment slopes 1.5:1 and 1.25:1 is demonstrated in the last two figures.

B. Deformation Analysis by using Geo-Studio SIGMA/W 2021

To perform deformation and stress analysis of earth structures, the finite element CAD software SIGMA/W was utilized. Deformation examination for mesh deformation and vectors has been completed at different embankment slopes. Maximum deformation was recorded and its value was compared with the experimental data. Figure 7 depicts the vector deformation of different embankment slopes of 2:1, 1.5:1, and 1.25:1. Vector deformation defined the deformation pattern during slope failure of each soil particle present inside the embankment slope after heavy rainfall.

(a) (b) (c)

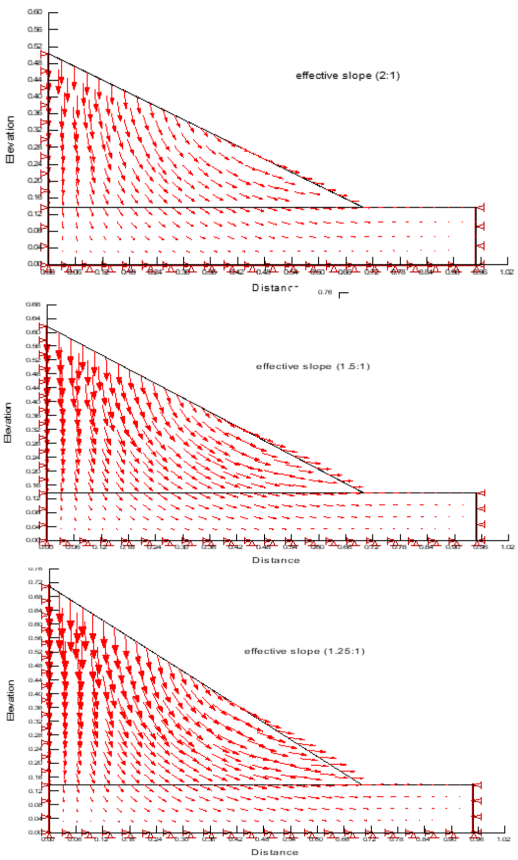

Fig. 7. Vector deformation of different embankment slopes.

Figure 8 depicts the matric suction comparison with and without 3 rows of jute for 50 mm/hr and 100 mm/hr rainfall at the middle of the slope. It shows that samples with jute perform better than the ones without jute. Figure 9 represents the variation of matric suction with time for the top, middle, and bottom of the slope. It is noticed that the matric suction variation for the top layer is higher than the matric suction variation of the middle and bottom layers.

(a) (b)

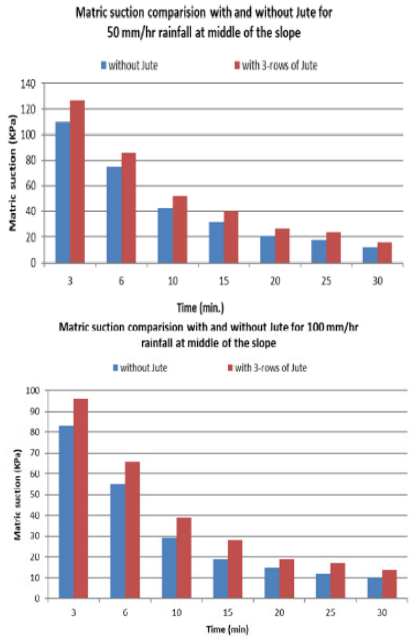

Fig. 8. Matric suction comparison with and without jute fibers.

(a) (b) (c)

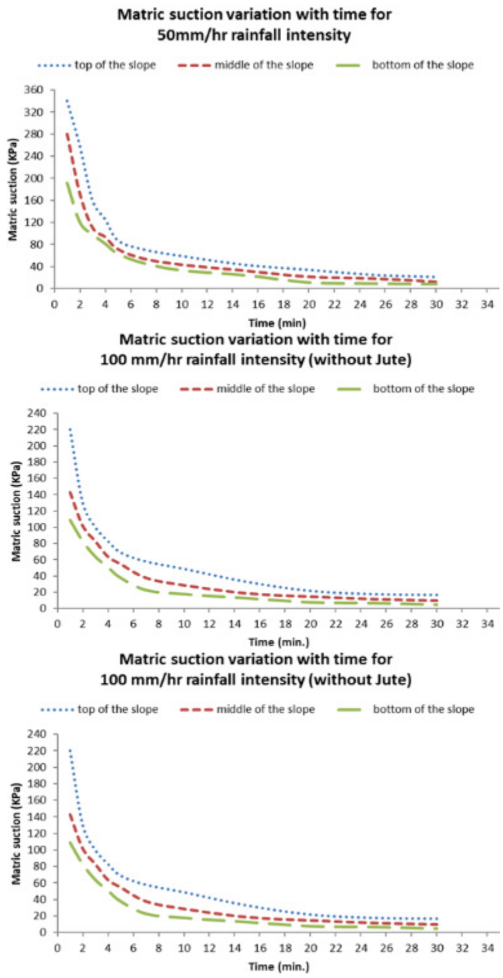

Fig. 9. Matric suction variation with time.

