Climate Resilient Slope Stability Improvement Using Vetiver on a Test Levee

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Abstract: Bioinspired slope improvements can achieve outcomes similar to traditional slope improvements for shallow slope failures, while incorporating plant material as a structural component and using a minimum of heavy equipment. Vetiver grass can mitigate the rain-induced slope instability of earthen infrastructure, such as levees, constructed using loess and clay soils. Vetiver grassroots can extend to depths greater than 3 m (10 ft), creating a new composite material with the grassroots and soil, thereby increasing shear strength to combat shallow slope failures. The objective of this study is to determine the feasibility of vetiver as a climate-resilient bioinspired slope stability improvement on a test levee constructed of loess in Vicksburg, Mississippi (MS). Vetiver was planted at 1 ft center-to-center intervals on a 9.1 m wide (30 ft) section of an approximately 12.2 m long (40 ft) downstream slope of a test levee and observed for 2.5 years. To consider the effect of extreme precipitation events, a finite element analysis was completed for a comparable clay slope using 500 year precipitation intensity–duration–frequency curves of Jackson, MS. Precipitation negatively impacts the collapsible and expansive nature of the local loess and clay, respectively. The results demonstrate that vetiver grass is a viable method to increase slope stability for earthen levees constructed with loess and clay, which are prevalent in Vicksburg and Jackson, respectively. Vetiver also holds promise as a climate resilient solution to combat rain-induced shallow slope failures. **DOI: 10.1061/NHREFO.NHENG-1924.** © *2024 American Society of Civil Engineers.*

Practical Applications: As society advances toward a more sustainable approach to managing infrastructure, traditional methods of using heavy machinery, concrete, and steel to repair landslides are being replaced with using minimal equipment, earthen and geosynthetic materials, and vegetation. Earthen infrastructure, such as dams and levees, provide protection against the flooding of basins, rivers, lakes, and other bodies of water; however, they are not immune from landslides. One common landslide that can occur in earthen infrastructure is a shallow slope failure, particularly in soil that destabilizes greatly with changes in climate, such as collapsible and expansive soils. The researcher is proposing to use vetiver grass to combat shallow slope failures in earthen infrastructure in MS. Vetiver grassroots can grow to depths greater than 3 m (10 ft), which exceeds the depths of shallow landslides. Vetiver was transplanted on a test levee that was no longer being used in Vicksburg to determine if vetiver could grow in loess. Further, computer modeling was done to predict the performance of vetiver on a levee constructed in clay following storms with an estimated return period of 500 years for Jackson. The use of vetiver was determined to reduce the possibility of shallow slope failures under the conditions specified.

Introduction

Traditional slope improvement techniques are used for their fundamental application, practical design, and commercial access to materials and equipment. Armoring a slope with riprap, buttressing the slope with a toe berm, replacing unstable soil with stable soil, or using other materials such as concrete or geosynthetics are all widely accepted techniques. The improvement method is applied depending on the slope, soil stratigraphy, access, climatic conditions, hydrology, and vegetation, if any (Washington State DOT 2022). Bioinspired slope improvement techniques such as using willow tree branches to armor or buttress a slope, constructing a crib wall of lumber at the toe, planting vegetation to reinforce unstable soil, or using other materials such as fascine or coir also improve slope stability by preventing shallow slope failures. Planting vetiver grass on a slope is considered a climate resilient slope improvement solution due to its ability to adapt to various environments that differ from its native locations, and its ability to withstand extreme climate changes.

Vetiver is a perennial grass of the Poaceae family native to India (Rahardjo et al. 2014). Vetiver can adapt to various climates with temperatures ranging from −10°C (14°F) to 48°C (118°F). It is indigenous to tropical and subtropical climates in the Indian Subcontinent and Indochina; thereby, it can sustain heavy annual rainfalls up to 508 cm (200 in.). It is also adaptive to various soil alkalinities (pH 3–11). The most widely used species is *Chrysopogon zizanioides*, also known as *Vetiveria zizanioides*, or "sunshine" vetiver. Identified by United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) as a domesticated and sterile type, sunshine vetiver grows in the US in plant hardiness zones 8 to 13. These zones include Florida, Louisiana, and South Carolina; portions of the Atlantic Ocean to Pacific Ocean coastal states; portions of Arizona, Arkansas,

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New Mexico, Oklahoma, and Tennessee; and the Pacific and Caribbean Islands (USDA 2023). Vetiver is planted as young tillers, or newly developed bunches of grass with small diameters and root lengths (e.g., approximately 2 and 4 in., respectively). These plants are typically harvested from the mother plant and put in nursery pots until they reach a desired maturity or size, since this type is reproduced by vegetative propagation—not seeds. Vetiver grass plant suppliers can be located on The Vetiver Network International website (TVNI 2022). Vetiver contributes to slope stability due to its fine fibrous roots, which extend deep into the soil, forming a new soil-root composite that increases soil suction in an unsaturated zone and increases water intake by roots to maintain plant growth (Chirico et al. 2013). Using vetiver to reinforce soil by increasing shear strength has been studied in various types of soil.

Studies conducted using triaxial and/or direct shear tests of vetiver planted in soil and grown over time have determined increases in shear strength of soil due to root reinforcement. Eab et al. (2015) conducted a study of vetiver planted in Edosaki sand, a fine sand, indicating that the shear strength of the soil can increase by 7 kPa (142 psf) in cohesion and 7° in internal friction. The results were obtained for a vetiver tiller planted and grown for four months, sheared at a depth of 0.9 m (3 ft), and tested at normal stresses less than 101 kPa (2,100 psf). The tests were performed using a direct shear testing device in accordance with ASTM D3080 (ASTM 1998). A shear strength increase of 6 kPa (125 psf) in cohesion and 7° in internal friction are indicated for a vetiver bunch of tillers planted and grown for six months under the same testing conditions, with the exception that a large direct shear box was used. The study also determined that vetiver could grow up to approximately 1.8 m (6 ft) in six months, at an average rate of 30.5 cm (12 in.) per month. These results are consistent with consolidated-drained (CD) triaxial tests from Rahardjo et al. (2014), where soil was sheared within a depth of 0.9 m (3 ft) at a net confining pressure of 49.8 kPa (1,040 psf) and matric suctions less than 101 kPa (2,100 psf) during a one-year maturation period. A shear strength increase of 8 kPa (167 psf) in cohesion and 5° in internal friction was observed for old alluvium, a silty, clayey sand, where vetiver was planted at field scale. Wang et al. (2020) studied vetiver planted in weak expansive clay and determined the shear strength properties of soil with vetiver grassroots after growth periods of 90 and 180 days. Four specimens were sheared at depths between the ground surface and 30.5 cm (12 in.) in direct shear tests in accordance with Trade Standard of P. R China (SL237-021 1999). For normal stresses 95.8–407 kPa (2,000–8,500 psf), the test results indicated a minimum 97% increment in cohesion and 15.4% increase in friction angle for soil with planted vetiver that matured for 180 days, which suggests that the shear strength gain in weak expansive soil may not be as significant as that obtained in sands. These studies illustrate that vetiver can improve shear strength. Locations susceptible to wet and dry seasons are good candidates for this improvement, as weathering can deteriorate the shear strength of the soil (Nobahar et al. 2019; Snowden and Priddy 1968).

