Vetiver Grass Performance on a Distressed Highway Slope of High-Plastic Clay under Excessive Rainfall

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ABSTRACT

With climate change frequency of extreme disasters is increasing day-by-day. Excessive rainfall causes shallow landslides during such extreme events, very commonly on highway slopes containing highly plastic clay. Mississippi results in a perfect area to study the Vetiver System (VS) performance for shallow slope failure under excessive rainfall, with an average annual rainfall intensity higher than other neighboring states in the south. A highway slope in Mississippi containing high-plastic clay is explored throughout the year 2019, where time-dependent slope movement along the depth is monitored with rainfall variation. A 9.1 m slope inclinometer along with a rain gauge and an air temperature sensor have been installed at that section. The slope has experienced a shallow movement at the slope surface with a depth of 1.9 m with already observed rainfall intensity. A 6 m^2 area of the slope is selected and reinforced with Vetiver grass. Nevertheless, quantitative studies of how much contribution the VS provides to slope stabilization in the field are still relatively scarce. The current paper presents a comparative study of the VS performance on the shallow slope movement in expansive soil observed from inclinometer data for the last two years. It is observed that due to Vetiver grass, the slope movement rate has reduced to 2% since plantation of Vetiver grass from that of 10% before Vetiver grass. Later, this result is further verified through a numerical investigation where Vetiver grass is simulated by changing soil property. Numerical analysis indicates root reinforcement from the root dimensions increases slope stability up to 30%. This study outlines an approach for the study of VS in terms of contribution to slope stabilization, including field observation and numerical analysis.

1. INTRODUCTION

From droughts, floods, and tornado outbreaks to hurricanes, winter storms, and wildfires, communities across the United States have weathered significant storm damage in the past decade. The National Centers for Environmental Information created 115 natural disasters responsible for at least $1 billion in damage in the United States between 2010 and 2019. Texas experienced the most billion-dollar natural disasters in the decade, with Kansas, Oklahoma, Missouri, and Illinois not far behind. In correlation with this, high plastic clay alone incurs more financial losses to U.S. property owners than earthquakes, floods, hurricanes, and tornadoes combined (Jones and Jefferson 2012). In a typical year, the associated financial losses caused by expansive soil can be as high as 15 billion dollars (Jones and Jefferson 2012). Unprotected natural or constructed earthen slopes are a significant point source of erosion problems resulting in serious sediment flows, slope failure, and slippage that often result in landslides, economic damage to property, and loss of life. The Vetiver System can effectively and at low cost protect slopes, stop, or significantly reduce this risk of slippage, and prevent slope failure. The Vetiver Grassroots has a high tensile strength - an average of 69 MPa that can increase the shear strength of soil by a factor of 40, and because when planted on slopes Vetiver will reduce slope hydraulic pressures through the removal of water.

When Vetiver roots interact with the soil in which it is grown, a new composite material comprising roots with high tensile strength and adhesion embedded in a matrix of lower tensile strength is formed. Vetiver roots reinforce soil by transfer of shear stress in the soil matrix to tensile inclusions. In other words, the shear strength of the soil is enhanced by the root matrix (Styczen and Morgan 2003). The combination of slippage prevention (mass wastage of soil) and its sediment filtering ability results in the systematic characterization of engineering properties of the Vetiver system about slope stability. These can be categorized as discussed into two groups: mechanical and hydraulic. In addition to the reduction of slope hydraulic pressures through the removal of water, the mechanical effects of the Vetiver system on the slope are highly beneficial, normally through reinforcement. Traditionally, the Vetiver root reinforcement contribution to soil shear strength is quantitatively expressed using the "soil cohesion due to root reinforcement" or "root cohesion," c^r. The value of root cohesion can be estimated using Eq. (1) (Wu et al. 1979; Jotisankasa et al. 2015).

$$c^r = t_R \left[\frac{A_R}{A}\right](\sin\theta + \cos\theta \tan\phi') \tag{1}$$

Where t_R is mobilized root tensile stress, $\frac{A_R}{A}$ is root area ratio (RAR) or ratio between root and total area, and θ is shear distortion angle in the shear zone. It is noted that the mobilized root tensile stress, t_R is dependent on the modes of failure that could occur in root-reinforced soils, such as fiber-break mode, fiber-stretch mode, and fiber-slip mode (Gray and Sotir 1996). A combination of these three failure modes would occur when root-reinforced soil is sheared.

