Development of a Risk Assessment Curve for a Highway Section with Numerical Modeling

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ABSTRACT

As climate change accelerates the frequency and intensity of extreme rainfall events, flood risk management has become increasingly critical, especially in flood-prone regions. This study presents a comprehensive approach to assessing the structural integrity of a highway section subjected to varying precipitation conditions. By employing Depth-Duration-Frequency (DDF) curves and advanced numerical modeling through Plaxis, factors of safety under different hydrological scenarios are determined. The DDF curves allow for the modeling of extreme rainfall events, providing realistic flood loading conditions that are applied to the highway section for analysis. Computed safety factors serve as inputs for the development of a fragility curve, which quantifies the probability of the failure of highway embankment slope under different stress conditions. The risk assessment curve is a critical tool for evaluating the resilience of flood defense structures, enabling better risk assessment and management strategies. This study provides a framework for balancing infrastructure investments with risk reduction efforts, offering insights to mitigate flood-related damages of highway embankments in a rapidly changing climate. This study advances the understanding of flood-induced risks and provides practical solutions for enhancing highway transportation safety. The findings are especially relevant for regions vulnerable to climate-driven flood hazards, offering a data-driven approach to improving erosion resilience and minimizing potential socio-economic impacts.

INTRODUCTION

Climate change has amplified the frequency and intensity of extreme weather events like floods and heavy rainfall, posing significant risks to infrastructure worldwide. These events erode foundations, destabilize slopes, and disrupt transportation networks. Rainfall-triggered landslides are typically studied using extreme rainfall estimates, which are based on the idea that the patterns of extreme events will stay mostly the same over a long time (Robinson et al., 2017). Proactive measures based on weather forecasts are essential to mitigate damage, requiring a thorough understanding of how structures respond to such stresses. Soil water content plays a critical role in stability, as seasonal variations influence pore pressures and soil strength, directly affecting embankments and highway slopes. A soil-water characteristic curve represents the relationship between soil suction (matric suction) and either the water content or the degree of saturation. Essentially, it reflects the soil's water storage capacity for a given level of suction. Traditionally, these curves (SWCCs) are obtained in the laboratory using a pressure plate apparatus, which does not allow for the application of vertical or confining stress (Ng & Pang, 2000). With intense rainfall events increasing by 20% over the last century, this trend underscores the urgent need for climate-resilient infrastructure planning (Stewart et al., 2011). According to the National Oceanic and Atmospheric Administration (NOAA), the United States has experienced significant changes in precipitation over the past century. The National Oceanic and Atmospheric Administration reports that precipitation patterns in the United States have undergone notable changes over the past century. Increased precipitation significantly affects soil mechanics and stability by raising soil bulk density and reducing shear strength, making it more prone to deformation and failure (Havaee, S., 2015). Prolonged high-water tables exacerbate the issue by lubricating mineral contact surfaces, reducing inter-particle friction, a crucial factor in the shear strength of granular soils (Crozier, 2010).

Increased precipitation impacts soil stability by raising bulk density and reducing shear strength, making soils more prone to deformation and failure. Prolonged rainfall leads to perched water tables, enhancing seepage and drag forces that can trigger piping and undermine structural integrity. These hydrological changes often destabilize slopes and embankments, leading to shallow failures requiring costly maintenance. Preventative measures are essential but rely on a clear understanding of subsurface soil and water conditions (Mourin, 2018). In Mississippi, expansive clay damage is largely due to Yazoo Clay, prevalent in several counties. The soil is divided into three zones: Zone A features a thin, highly weathered, organic-rich silty clay layer influenced by weathering processes, while Zone B consists of a thicker, stiff clay layer with deep desiccation cracks often filled with selenite crystals. These characteristics contribute to the region's soil stability challenges.