According to the Mississippi Section of the ASCE (2020). "ASCE's 2020 Infrastructure Report Card for Mississippi Infrastructure," precipitation has increased in MS at a rate of 1.45 cm (0.57 in.) per decade, affecting the state's 114 earthen and concrete levee systems, which have an average age of 61 years. Earthen levees constructed with local Peorian loess or Yazoo clay are at risk of greater distress at the onset of increasing rain.

The purpose of this study is to consider vetiver for slope improvement of earthen levees constructed in loess and clay and quantify the potential advantage of vetiver planted on the downstream slope of a test levee prior to extreme precipitation events.

Field Study

A field study was conducted on an existing inactive earthen test levee section at the Full-Scale Levee Breach and Hydraulic Test Facility at the Engineering Research and Development Center (ERDC) in Vicksburg, MS. The test facility was constructed in 2010. The levee section is located on the levee downstream of the catch basin. The upstream and downstream slopes are three horizontal to one vertical (3H:1V) and the crest height is 3.7 m (12 ft) above the downstream toe, per the as-built drawings (Mendrop-Wages 2010). The test levee subgrade is a minimum of 3.7 m (12 ft) of on-site loess fill below the crest, recompacted at ±2% optimum moisture content and 95% compaction of maximum dry density, which transitions to in situ loess at the toe that extends 6.1 m (20 ft) into the foundation. The 2010 geotechnical report provided Atterberg limits for the in situ soil at the test section location. The liquid limit (LL) of 34 and plastic limit (PL) of 26 yield a plasticity index (PI) of 8, such that the soil is classified as a low-plasticity silt according to ASTM D2487 (ASTM 2017), the Unified Soil Classification System (USCS). The in situ gravimetric moisture content was between 21.3% and 26.8%, corresponding to volumetric moisture contents of 35.2% and 41.6%. The average gravimetric moisture content of Peorian silt in MS is between 26.1% and 28.3% at depths between 7.6 cm (3 in.) and 30.5 cm (12 in.) and 28% at a depth of 45.7 cm (18 in.) (Snowden and Priddy 1968). These values correspond to volumetric moisture contents of 43.2%, 46.8%, and 46.3%, respectively. Geologic studies show that the loess is Peorian; originating in Peoria, Illinois, it is the youngest of aeolian deposits in the region (Snowden and Priddy 1968). On the upstream slope, a 61 cm (24 in.) thick clay cap overlays the loess, which serves as a hydraulic barrier due to its low permeability. The Atterberg limit requirements of the cap were LL < 60 and 10 < PI < 40. The USCS classification of the cap is high plasticity clay. The nearby Yazoo clay, which is known for its high swelling and shrinking capacity, is likely the source. The test levee did not appear to have visible cracks or other surface defects, making it a good candidate for improvement of an existing stable condition. Without prior studies on vetiver's growth in Peorian loess, vetiver was planted on the test levee downstream slope in two phases.

Vetiver Growth Monitoring

The first phase commenced in spring 2020 when 200 vetiver tillers were transplanted as a trial in a test section of 6.1 m (20 ft) length along the slope and 3 m (10 ft) width, at 30.5 cm (12 in.) center-to-center staggered spacing along the slope length and width. A 10.16 cm (4 in.) thick vegetative cover containing topsoil, Bermuda grass, and crimson clover was the planting bed for the vetiver. No fertilizer was used, and the topsoil was not tilled prior to planting. Due to the moistness of the ground surface, minimal effort was needed to create small holes within the existing grass such that planting was completed using traditional gardening tools and manual field labor. Planting vetiver in the spring was advantageous to optimize its perennial summer growing season. Field observations and watering were completed on alternate days for two weeks during which firm anchorage development was observed, indicating that the root depth grew 20.3–25.4 cm (8–10 in.) into the loess. Qualitative observations regarding root properties were made since the team was instructed against excavation of the test levee. Thereafter, biweekly monitoring ensued, and watering was reduced to rainfall only. Additionally, the catch basin water level was not measured during this study; however, it was primarily maintained at the riser level of 0.9 m (3 ft) below the crest of the levee, based on observation.

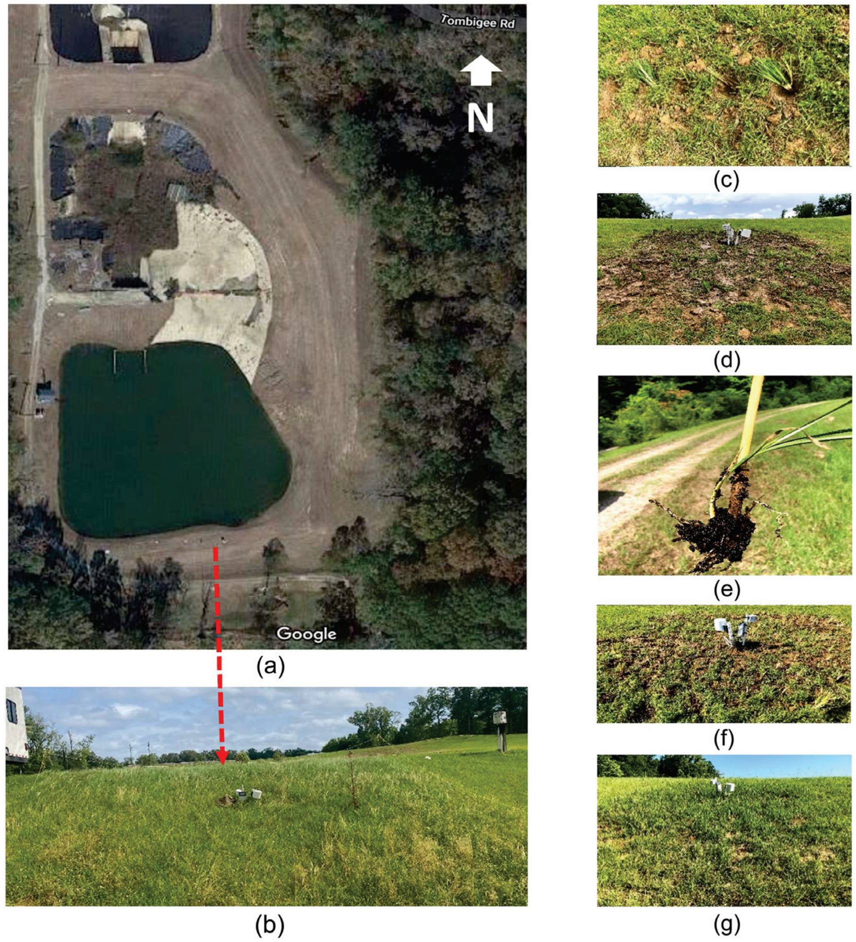

Fig. 1. Location of study area: (a) site map (image © 2022 Google); (b) test location; (c) installation; (d) backfill; (e) tiller; (f) first week; and (g) second month. [Reprinted (b–g) from Spears et al. 2023, © ASCE.]

Free water was not observed anywhere along the slope nor at the ground surface at the downstream toe. The site map and test location are provided in Figs. 1(a and b); installation and backfill photos are provided in Figs. 1(c and d); one tiller before transplanting is provided in Fig. 1(e); and growth after the first week and second month are provided in Figs. 1(f and g).