Practically, it could be reasonably assumed that the mobilized root tensile stress, t_R, would be a function of the ultimate root tensile strength, T_R. Traditionally root reinforcement model from the root dimensions measured at the shear surface analysis of the in-situ tests where an average root diameter for each test is calculated. The tensile strength T_R of this 'average' root, plotted against root diameter (Figure 1) for each in situ shear test. Figure 1(b) shows test results of the strength of sandy soil with and without Vetiver roots in soaked conditions. It should be noted that due to very limited root strength analysis in highly plastic clay soils, the test results for other soil types are mentioned to provide a strength variation overview. For analysis and design of slope, engineers need information on the soil cohesion due to roots to calculate the Factor of Safety (FS).

According to Eq. (1), the root cohesion, c^r, can be expressed as a function of RAR. It can also be expressed as a function of root bio-mass per unit volume of soil, ρ_R. Eq. (2) thus expresses the rate of increase in cohesion due to root percentage in two forms, using either k-parameter or a-parameter.

$$c^r = k\left[\frac{A_R}{A}\right] = a \cdot \rho_R \quad (2)$$

From Figure 1(b), the rate of increase in strength due to root biomass, a is 1.9 kPa/kg/m^3 of dried root/unit volume of soil (Jotisankasa et al. 2015).

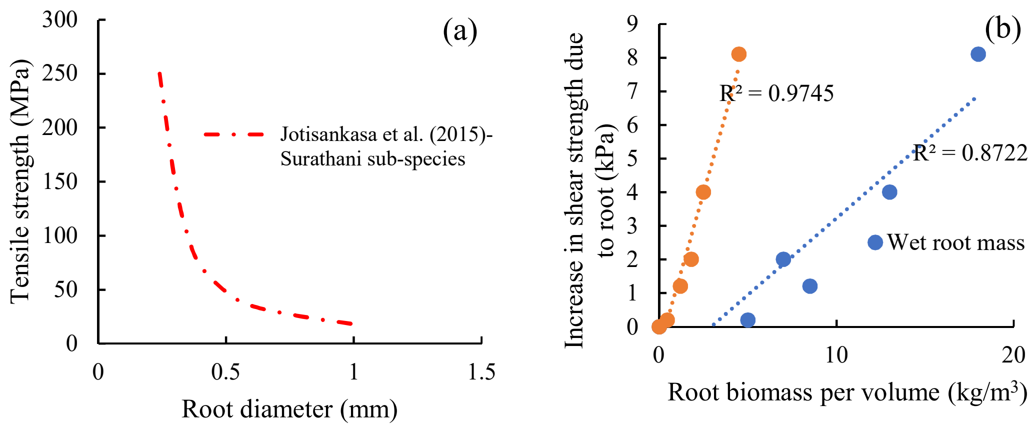

FIG. 1. (a) Tensile Strength variation with Diameter (b) Shear resistance variation with root biomass (After Jotisankasa et al. 2015).

This strength is about only one-third the value from tests of Hengchaovanich (1998) which were tested in natural (unsoaked) field condition as a is 10 kPa/kg/m^3 of root mass/unit volume of soil. Similarly, Sungwornpatansakul and Rajani (2006) found that the k value was about 60 kPa per percent bulk root area. Table 1 is a compilation of soil strength studies that are increased due to vetiver roots and are commonly used in practice. In this study 6 kPa/kg/m^3 is considered for calculation of root cohesion, c^r.

The root-reinforced soil is expected to be of higher strength as well as higher permeability, which would help to reduce runoff by providing more infiltration, thus improving the soil and water conservation. Nevertheless, this would also lead to an increase in pore water pressure and possibly a decrease in slope stability in some cases. In several studies, numerical investigations have been carried out of Vetiver grass having different root depths. Jotisankasa et al. (2020) used the finite element method to analyze infiltration of rain into slope and limit-equilibrium method for slope stability calculation of 2 hypothetical slopes. It was found that for natural soil slope with a gradient of 26^0, the 2-meter-deep Vetiver Grassroots appeared to increase the pore water pressure only marginally, and thus the stability of the soil was improved by reinforcement of the roots. Islam et al. (2020) investigate soil characteristics of CHT hill slopes and analyze the stability of hill slopes having different slope angles using PLAXIS 2D. The stability of hill slopes was analyzed in terms of FS and the Strength Reduction Method (SRM) was used to calculate FS. Results from the numerical analysis showed that the FS decreases with the increase in slope angle, and for soft clay soil, slope fails at different slope angles. However, the presence of Vetiver grass on hill slopes increases FS by 2%–15% for sandy soils, but for clay, the increase in FS is insignificant because of deep-seated base failure.