TABLE IV. EXPERIMENTAL AND NUMERICAL VALUES OF USING JUTE FIBERS

Emb. slope	No jute (mm)		2 rows of jute (mm)		3 rows of jute (mm)		4 rows of jute (mm)	
	Exp. value	Num. value	Exp. value	Num. value	Exp. value	Num. value	Exp. value	Num. value
2:1	12.5	9.8	10.6	7.6	8.5	5.6	4.4	2.3
1.5:1	17.7	14.6	16.6	13.7	13.4	7.8	9.6	4.6
1.25:1	33.8	25.8	29.2	22.4	24.8	14.6	18.5	11.8

(a)
(b)
(c)
(d)

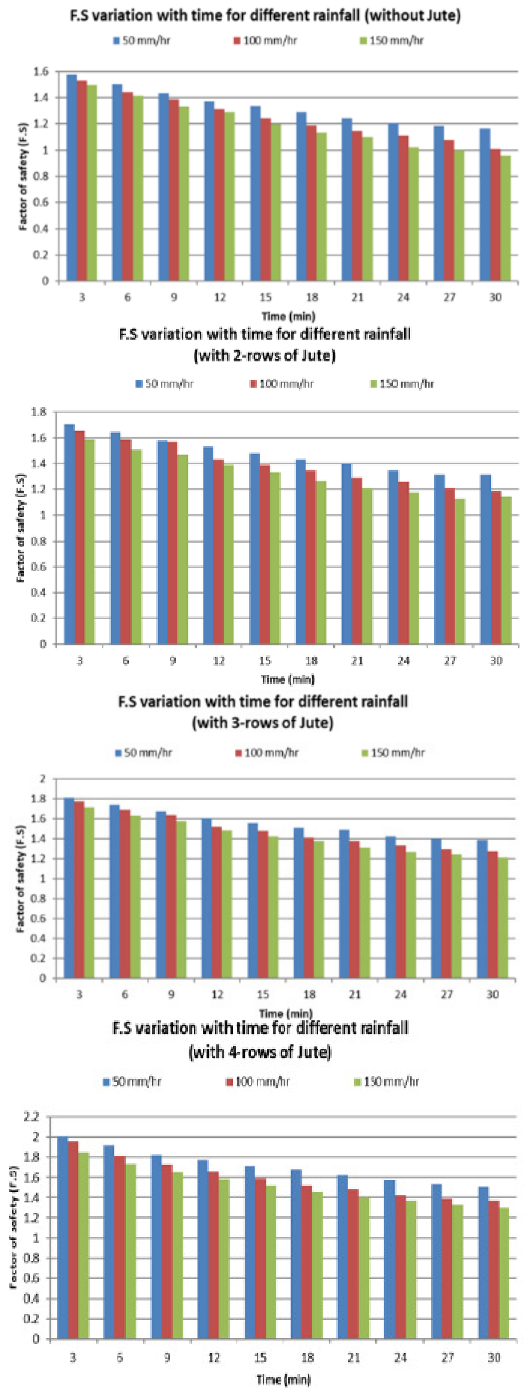

Fig. 10. FoS variation with (a) 2, (b) 3, (c) 4 rows of jute fibers and (d) without jute fibers.

Table IV reveals the deformation values for different embankment slopes, using 2, 3, and 4 rows of jute and without jute. It can be seen that the deformation when using jute is very lower than when not using jute. The performance of using 4 rows of jute is higher than the others.

Figure 10 demonstrates the FoS variation with and without using jute for the rainfall intensity of 50, 100, and 150mm/hr. The Figure clearly shows that the performance of 4-row jute samples is better than the others'.

IV. CONCLUSIONS

Soil stabilization is very important for embankment, but soils like clay and silt are weak for slope embankment. During heavy rainfall, these soils produce cracks and slope failures. To overcome these problems, jute fibers are combined with the soil to improve its stability. This research attempts to experimentally test slope stability. The rainfall intensity is used to assess the slope's stability and several soil tests were carried out. During the experimental and numerical analysis of the slope stability, several cracks and deformations occurred. Due to this failure, the inclusion of jute fibers and its effectiveness to strengthen the soil slope under heavy rainfall condition was assessed. For the embankment slope 2, 3, and 4 rows of jute fibers were considered, and the factor of safety and matric suction were calculated. The main conclusions of the current study are:

- According to the sieve analysis, the soil samples are well-graded with 27.17% silt and clay soil and 72.83% sand.
- The liquid limit of the soil is 21%, the plasticity limit is 15%, and the plasticity index is 6%.
- The results from the soil permeability test gave a dry unit weight of 14.5kN/m^3 and a saturated unit weight of 18.67kN/m^3.
- Regarding the direct shear test for sample test 1, the normal stress is 0.5kg/cm^2, and the strain rate is 0.25mm/min. The predicted shear load failure is 0.093kN, the failure shear stress is 0.29588kg/cm^2. For sample test 2, the normal stress is 78.48kN/m^2, and the strain rate is 0.25mm/min, the shear load and shear stress failure are 0.133kN and 42.97kN/m^2. For sample test 3, the normal stress and the strain rate are 98.1kN/m^2 and 0.25mm/min, and the shear load and shear stress failure are 0.160kN and 51.993kN/m^2.
- The experimental results for slope deformation and factor of safety were determined, and the vector deformation and mesh deformation were expressed for embankment slopes of 2:1, 1.5:1, and 1.25:1. The deformation analysis was performed in Geo-studio SIGMA/W 2021.
- The experimental results utilizing jute fibers for factor of safety, mesh deformation, and matric suction are described in the test results section above. The overall performance of 4-row jute fiber samples is better than without using jute fibers or by using less rows of fibers.
- Utilizing jute fibers improves the stability of the soil, the factor of safety, and matric suction performance.

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