After observing significant growth and vitality of the Phase 1 trial section, a second phase was initiated in fall 2020 when 1,000 additional vetiver tillers were transplanted surrounding the existing study area, increasing the study area to 12.2 m (40 ft) in length and 30 ft (9.1 m) in width. Similar to Phase 1, planting was completed in one day with traditional gardening tools and manual field labor. The test section soon became dormant, including vetiver from Phase 1, due to their perennial nature. Growing season did not recommence until the end of March 2021, and a survival rate of more than 95% was observed at the end of the summer. Phase 2 is ongoing.

Instrumentation and Monitoring

Instrumentation was installed following plantation of vetiver in Phase 1 to observe conditions under different rainfall events; however, most results provided are during Phase 2. It is assumed that the planting of additional vetiver in Phase 2 did not impact the instrumentation results, since these were added outside of the footprint of Phase 1, and the sensors influence area is 1,000 cm^3 (61 in^3) or less. An air temperature and humidity sensor, rain gauge, and barometer were installed. Moisture and matric suction sensors were installed at depths of 15.2 cm (6 in.) and 45.7 cm (18 in.) at the center of the slope to monitor moisture and matric suction above the phreatic surface 0.9 m (3 ft) below the crest of the levee; these sensors also include temperature sensors. A data logger was installed, and data collection was completed during field visits via an app on a field laptop with a connection to the data logger through a USB cable. Figs. 2(a and b) show the location and depth

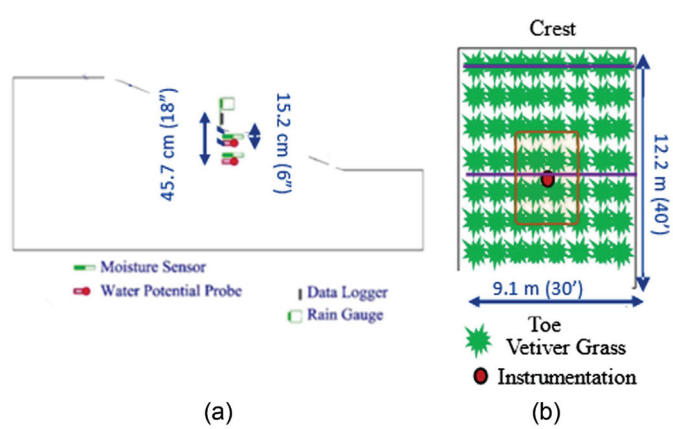

Fig. 2. Field instrumentation: (a) cross-section view of instrumentation; and (b) plan view.

of the sensors, the position of the rain gauge (i.e., a weather station, including temperature and humidity sensors and a barometer) and data logger, and the dimensions of the section with vetiver. Seepage from the catch basin was assumed to create a constant phreatic level located 0.9 m (3 ft) below the crest of the test levee or 2.7 m (9 ft) above the downstream toe. Thus, the loess was assumed to be fully saturated below this level. While roots were anticipated to reach more than 3 m (10 ft) in depth within the first year, therefore drawing water from the seepage, it is assumed that this made negligible changes to the constant phreatic level. Instrumentation was installed above the phreatic line, where a vadose zone likely exists. Volumetric moisture content, matric suction, temperature, and rainfall were all measured, providing insight into the properties of the vadose zone.

Variation of moisture content presented in Fig. 3(a) shows the volumetric moisture contents were approximately equal, with an average moisture content of 32% and 31% at depths of 15.2 cm (6 in.) and 45.7 cm (18 in.), respectively. Therefore, the volumetric moisture contents measured from the sensors are slightly less than those in situ moisture contents encountered onsite prior to construction. The optimum moisture content and maximum dry density during construction of the recompacted loess were not provided. The volumetric field capacity of 51.3% obtained from literature suggests the soil was not saturated (Snowden and Priddy 1968). Studies show that collapsible loess experiences a sudden significant volume decrease (settlement) as full saturation is approached (Li et al. 2015). There were no observations of settlement following the plantation of vetiver. Standard deviations of 4% and 2% for the 15.2 cm (6 in). and 45.7 cm (18 in.) depths, respectively, show little variation. Summer and fall seasons had frequent variations in moisture content, whereas winter and spring had moderate, reflecting the reduced daily variations in rainfall observed for the winter and spring. The field rain gauge measurements were not used due to it malfunctioning, as determined by precipitation measurements being grossly under the nearby weather station measurements. The nearest weather station was used for daily precipitation values instead (Weather Underground 2022). One case of precipitation exceeded 76.2 mm (3 in.) at the site for the 2.5 year monitoring period, which is considered an extreme precipitation event (Lukas et al. 2022). Gaps in the data are due to the sensors not working properly during the corresponding timeframe. Matric suction displayed similar trends.

Matric suction presented in Fig. 3(b) illustrates matric suction was at a maximum at 15.2 cm (6 in.) depth during late summer and early fall of 2020 and 2022. The maximum suction at a depth of 45.7 cm (18 in) was also during this timeframe. Suctions of −208 kPa (−4,337 psf) and −124 kPa (−2,590 psf) represent these depths, respectively. Soil above the groundwater table results in negative suctions, indicating that the soil is unsaturated and confirming the presence of the vadose zone. Average matric suction for 15.2 (6 in.) and 45.7 cm (18 in.) depths were much lower than the maximum values, at −28.7 kPa (−598 psf) and −32.6 kPa (−680 psf), respectively. Increases in suction are directly related to an increase in shear strength (Nobahar et al. 2019). Studies show that a collapse phase begins at intermediate values of matric suction