TABLE 1. Calculation table for mean strength of Vetiver roots.

Depth from the surface (m)	Cross-section of roots (mm^2)	Increased shear strength of soil (kPa)	Shear strength of vetiver root (MPa)	Remark/Source
0.5	175	4.2	24.5	Mean shear strength = 25 MPa Chengchun et al. (2003)
1.0	105	2.6	25.3	
1.5	45	1.2	27.2	
Root biomass (kg/m^3)	**Avg. diameter of roots (mm)**	**root cohesion, c^r (kPa)**	**Tensile strength of Vetiver root (MPa)**	**Source**
1	0.4	1.9	75	Jotisankasa et al. (2015)
1	0.66	6-10	85	Hengchaovanich (1998)
1	-	6	-	Sungwornpatansakul and Rajani (2006)
-	0.3 -1.4	2.4 - 2.7	17 - 2	Mickovski and Van Beek (2009)

To justify the beneficial effects of the Vetiver System in high plastic clay which behavior is highly dependent on moisture content changes, the mechanical and hydraulic properties of Vetiver grass need to be assessed. Present in both humid and arid/semi-arid environments, high plastic clay covers nearly a quarter of the United States area (Nelson and Miller 1997), which are highly susceptible to slope failure under excessive rainfall (Khan et al. 2020). Considering this broader scenario, the objective of this study is to investigate the effect of the Vetiver System for slope stabilization in a slope of high plastic clay during excessive rainfall using field monitoring data and evaluate its impact on the safety of the slope through numerical analysis. A total of two major tasks was undertaken during this proposed study. In the beginning, ground preparation like acquisition, plantation of Vetiver grass, instrumentation, and growth monitoring were conducted. A 6 m^2 area of a repaired highway slope was selected, reinforced with Vetiver grass, and comprehensively to monitor the moisture content, matric suction, and temperature variation, and the movement of the slope is ongoing. Finally, this study performed a numerical investigation of the slope to evaluate the effect of different frequencies and duration of rainfall (based on historical rainfall data of Mississippi) on the infiltration and corresponding change in the FS of the highway slope.

2. SITE SELECTION AND PLANTATION

Mississippi receives an average annual rainfall intensity higher than other neighboring states resulting in a variation of rainfall, temperature, and soil condition, which eventually works as a stressor to cause shallow slope failure. The presence of high plastic clay named Yazoo clay in the Jackson area of Mississippi makes the case worsen. Historically, this rainfall with high plastic clay has caused much damage to Mississippi transportation infrastructures such as highways, embankments, and slopes. Soil profile in Jackson consists of a weathered upper zone overlying an un-weathered lower zone of Yazoo clay. The upper zone weathered portion of the

Yazoo clay varies in-depth. However, it mostly extends to a depth of around 9.1 m (Taylor 2005). Based on the plasticity index values reported for Yazoo Clay, a very high shrink/swell potential exists. As a result, moisture changes cause swelling, shrinkage, and otherwise destructive behavior, which in turn cause detrimental effects to the roads, foundations, and related infrastructure in the central Mississippi region (Douglas and Dunlap 2000; Lee 2012; Khan et al. 2020).

Excessive rainfall with high plastic clay makes Jackson, Mississippi, an ideal site to test the effect of hydraulic and mechanical characteristics of Vetiver grass. The site is located on a highway slope along the I20E exit toward Terry road. It is a 3.5 H: 1V to 4H: 1V slope with a height of 4.5 m. The location and site photo of the slope is presented in Figure 2. A 6 m^2 area of slope section was selected as the test section for the Vetiver grass and prepared for plantation of the Vetiver grass. The bed was prepared within the first week of May 2020. Handheld equipment had been used for the plantation.