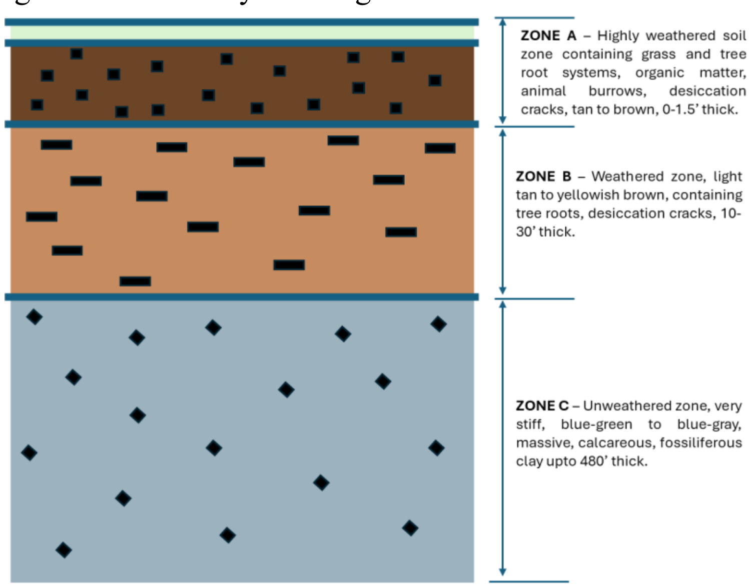


Figure 1: Generalized vertical profile of Yazoo Clay

Yazoo Clay, rich in montmorillonite, is a poor foundation material due to its significant volume changes with moisture. Wet conditions reduce shear strength, while drought-induced cracks allow water infiltration, weakening slopes. The clay's plate-like structure expands when wet and shrinks when dry, causing instability, deformation, and slope failure.

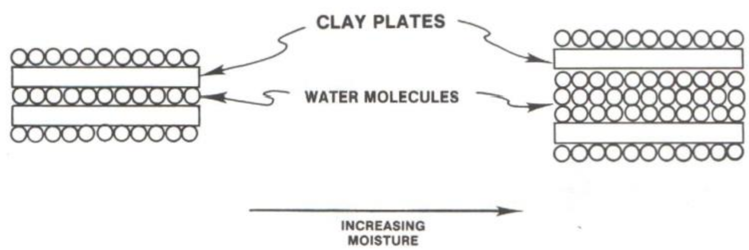


Figure 2: Physical change in expansive clay due to moisture

Clay particles, with their plate-like structure, expand when wet and shrink when dry, leading to soil volume changes. This process weakens slope stability by reducing soil strength during expansion and creating cracks during shrinkage, increasing the risk of slope deformation and failure (Khan et al., 2017). The primary objective of this research is to quantify the effects of future climate change on the stability of typical highway soil embankments throughout Mississippi. Finite Element Methods (FEM) have been used to simulate the impacts of extreme events on slope stability. The resulting fragility curve offers a quantitative assessment of the likelihood that a highway embankment slope will experience varying levels of damage under specific loading conditions.

METHODOLOGY

A highway slope in Jackson area of Mississippi has been selected to conduct this study. The climate of the study area is humid sub-tropical with an average annual rainfall of 57.35 inches (1,457 mm). The region experiences rainfall throughout the year. Winter and Spring are the wettest seasons while September and October are usually the driest months ("Jackson, Mississippi," 2024). Typically, the monsoon season brings intense rainfall that significantly impacts slope stability. The average temperature of the study area ranges from 38ºF to 93ºF. The geological composition of the study area is mostly Yazoo clay.

The slope is located along I20E near McRaven Road. The slope is 4H:1V with a height of 15 ft. Some sections of the slope had shown movement before, so they were rebuilt, re-graded, and the drainage system was restored. For this study, only the as-built section is considered. The exact co-ordinate of this slope is 32°17'45.71"N, 90°16'17.17"W.

Advancements in technology have made it easier to simulate how structures behave under different conditions, helping engineers plan maintenance and improve safety (Latief & Zainal, 2019). Tools like REF-ET, which calculate water loss through plants and soil, and

PLAXIS 2D, a software for analyzing soil and slope stability, play a key role in understanding these behaviors. The fragility framework is used to assess how likely structures are to fail during extreme events, using factors like slope angle, soil strength, water content, and external forces (Kadkhodayan et al., 2015). This helps engineers design stronger, more resilient infrastructure and better prepare for disasters.