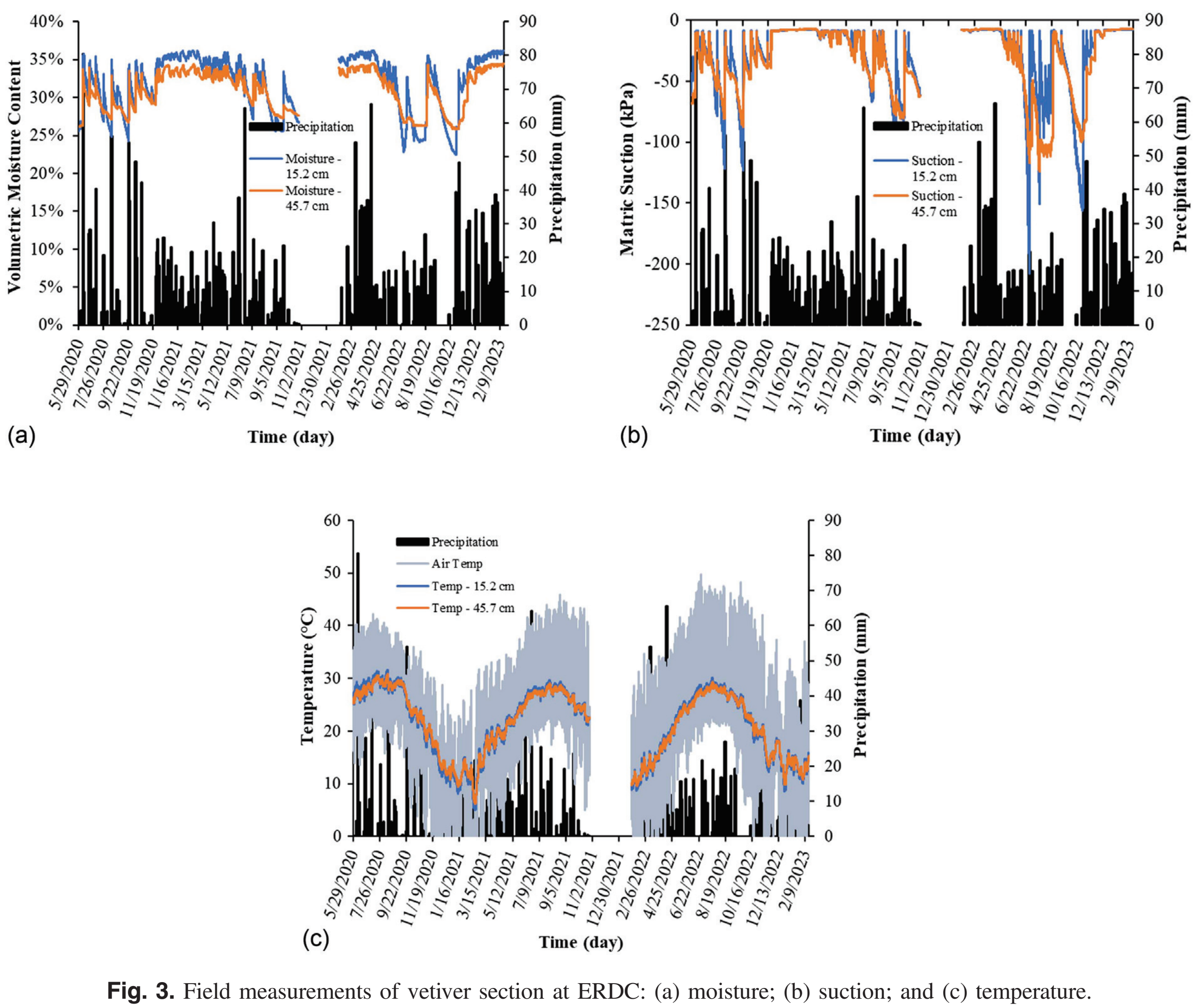

Fig. 3. Field measurements of vetiver section at ERDC: (a) moisture; (b) suction; and (c) temperature.

(Li et al. 2015). However, as noted, there were no visible indications of collapse on the slope. Similar to the average values, which had little variation between depths, the standard deviations were 26.5 kPa (553 psf) and 27.7 kPa (578 psf) for depths of 15.2 (6 in.) and 45.7 cm (18 in.), respectively. As with the moisture content, large variations in matric suction were attributed to the summer and fall seasons, whereas winter and spring have moderate variations and low suction values. The dormant phase of the vetiver occurs in winter and spring, causing transpiration in the roots to be significantly less than during growing season. Soil and air temperature displayed trends similar to weather-related changes in moisture and matric suction.

Soil was measured from moisture and matric suction sensors and air temperatures from a barometer. Fig. 3(c) displays the temperature at depths of 15.2 cm (6 in.) and 45.7 cm (18 in.) as approximately equal, with an average temperature of 22°C (72°F) at both depths. The average air temperature was slightly less, at 20°C (69°F). The standard deviations for soil temperature were also equal at 6.7°C (12.1°F) despite a larger air temperature standard deviation of 11.2°C (20.2°F). Larger soil and air temperature changes occurred between seasons, reflecting the seasonal changes in weather just as observed in the moisture and matric suction data. Moisture and suction measurements were also obtained for the numerical analysis, which was developed for a slope with the same downstream slope height and length.

Numerical Analysis

The current study investigates the effect of rainfall on a levee constructed with Yazoo clay using finite element analyses (FEA) in Plaxis 2D. Yazoo clay is from the Yazoo Formation of the Jackson Group, spanning parts of Louisiana, Mississippi, and Alabama (Hosman 1996). Increased precipitation impacts earthen infrastructure made of Yazoo clay because the surficial layer responds to seasonal weather variations by shrinking and swelling. This creates a weathered layer with desiccation cracks during dry, high temperature periods that leave pathways for large volumes of water to infiltrate otherwise low-permeability clay during rainy seasons, increasing risk on earthen infrastructure. A significant portion of the maintenance budget is used to repair highway embankment slope failures (Nobahar et al. 2019). Yazoo clay in the Jackson, MS, area extends to an average depth of 9.1 m (30 ft) overlying the unweathered zone. It has a LL between 70 and 100, PL between 20 and 30, and PIs that can exceed 50 (Douglas and Dunlap 2000). Oven-dried samples increase from 100% to 235% in volume when moisture approaches the LL (Lee 2012). The Plaxis 2D model takes into consideration the time-dependent changes in the clay and determines the factor of safety using the strength-reduction method.

Gravity loading is used for the initial phase, representing the levee following construction. Plastic loading establishes the seepage face, and fully coupled flow-deformation analysis with an associated safety phase is used thereafter. Coupled flow-deformation analyzes the development of deformations and pore pressures in saturated and partially saturated soils for time-dependent changes of the hydraulic boundary conditions. Rainfall was only applied to portions of the levee that were not submerged below the reservoir level. These rainfall events resulted in precipitation depths of approximately 76.2 mm (3 in.) or greater, as shown in the cumulative rainfall columns in Table 1. The historical rainfall pattern of a station near Jackson, MS, is based on a frequency analysis of partial duration series from the National Oceanic and Atmospheric Administration (NOAA) (NOAA 2014). The impact of rainfall events is evaluated at different intensities and durations of precipitation based on a return period of 500 years. This return period was selected to consider the increase in precipitation and extreme weather events due to climate change in Mississippi, which are comparable to the storm experienced in Jackson in August 2022 (Mississippi Emergency Management Agency 2022). Table 1 provides all the rain event scenarios for the modeled levee. The modeled levee geometry and soil properties are comparable to that of the test levee in the field study.

Table 1. Precipitation frequency estimates for 500 year return period

Duration of rainfall event (day)	Intensity [mm/hr (in/hr)]	Cumulative rainfall [mm (in)]
30 min (0.02083)	175.8 (6.9)	88.6 (3.5)
60 min (0.04167)	125.5 (4.9)	127 (5)
24 h (1)	12.3 (0.48)	294.6 (11.6)
3 day (3)	4.6 (0.18)	335.3 (13.2)

The modeled levee has an upstream reservoir slope height of 6.1 m (20 ft) and a reservoir head level of 4.6 m (15 ft). Both upstream and downstream slopes are 3H:1V, and there is no free water surface at the toe of the downstream slope; these conditions are based on those of the test levee. The levee crest is 10 ft (3 m) long. Only the upstream slope of the test levee consists of a 61 cm (24 in.) thick clay cap of high plasticity clay overlain by in situ loess that extends deep into the foundation. The test levee site stratigraphy did not represent a marginal case where the failure surface would be primarily through the downstream slope and within the weathered Yazoo clay. Therefore, the numerical model soil profile consists of a surficial layer of weathered Yazoo clay extending to a depth of 3 m (10 ft) below the ground surface on both the upstream and the downstream sides. Unweathered Yazoo clay underlies the weathered Yazoo clay with a thickness that varies between 3 m (10 ft) and 9.1 m (30 ft) below ground surface, which includes the levee's core. Low plasticity clay is below the unweathered Yazoo clay. The levee profile for the modeled levee with vetiver is provided in Fig. 4; the modeled levee profile without the vetiver section has the same geometry. Soil parameters adopted for this analysis are based on back-analyzed parameters to create a marginal condition with an initial factor of safety of 1.3. A conservative increase of 3.6 kPa (75 psf) in cohesion and 4° in internal friction was used to represent the section with vetiver and is comparable with values presented in literature (Wang et al. 2020). Table 2 provides the soil properties used. Each model was run for the event-duration and time thereafter, up to 30 days.