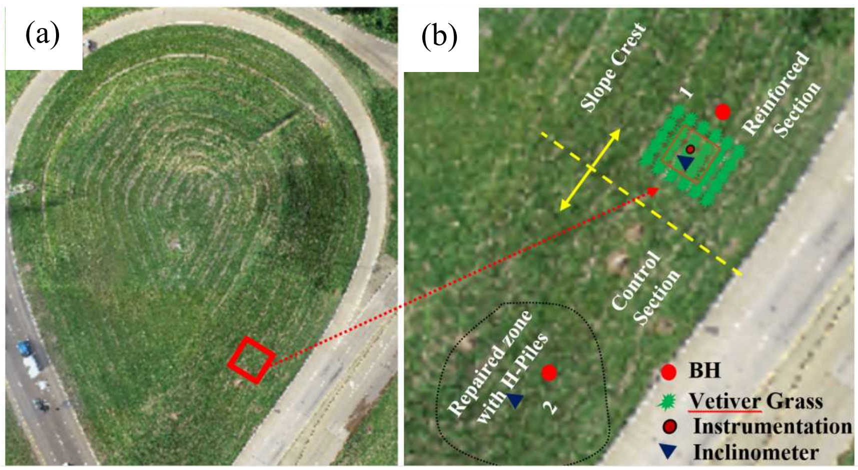

FIG. 2. (a) Initial state of the studied highway slope section (b) Schematic of the reinforced and control section.

TABLE No. 2. Site investigation details at Highway slope.

Borehole	Borehole Depth (m)	Slope Area	Test Designation	Time
BH-1	9.1	Reinforced Section	Inclinometer 1	October 2018
BH-2	9.1	Control section	Inclinometer 2	October 2018

The Vetiver Grassroots were planted at 0.6-0.9 m. spacing along with both directions and then was allowed to grow naturally. A schematic of the testbed was presented in Figure 2. The schematic of the field investigation and instrumentation plan is presented in Figure 2. A micro weather station is installed on the slope to monitor the weather conditions in the field. The weather station is equipped with a high-precision rain gauge (precipitation) and an air temperature sensor. At the location inclinometer, instrumentation set up are displayed in Table 2. All the sensors are connected to automatic data loggers, which are programmed to collect hourly intervals. The data logger is capable of storing in the server, and data were collected remotely. The field site is examined weekly to monitor the growth.

3. GROWTH RATE MONITORING

Vetiver grass is planted horizontally across slopes to create a bench, slow the migration of water, and trap sediment; in gullies to slow water flow, or around engineered structures to stabilize soil (Grimshaw and Faiz 1995). As from literature, Vetiver hedges can take two months to 4 years to establish. The preliminary results are very encouraging, as shown in Figure 3, which indicates that within five months (from June 20 to October 20), Vetiver grass had substantive growth in Yazoo clay.

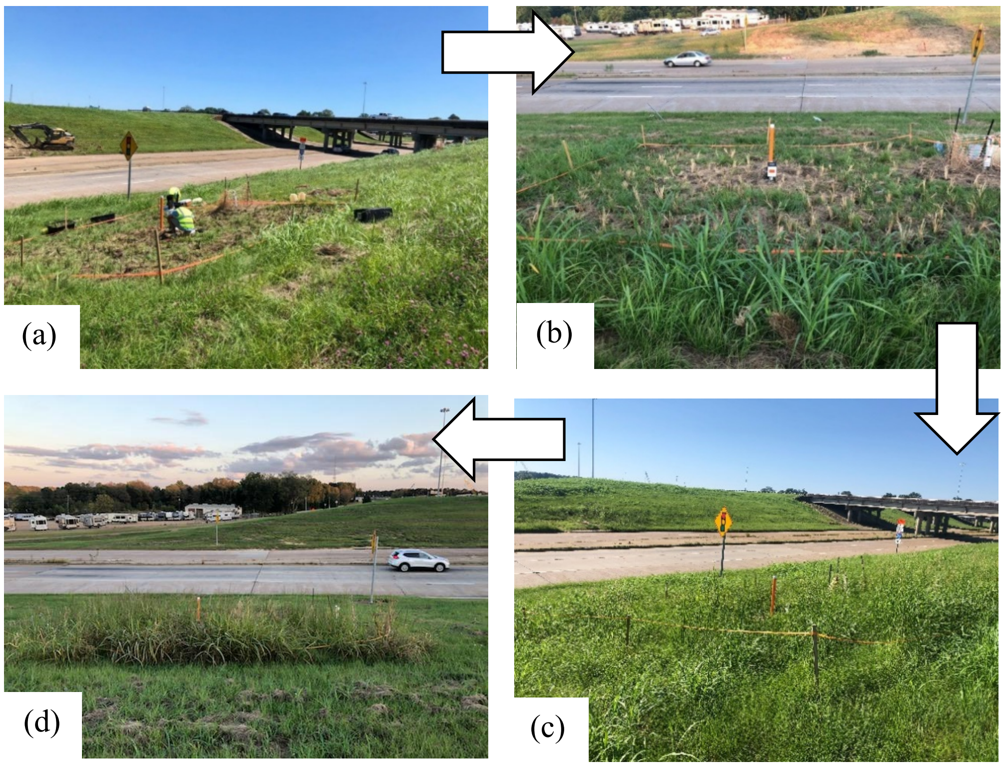

FIG. 3. Chronological growth of Vetiver grass in reinforced Highway Slope Section (a) June 20 (b) July 1 (c) July 17 (d) Oct 21.