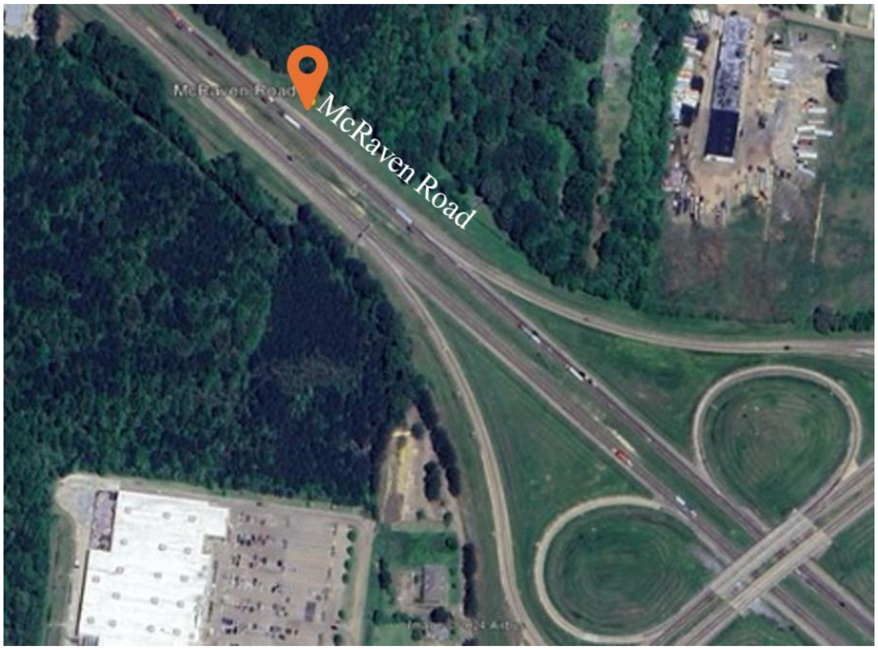


Figure 3: Location of the Study Area

This study analyzes the infiltration and deformation behavior of embankment slopes under extreme climatic conditions, focusing on Mississippi's highway embankments (Lu et al., 2013). The methodology integrates data collection, rainfall return period analysis, numerical simulations, model validation, and fragility analysis to provide a holistic assessment of slope stability.

(i) Data Collection: Data were collected from field measurements and historical records. Instruments such as inclinometers, piezometers, and weather stations monitored slope movement, pore water pressure, and climatic conditions. Soil properties, including shear strength parameters, were determined through laboratory testing and in-situ geotechnical investigations.

(ii) Rainfall Return Period Analysis: The study utilized statistical techniques to estimate 100- and 500-year-rainfall return periods, representing extreme precipitation scenarios. These projections were based on NOAA's climatic data and hydrological models, providing a foundation for assessing future climate impacts.

(iii) Numerical Analysis: PLAXIS 2D, a Finite Element Method (FEM) software, was employed to simulate the effects of projected extreme events on slope stability. The numerical model incorporated soil-water characteristic curves (SWCC) and Van Genuchten parameters to analyze seepage and deformation under varying rainfall intensities.

(iv) Model Calibration and Validation: Model accuracy was ensured through calibration using field data and validation against observed slope behavior. Displacement, pore water pressure, and factor of safety (FS) were compared to validate the predictive capabilities of the model.

Table 1. Soil properties for Finite Element Method Analysis

Parameter	Symbol	Unit	Slope 1 (I20 at McRaven Rd.)		Slope 2 (I20 at Terry Rd.)	
			Unweathered Yazoo Clay	Weathered Yazoo Clay	Unweathered Yazoo Clay	Weathered Yazoo Clay
SOIL PROPERTIES						
Bulk Unit Weight	Υ_{unsat}	kg/m^3 (pcf)	2027.94 (126.6)	2058.37 (128.5)	2027.94 (126.6)	2016.72 (125.9)
Saturated Unit Weight	Υ_{sat}	kg/m^3 (pcf)	2027.94 (126.6)	2151.28 (134.3)	2027.94 (126.6)	2160.89 (134.9)
Modulus of Elasticity	E	kg/m^2 (psf)	9.7E+05 (1.98E+05)	7.2E+05 (1.48E+05)	9.7E+05 (1.98E+05)	7.2E+05 (1.48E+05)
Poisson's Ratio	N	-	0.25	0.3	0.25	0.3
Cohesion	c	kg/m^2 (psf)	488 (100)	146 (30)	1875.82 (384.2)	1318.25 (270)
Friction Angle	ϕ	degree	15	8	20	21
HYDRAULIC PROPERTIES						
Permeability	$k_x=k_y$	m/day (ft/day)	2.6E-03 (8.60E-03)	2.6E-03 (8.60E-03)	2.6E-03 (8.60E-03)	2.6E-03 (8.60E-03)
Residual Saturation	S_{res}	-	0.1283	0.1283	0.1283	0.1283
Van Genuchten Parameters	g_a	1/m (1/ft)	0.04902 (0.01494)	0.04902 (0.01494)	0.04902 (0.1494)	0.04902 (0.1494)
	g_n	-	1.08	1.08	1.08	1.08
	g_l		0.074	0.074	0.074	0.074