Results

The results of the numerical modeling are provided in Figs. 5–11. Saturation, suction, and factor of safety profiles of the most common extreme storm (one day) are provided in Figs. 5–7, respectively. These profiles represent the downstream levee slope just prior to the storm and at 3, 6, 9, 12, and 24 h of the one-day 500 year storm for the levee without vetiver (a–e) and the levee with vetiver (f–j). Total displacement profiles at different times and rain events are provided in Figs. 8–11. Figs. 5(a–e) represent the saturation of the levee without vetiver. Figs. 5(f–j) represent the saturation of the levee with vetiver at the same periods. Note that the numerical values of saturation ranged from 81% (represented in blue) up to saturations of 100% (represented in red). The levee was mostly fully saturated due to the reservoir level. Although there is no seepage line drawn, it could be assumed that the seepage would follow a parabolic shape, entering perpendicularly to the slope

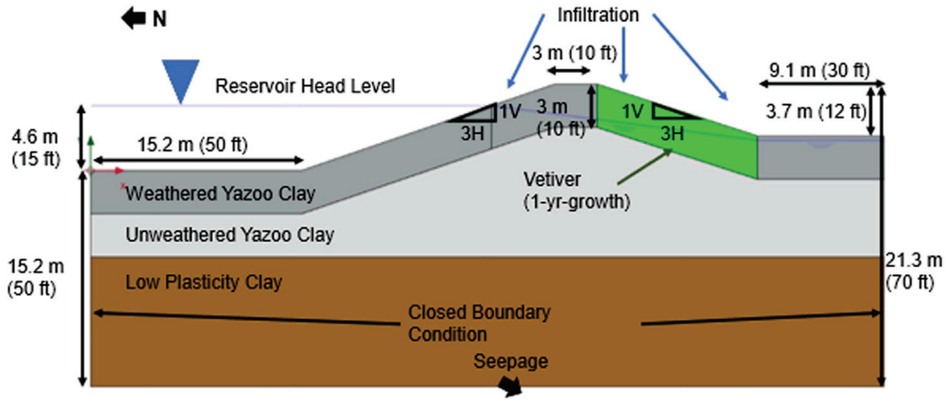

Fig. 4. Plaxis 2D FEA levee profile with vetiver.

Table 2. Soil properties for numerical analysis

Soil type	Cohesion (c) [kPa (psf)]	Friction angle (θ) (degrees)	Unit weight (γ) [kN/m^3 (pcf)]	Permeability (kv) [cm/s (ft/s)]	Anisotropy (kv/kh)
Weathered Yazoo clay	3.4 (70)	12	18.9 (120)	3.05×10^{-6} (1.00×10^{-7})	1/2
Unweathered Yazoo clay	5.3 (110)	18	18.9 (120)	3.05×10^{-6} (1.00×10^{-7})	1/2
Low plasticity clay	14.4 (300)	15	18.9 (120)	1.00×10^{-5} (3.28×10^{-7})	1/2
Weathered Yazoo clay with vetiver	6.9 (145)	16	18.9 (120)	3.05×10^{-6} (1.00×10^{-7})	1/2

at the reservoir level, 1.5 m (5 ft) below the crest, and discharging tangentially to the discharge face located at the downstream, landside toe. In some areas the slope was not fully saturated prior to rainfall on the upstream slope, crest, and downstream slope within the weathered Yazoo clay. Saturation profiles are approximately equal for the levee with and without vetiver at each duration, except the levee with vetiver has slightly lower (within 6%) saturations; however, this does not confirm that planting vetiver on the downstream slope would reduce saturation as expected and is considered minimal. For all profiles, saturation is the least near the center of the downstream slope; yet, this also is not an anticipated result of planting vetiver. Since the saturation profile does not illustrate an active capillary area in the vadose zone, which lies above the stable capillary area, seepage is the dominating mechanism in the saturation of the slope in the model.

Whereas the stable capillary area in the vadose zone creates fully saturated areas above the groundwater table (seepage line), the active area represents highly variable suction. This area would exist throughout the vadose zone, not just in the few areas observed in some profiles. The air entry head of the soil—the height of the water in a capillary void for which the soil becomes unsaturated—can be determined based on the type of soil and its respective soil water characteristic curve. The air entry head can be used to approximate the height of the capillary rise. The stable area and active area (capillary fringe) in the vadose zone are delineated based on the height of the capillary rise. A rough approximation of the height of capillary rise considers typical inputs for temperature, surface tension, contact angle, and unit weight of water to determine that it can vary from a ratio of 0.73 to the diameter of the soil particle as the minimum bound and a ratio of 2 to the diameter of the soil particle as the upper bound. Yazoo clay particles can often be less than 2 μm (2×10^{-4} cm, 7.87×10^{-5} in.); therefore, the maximum height of the capillary rise, and thus the minimum depth of the active zone, can reach 10 m from the saturated zone to the ground surface (Lee 2012). With less than 10 m of soil above the saturated zone, the behavior of the capillary fringe is not captured, and only part of the stable capillary area is illustrated. Changes in infiltration are not producing as significant a result as the stable area above the saturated zone. Similar trends were observed in the suction profiles.

Figs. 6(a–e) represent the suction of the levee without vetiver just prior to the storm, and at 3, 6, 9, 12, and 24 h of the one-day 500 year storm, respectively. Figs. 6(f–j) represent the suction of the levee with vetiver at the same periods. Suction ranged from 0 (represented in blue) up to suctions of 162.8 kPa (3.4E3 psf; represented in red), in some instances. However, qualitatively, the figures are consistent with the saturation figures provided in Fig. 5 since suction reduces saturation. In places above the seepage line prior to rainfall, there were some increased suctions on the upstream slope, crest, and downstream slope within the weathered Yazoo clay. While the levee with and without vetiver had the highest suction values during rainfall, following this the difference between the suction with and without vetiver ranged from 0.5–71.8 kPa (10.4–1,449 psf) for each case. After 6 h of rainfall, suction in the levee without vetiver was significantly higher than suction in the levee with vetiver. Similar to the saturation, these results do not denote the impact of vetiver, which corroborates with seepage dominating the profile instead of infiltration. Further, evapotranspiration was not considered, which suggests why increasing suction did not result in an increasing factor of safety. The factor of safety profiles provides more detail regarding how saturation, suction, and total displacement effects the overall stability of the slope.