Again, Vetiver grass has not been observed to be an invasive species; generally, it produces no seeds, but if seeds are produced, they tend to be sterile (Grimshaw and Faiz 1995). However, within different species, the Sunshine Vetiver grass genotype (Chrysopogon Zizanioides or Vetiveria Zzizanioides) is identified by USDA Natural Resources Conservation Service (NRCS) as a domesticated and sterile type to grow in the USA. In the present study, 'Sunshine' Vetiver grass has been planted. The Vetiver grass has been watered weekly based on rainfall patterns. Around 110 mm rainfall is recorded after plantation since May 20. So far, the Vetiver Grassroot has grown around 2.1 m in high plastic Yazoo clay under excessive rainfall.

4. SLOPE MOVEMENT DATA

The horizontal movement data from the slope was observed for the last two years using a slope inclinometer. Slope inclinometer measurements were collected at every 0.6 m. spacing along the slope inclinometer pipe. After data collection, the slope movement data is downloaded and analyzed to determine the slope movement. The horizontal movement data from Inclinometer 1 at the reinforced section and Inclinometer 2 at the control section at the surface of the slope is presented in Figure 4. As observed from the inclinometer data, on the control section, displacement is low, and the lack of movement is due to recent slope repair with the deep H piles for mitigating deep-seated slope slip surfaces. But still, the displacement is there, and the trend is increasing. On the other hand, the reinforced section experienced movement from January 2019 and has moved up to 0.63 m at the slope surface till April 2020. Since May 2020, the section is reinforced with Vetiver grass, the change is fairly static and reaches up to 0.66 m in the last four months. It is observed that due to Vetiver grass, the slope movement rate has reduced to 2% since plantation of vetiver grass from that of 10% before Vetiver grass. The change in slope displacement is quite significant. Usually, Vetiver grass-root reaches 3-3.9 m in the first year, reinforcing the soil. It isn't easy to be dislodged under high-velocity flows (Hengchaovanich 1999; Hengchaovanich and Nilaweera 1998; Truong 2000). Here, the root growth observed in the last six months is 2.1 m, which is fairly within the normal range and the results of inclinometer results validate the previous study for high plastic clay. It should be noted that the extended field performance monitoring results, as well as lab testing results, will be taken into account for future research investigations. This effect of the Vetiver root system will be further studied in the numerical investigation of the slope.

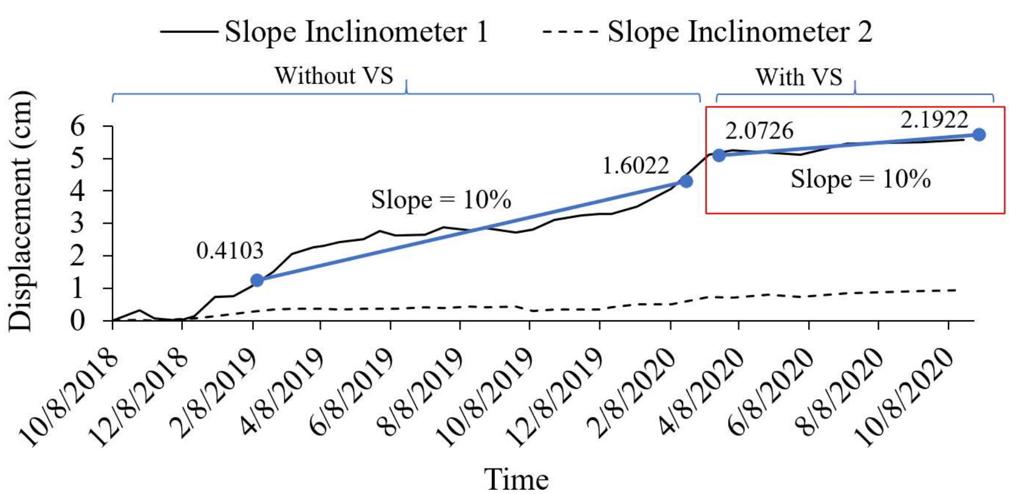

FIG. 4. Displacement in slope with time at two inclinometers.

5. NUMERICAL INVESTIGATION

Due to the presence of Vetiver root result from the inclinometer is significant. As a further study, the slope stability analysis by elastoplastic finite element analysis (FEA) is used, which is an accurate, robust, and advanced method. The graphical presentation of the FEA program allows a better understanding of the failure mechanism, and the deformation analysis evaluates the performance of the slope. The Mohr-Coulomb soil model was utilized for deformation and stability analyses using 15 triangular node elements. The slope was modeled with and without the Vetiver grass patch to compare the effects of vetiver on stability. As shown in Figure 5, for the with-Vetiver case, the Vetiver root zone had a depth of 2.1 m and root diameter of 0.05 cm.

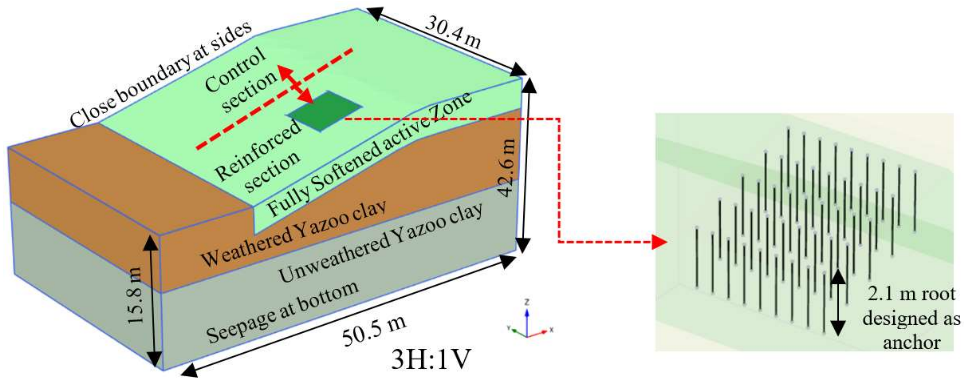

FIG. 5. FEM soil model with the boundary conditions of the slope.

TABLE No. 3. Soil parameters for FEM analysis (Khan et al. 2020).

Parameter	Name	Unit	Weathered Yazoo clay in Active Zone without Vetiver	Weathered Yazoo clay in Active Zone with Vetiver	Weathered Yazoo clay	Unweathered Yazoo clay
Bulk unit weight	Υ_{unsat}	kg/m^3	2018.3	2018.3	2016.7	2039.15
Saturated unit weight	Υ_{sat}	kg/m^3	2162.4	2162.4	2160.8	2039.15
Permeability	k_y	cm/sec	0.034	$3.03\text{x}10^{-6}$	$3.03\text{x}10^{-6}$	$3.03\text{x}10^{-6}$
Young's modulus	E	MPa	4.7	4.7	7.1	9.5
Poisson's ratio	ν	-	0.3	0.3	0.3	0.25
Cohesion	C	MPa	0.0028	0.0028	0.0071	0.0119
Friction angle	Φ	degree	14 °	14°	16 °	15 °

The spacing between the Vetiver row was 0.6 m (in both directions), and the total length of the slope was 22.5 m. As for the without-Vetiver case, the slope profile was the same as for the with-Vetiver case, except that there was no Vetiver root zone in the modeled slope during this study.

The 3D slope stability analyses were performed using the FEM program PLAXIS 3D. From literature, it is observed that roots with smaller diameters break under higher stresses when submitted to tension, while thicker roots usually break under lower tensile stresses (Waldron and Dakessian, 1981; Operstein and Frydman, 2000; Mickovski and van Beek, 2009). Here roots are modeled as elastic anchors and soil as elastoplastic material. It is assumed that the roots act with a fully elastic nature in the failure mode. The roots from an overall study of published articles, other parameters for FEM are selected, as shown in Table 3 and Table 4.

According to Figure 4, The slope has faced consistent movement throughout the monitoring period. During this study, stability analysis was conducted, and an increased FS for that particular slope condition was observed, as presented in Figure 6.

TABLE No. 4. Vetiver root parameters for FEM analysis.