Figs. 7(a–e) represent the total displacements for the critical slope failure associated with the reported factor of safety of the levee without vetiver just prior to the storm, and at 3, 6, 9, 12, and 24 h of the one-day 500 year storm, respectively. Figs. 7(f–j) represent the total displacements of the levee with vetiver at the same periods. Larger total displacements for the levee without vetiver were on the order of 10^{10} m (10^{11} ft). The maximum total displacement occurred at 6 h of rainfall for the levee without vetiver and after 24 h of rainfall for the levee with vetiver. The upstream slope was the most critical slope for the levee with vetiver just prior to rainfall and after 24 h, whereas the downstream slope was always

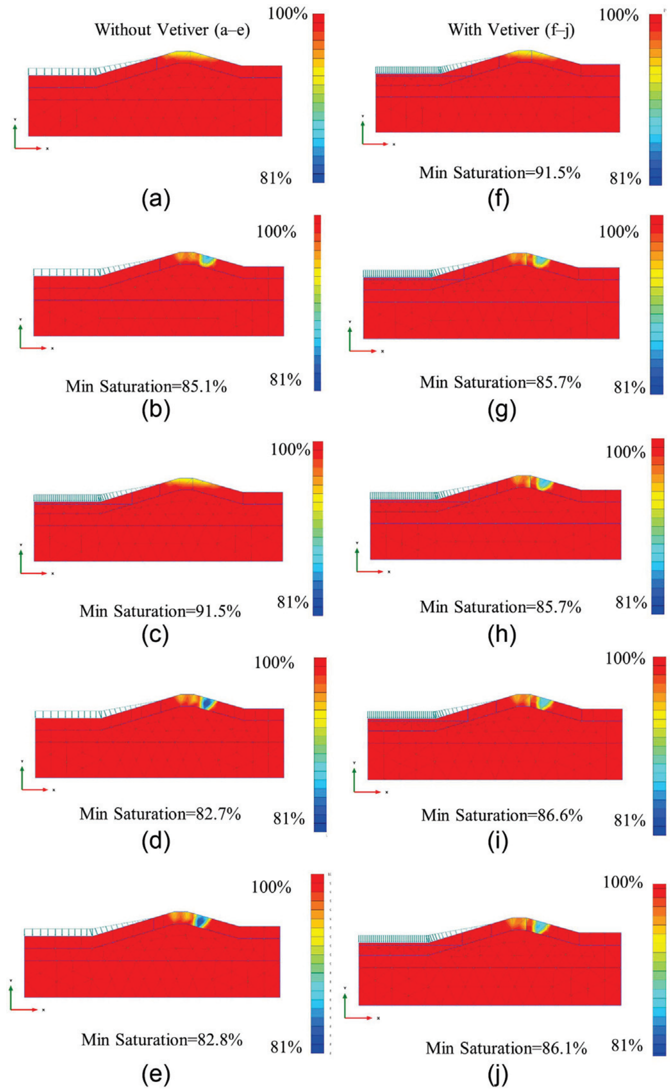

Fig. 5. Saturation for levee (a–e) without vetiver; and (f–j) with vetiver during one-day 500 year storm.

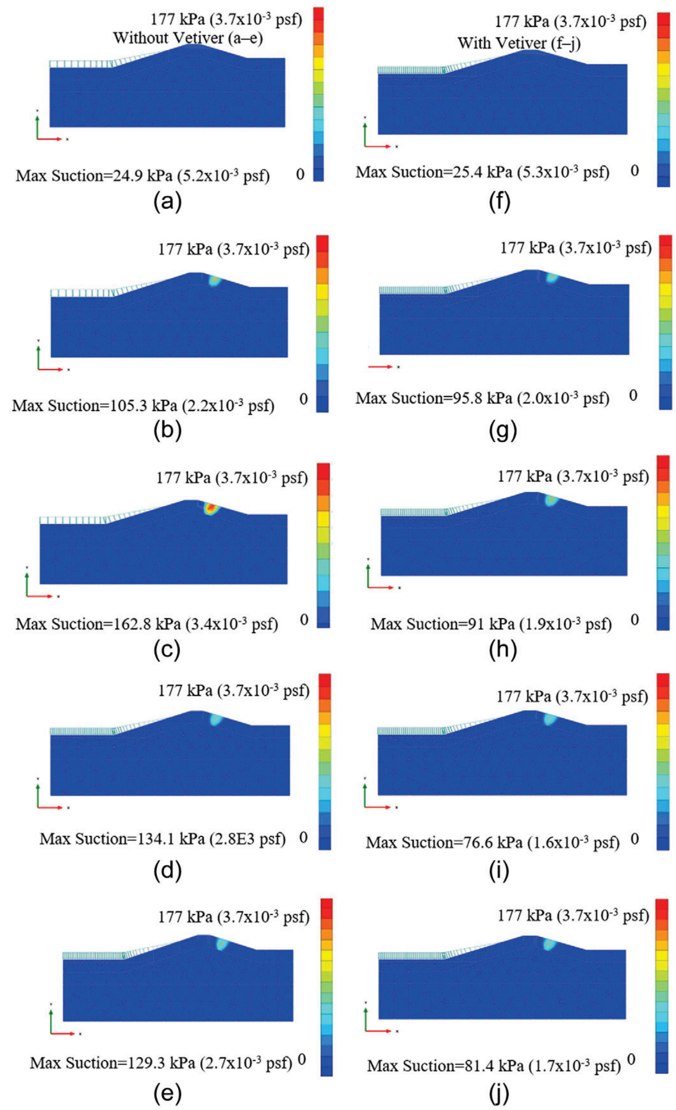

Fig. 6. Total suction for levee (a–e) without vetiver; and (f–j) with vetiver during one-day 500 year storm.

critical for the levee without vetiver. The most critical slope switched to the upstream slope is due to the upstream slope lacking vetiver and having a longer slope than the downstream slope. Total displacements were greater for the levee with vetiver for just prior to rainfall, 3 and 24 h; yet, the factor of safety values was also greater for the levee with vetiver for these times and all other times, again, due to the most critical slope being the upstream slope once the soil's shear strength properties were increased to represent a slope improved with vetiver. For a given storm, the changes in the factor of safety with time of failure of the slope can also be observed graphically to determine trends.

Figs. 8–11 represent the factor of safety associated with the reported factor of safety of the levee without and with vetiver for 30 min, 1 h, one- and three-day 500 year storms, respectively. The factor of safety corresponding to the levee without vetiver is denoted by the "Levee ..." dashed line, and the levee with vetiver, the "Vetiver..." solid line. The cumulative precipitation at each time-step of each storm duration is also provided, where precipitation beyond the storm duration remains constant since the rainfall stops after the duration. A higher factor of safety value was associated with the vetiver-stabilized slope with an exception to the one- and three-day, 500 year storms. Factor of safety values range from 1.08 to 1.52. For the levee without vetiver, the factor of safety value starts at 1.3 prior to rainfall and then reaches a minimum following short periods of time, such as 3 or 6 h, before increasing, sometimes exceeding the initial factor of safety prior to the end of rainfall. For the levee with vetiver, the factor of safety value starts at no less than 1.40 prior to rainfall and then reaches a minimum following short periods such as 3 or 6 h, before also increasing, sometimes also exceeding initial factor of safety prior to the end of rainfall. The trends in factor of safety with time are most similar between the 500 year storms at the 30 min, one- and three-day durations. These results provide potential outcomes of a levee constructed with a geometry comparable with the test levee site, with soil properties that may represent the conditions that the soil has degraded to due to weathering.