Vetiver root Modelling	Depth from the Surface (m)	Avg Diameter of Roots (cm)	Cross-section of Roots (in^2)	Tensile Strength of Vetiver root (MPa)	Unit Wt of the root, (kg/m^3)	Spacing between Vetiver grass (m)	Tension (KN)	Material Type
Anchor	2.1	0.06	0.0025	82.04	640.7	0.6	0.023	Elastic

Based on numerical analysis, the FS of the slope was determined using the phi-c reduction method in PLAXIS 3D, which is alternately known as the shear strength reduction analysis. It is observed from the numerical investigation, as shown in Figure 6, that due to the hydraulic and mechanical advantage of the Vetiver root system, the FS increase from 1.15 to 1.5. This increased FS is quite validating the stable displacement trend of inclinometer data, as shown in Figure 4.

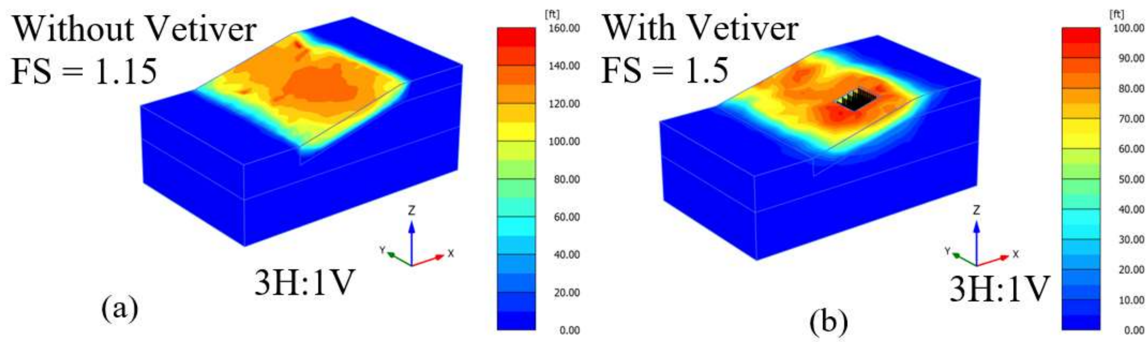

FIG. 6. Variation in FS of slip surface (a) without Vetiver Grassroots (b) with Vetiver Grassroots developed 2.1 m (1 ft.=0.3 m).

It is observed that with the growth of Vetiver roots, the trend of displacement is static and a decrease of the previous increasing trend. The numerical simulation shows that Vetiver roots as anchors increase soil shear strength by acting as a nail. Despite FEM limitations such as inherent limitations, approximation methods for the analysis, with further development of the Vetiver grass system, the current and extended results of the current study could help practitioners to consider vegetation as an effective long-term co-stability solution for various highway and embankment slope ratios for shallow slip surface and erosion control.

6. CONCLUSION

Slope failures are frequent in highway slopes on highly plastic clay in Mississippi due to the rainfall and climatic variation. The objective of the current study was to investigate the effect of Vetiver grass on the stability of highway slopes containing high plastic clay. One highway slope was instrumented with an inclinometer and rain gauge to monitor horizontal displacement and rainfall. Besides field monitoring, numerical modeling was conducted to understand the effect of the Vetiver root system on the highway slope. The findings of this study are mentioned below:

- Based on the slope deformation data from the inclinometer, it is observed that the control section experienced movement up to 0.63 m from January 2019 to the end of April 2020. After Vetiver grass plantation in the first week of May 2020, the deformation of the slope is measured 0.66 m at the end of August 2020. So, it is confirmed that due to Vetiver grass, the slope movement rate has reduced to 2% than that of 10% without Vetiver grass. The site is still under observation and significant improvement of the slope stability is supported.
- A numerical investigation of that slope considering fully saturated condition indicates that due to the hydraulic and mechanical advantage of the Vetiver root system, the FS increase from 1.15 to 1.5. This increase in FS is further validating the lower displacement trend as observed from inclinometer data.

Usually, the root-reinforced soil is expected to lead to an increase in pore water pressure and possibly a decrease in slope stability in some cases. Here Vetiver grassroots appeared to improve soil stability and thus it can be reasonably assumed that the increase in pore water pressure was marginal. Further study can be conducted on the change of pore water pressure with the growth of the Vetiver root system.

REFERENCES

Chengchun, K., Ziyuan, F., Xijing, W., and Figen, T. (2003). "Design principles and engineering samples of applying vetiver ecoengineering technology for steep slope and riverbank stabilization." *Proc., 3rd Int. Conf. on Vetiver*, China Agricultural Press, Beijing, 365-374.

Douglas, S. C., and Dunlap, G. T. (2000). "Light commercial construction on Yazoo clay." *Proc. Inst. Civ. Eng.: Forensic Eng.*, 607-616.

Gray, D. H., and Sotir, R. B. (1996). *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*, John Wiley and Sons.

Grimshaw, R. G., and Faiz, A. (1995). "Vetiver Grass: Application for Stabilization of Structures. " *Proc., Sixth Int. Conf., on Low-Volume Roads*, 25-29.

Hengchaovanich, D. (1998). *Vetiver grass for slope stabilization and erosion control, with particular reference to engineering applications*. Pacific Rim Vetiver Network, Thailand.

Hengchaovanich, D. (1999). "Fifteen years of bioengineering in the wet tropics from A (Acacia auriculiformis) to V (Vetiveria Zizanioides). " *Proc., Ground and Water Bioengineering for Erosion Control and Slope Stabilization*, Manila. 31-40.

Hengchaovanich, D., and Nilaweera, N. S. (1998). "An assessment of strength properties of vetiver grassroots in relation to slope stabilization. " *Proc., First Int. Vetiver Conf.*, Thailand, Bangkok, 153-158.

Islam, M. D. A., Islam, M. S., and Elahi, T. E. (2020). "Effectiveness of Vetiver Grass on Stabilizing Hill Slopes: A Numerical Approach." *Geo-Congress 2020: Engineering, Monitoring, and Management of Geotechnical Infrastructure*, Reston, VA: ASCE. 106-115.

Jones, L. D., and Jefferson, I. (2012). "Problematic soils and site investigation." *ICE manual of Geotechnical Engineering, volume 1, Geotechnical Engineering Principles*, 413-441.

Jotisankasa, A., Sirirattanachat, T., Rattana-areekul, C., Mahannopkul, K., and Sopharat, J. (2015). "Engineering characterization of Vetiver system for shallow slope stabilization. " *Proc., 6th Int. Conf., on vetiver*, Danang, Vietnam, 5-8.

Jotisankasa, A., Mairaing, W., and Tansamrit, S. (2020). "Infiltration and stability of soil slope with vetiver grass subjected to rainfall from numerical modeling." *Unsaturated Soils: Research & Applications*, CRC Press, 1241-1247.

Khan, M. S., Amini, F., and Nobahar, M. (2020). "Performance Evaluation of Highway Slopes on Yazoo Clay." Mississippi. Dept. of Transportation, FHWA/MDOT-RD-20 286.

Lee, L. T., Jr. (2012). "State Study 151 and 236: Yazoo Clay Investigation." U.S. ACE, ERDC.

Mickovski, S. B., and Van Beek, L. P. H. (2009). "Root morphology and effects on soil reinforcement and slope stability of young vetiver (Vetiveria Zizanioides) plants grown in a semi-arid climate." *Plant Soil*, 324(1), 43-56.

Nelson, J., and Miller, D. J. (1997). *Expansive soils: problems and practice in foundation and pavement engineering*, John Wiley & Sons.

Operstein, V., and Frydman, S. (2000). "The influence of vegetation on soil strength." *Proc., Inst. Civ. Eng.: Ground Improv.*, 4(2), 81-89.

Sungwornpatansakul, W., and Rajani, S. (2006). "Shear strength of soil reinforced with Vetiver grass roots." *Proc., of the 6th Symposium on soft ground improvement and geosynthetics*, Bangkok, Thailand.

Styczen, M. E., and Morgan, R. P. C. (2003). *Engineering properties of vegetation*, Taylor & Francis.

Taylor, A. C. (2005). *Mineralogy and Engineering Properties of the Yazoo Clay Formation*. Jackson Group, Central Mississippi, Mississippi State University.

Truong, P. N. (2000). "The global impact of vetiver grass technology on the environment." *Mercury*, 1-2.

Waldron, L. J., and Dakessian, S. (1981). "Soil reinforcement by roots: calculation of increased soil shear resistance from root properties." *Soil Sci.*, 132(6), 427-435.

Wu, T. H., McKinnell, W. P., III, and Swanston, D. N. (1979). "Strength of tree roots and landslides on Prince of Wales Island, Alaska." *Can. Geotech. J.*, 16(1), 19-33.