Discussion

According to the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) "State Climate Summary for Mississippi," the temperature in MS rose only 0.5°C (0.1°F) on average since 1900 but could rise

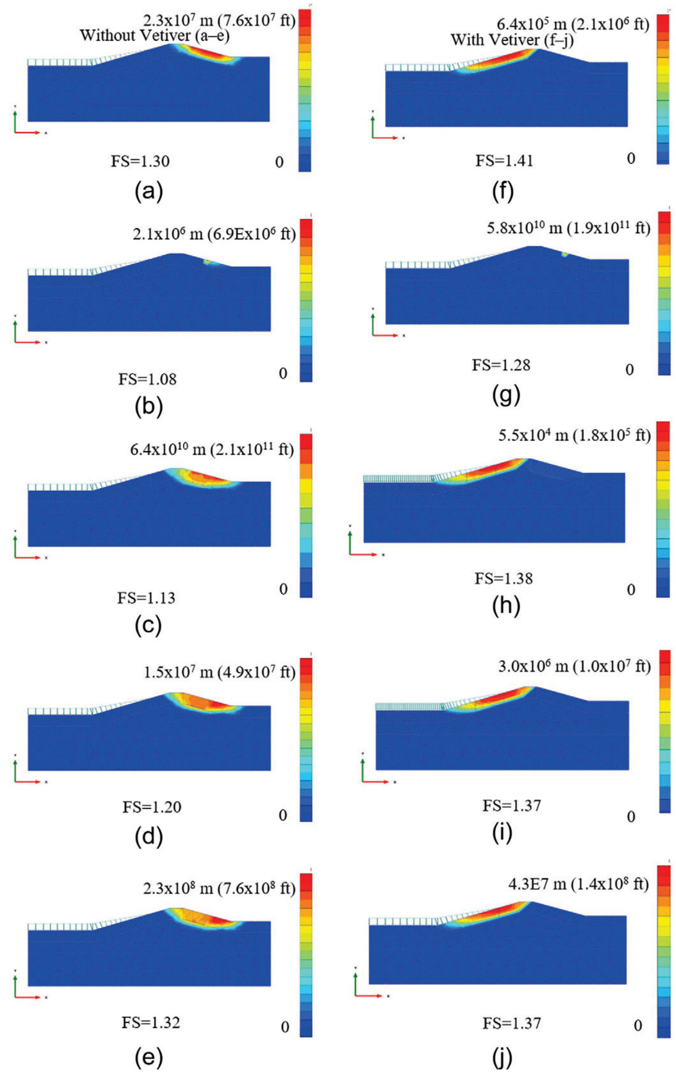

Fig. 7. Factor of safety for levee (a–e) without vetiver; and (f–j) with vetiver during one-day 500 year storm.

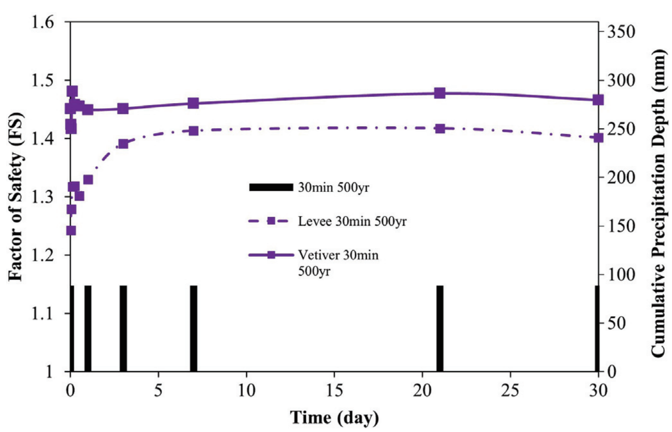

Fig. 8. Factor of safety versus time, levee with and without vetiver for 30-min 500 year storm.

as much as 7.3°C (13°F) if the higher emissions, such as greenhouse gases emissions, projected between 2022 and 2100 occur (Lukas et al. 2022). Even with the low rise in temperatures, MS's annual precipitation and number of 76.2 mm (3 in.) extreme precipitation

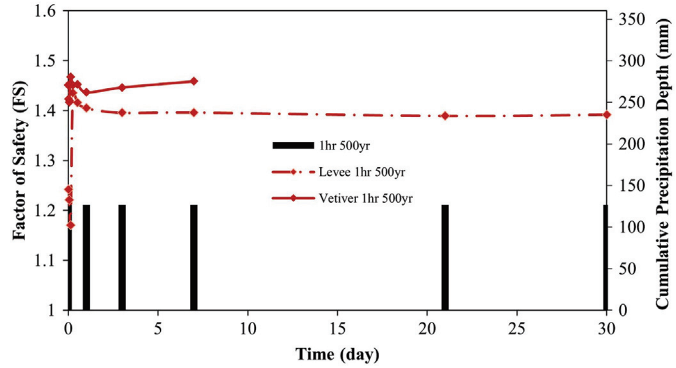

Fig. 9. Factor of safety versus time, levee with and without vetiver for 1 h 500 year storm.

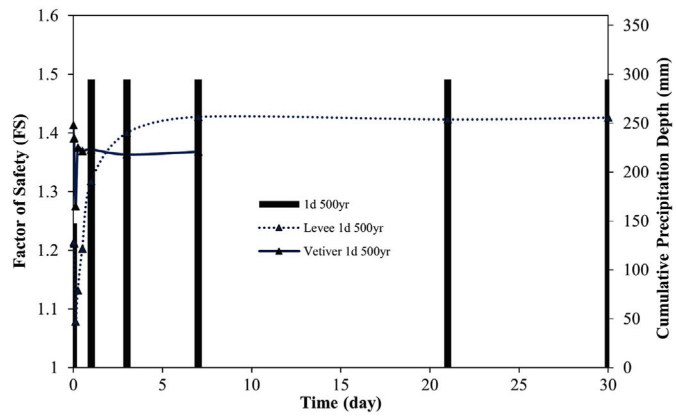

Fig. 10. Factor of safety versus time, levee with and without vetiver for one-day 500 year storm.

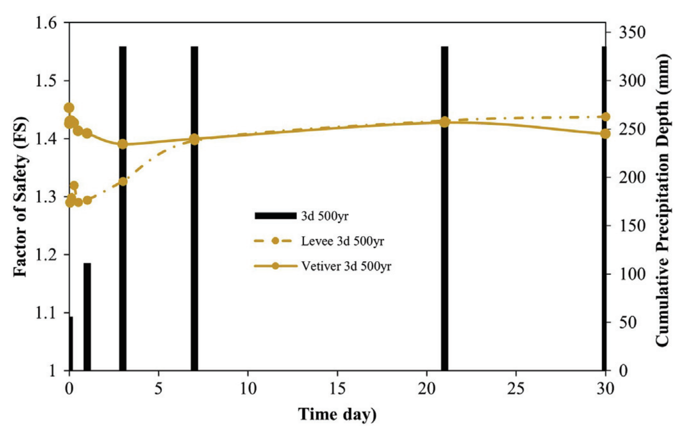

Fig. 11. Factor of safety versus time, levee with and without vetiver for three-day 500 year storm.

events are greater than the national average based on charts prepared by North Carolina State University for the national climate summary. MS's precipitation increasing at a rate greater than the national average can be observed when comparing its annual precipitation in 2011 and 2021 with the nation's, as provided in Table 3 (NOAA NCEI 2022). Table 3 also compares MS's precipitation with other states in the Gulf Coast Region. In 2011 and 2021, MS's

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Table 3. 2011 and 2021 annual precipitation

State	2011 annual rainfall [mm (in.)]	2021 annual rainfall [mm (in.)]	Increase in rainfall [mm (in.)]
Alabama	1,288 (50.7)	1,655 (65.2)	367 (14.4)
Florida	1,188 (46.8)	1,406 (55.4)	218 (8.6)
Louisiana	1,092 (43.0)	1,688 (66.5)	596 (23.5)
Mississippi	1,342 (52.8)	1,695 (66.7)	353 (13.9)
Texas	373 (14.7)	732 (28.8)	359 (14.1)
US	764 (30.1)	773 (30.4)	9 (0.4)

Source: Data from NOAA NCEI (2022).

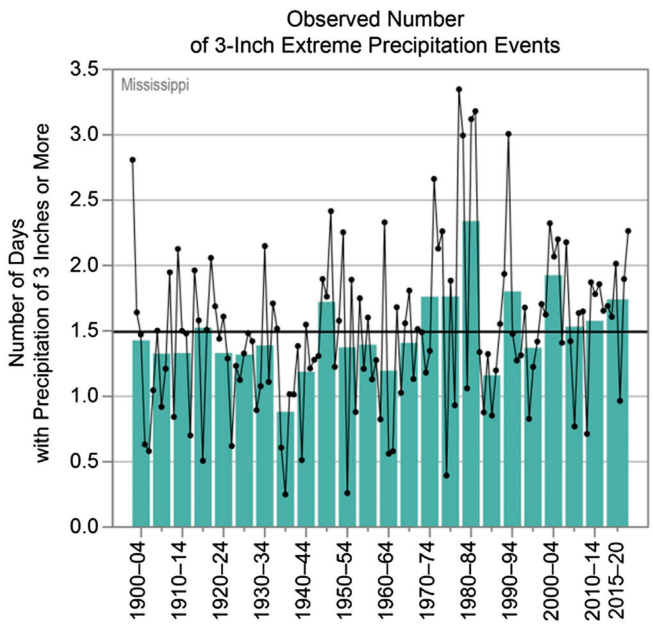

Fig. 12. Observed number of 76.2 mm (3 in.) extreme precipitation events in Mississippi. (Adapted from Runkle et al. 2022.)

annual rainfall was greater than other states in the region; however, MS did not experience the greatest increase in rainfall between these years. Fig. 12 shows that the average number of days that 76.2 mm (3 in.) or more of rainfall occurs in MS is 1.5 days between 1900 and 2020 (Runkle et al. 2022). The annual averages are provided by dots, whereas the bars represent the averages over a five-year period with an exception to the last bar, which represents a six-year period (2015–2020). Between 2000 and 2020, it can also be observed that the five-year averages exceeded the overall average of 1.5 days, indicating that extreme rainfall events have, on average, lasted longer in the new millennium. This consistent upward trend of the number of days of extreme rainfall over the last 20 years is not observed anywhere else in history. The state of climate in MS requires preparation to combat exacerbated conditions of collapsible and expansive soils used often for maritime and multimodal infrastructure.

By observing the field monitoring results at the test levee site, the changes in moisture content and matric suction were observed; however, the anticipated behavior of the soil to collapse following extreme rainfall was not present in the test section nor adjacent areas. With the moisture content of the loess below field capacity, the vetiver plantation may require soil and soil-root samples adjacent to and within the test section to determine the soil root composite index and strength properties with originally planted grasses and the soil root composite with vetiver, when monitoring a control section is not feasible. Changes in moisture content and matric suction provide insight into the pore pressures of the soil-composite, which directly impact shear strength. Due to the high infiltration rate of loess and its reduced surficial thickness in Jackson, MS, Yazoo clay was a better candidate to consider storms comparable with the August 2022 storm. In May 2022, approximately 5,000 vetiver plant tillers were planted on a 4.6 m (15 ft) high transportation embankment in MS for stabilization of the slope following a couple of rain-induced shallow failures. This constructed slope has a surficial layer of Yazoo clay. The August 2022 storm caused a localized failure within the already failed section of the embankment. The numerical analysis' saturation and matric suction values did not vary as much between the levee without vetiver and the levee with vetiver. Therefore, the effects of seepage on the soil root composite also need to be further investigated on a slope whose geometry creates conditions where the vetiver section would still be the most critical following plantation, rather than the critical failure surface moving to the upstream slope following plantation. In areas of MS, where both soils are present, understanding the behavior of these soils under excess moisture and determining if the soil is more stratified (loess and clay are separate), or if the loess contains a high percentage of clay fines, would be critical to further determining the improvement of shear strength and other properties provided by vetiver.

Summary and Conclusion

Bioinspired slope improvements can improve slope stability in ways comparable with traditional slope stability techniques; a change in culture, however, must occur to adjust to using more labor with minimal equipment and learning more about trees, lumber, vegetation, and other plant material, living or dead, that are most suitable to the soil conditions presented at each site. While natural disasters that cause catastrophic infrastructure failures are at the forefront of concern, frequently occurring shallow slope failures take away from the funds available to maintain fair to moderate infrastructure before these catastrophes occur.

Maritime and multimodal transportation earthen infrastructure experiences adverse environmental impact due to climate and lifecycle degradation. Vetiver grass is widely adaptive to various climates and can mitigate the rain-induced slope instability of earthen infrastructure constructed using loess or clay, such as levees. With grassroots that can extend to depths greater than 3 m (10 ft), a new composite material with the grassroots and soil has been demonstrated to increase shear strength to combat shallow slope failures that typically occur between 1.8–2.4 m (6–8 ft) depths. Earthen infrastructure constructed using low plasticity silt, such as Peorian loess, and high-plasticity clay, such as weathered Yazoo clay, succumbs to increased precipitation by reducing its stability in some cases. Greenhouse gas emissions are affecting MS by increasing temperatures and precipitation, among other climate-related changes. This study determined that vetiver is feasible to plant on a levee constructed of collapsible Peorian loess in MS and can be considered for use in other MS problematic soils, such as Yazoo clay. There is also a need to determine how many levees are constructed with these soils. The test levee did not show signs of seepage on the downstream slope or toe for the duration of this study. The FEA analysis provided insight regarding the effects of extreme rain events on a comparable levee constructed in Yazoo clay with to consider the August 2022 storm event in Jackson, MS.

A FEA analysis modeled the effect of extreme precipitation for a slope with a 3H:1V upstream and downstream slope, with a height

3.7 m (12 ft) above the downstream toe, as with the test levee section at ERDC. Using the 500 year precipitation intensity-duration-frequency curves of Jackson, MS, the saturation, suction, and total displacement were determined for each rain event. The factor of safety values was higher for slopes with the vetiver planted on the downstream slope of the modeled levee, due to the increased shear strength of the weathered Yazoo clay.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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