(v) Fragility Analysis: A fragility framework was developed to quantify the probability of slope failure under different rainfall scenarios. Fragility curves were constructed based on numerical simulations, accounting for variables such as slope angle, soil properties, and water content. These curves provide a probabilistic assessment of slope vulnerability, aiding in risk-based decision-making.

This methodological approach combines field data, advanced simulations, and probabilistic analysis to assess the resilience of highway embankments under climate-induced stresses, supporting the development of sustainable infrastructure solutions.

RESULTS & DISCUSSION

Rainfall data from NOAA (1963–2024) was validated with field measurements to assess slope stability under extreme weather. ECRN-50 tipping-bucket rain gauges, EM50 data recorders and RT-1 air temperature sensors were installed in the study location. Station USW00003940 (Jackson International Airport) was selected for its broader dataset, showing good correlation with field data (MAE: 0.3169, RMSE: 0.7531). Annual maximum rainfall trends revealed frequent extreme events (≥3 inches) in Mississippi, posing significant risks to slope stability, especially with expansive Yazoo clay. The observation is computed from September 8th, 2018, to March 31st, 2020. Long term data allows for the identification of trends and patterns that might not be evident in short term datasets. This is particularly important for the rainfall return period determination.

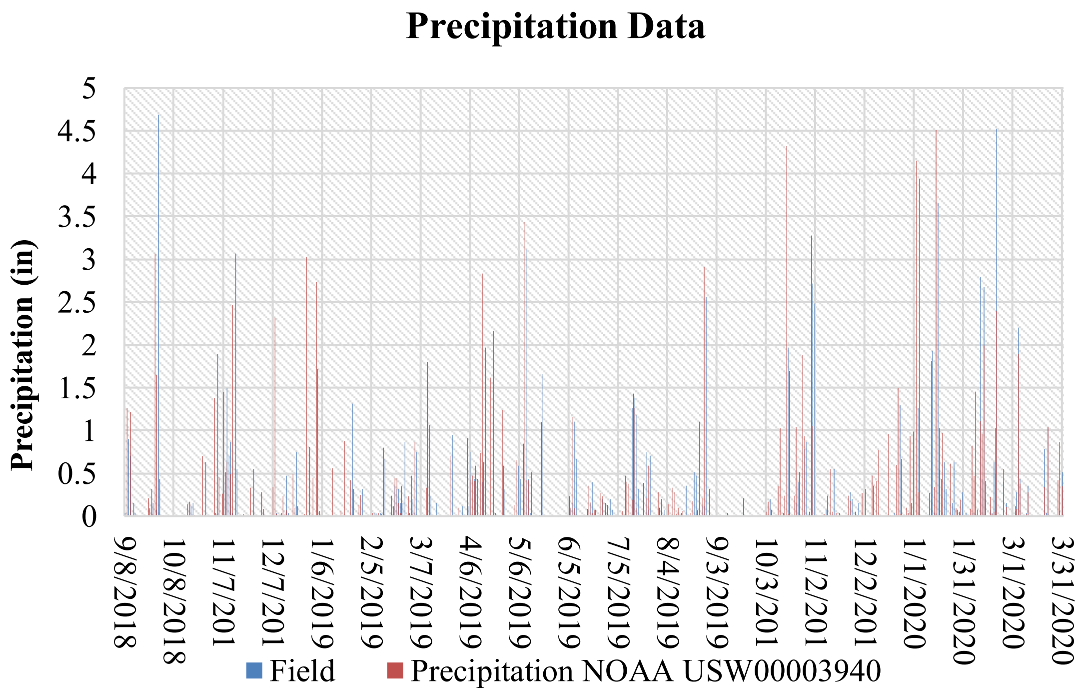


Figure 4: Precipitation pattern in Study Area (a) Variation of sensor observed data and NOAA data

With large sample data points statistical analyses are more likely to be significant as they have been trained and validated on a wider range of conditions and scenarios. With the help of rainfall data of 61 years, anomalies and outliers were identified and inconsistencies were identified and corrected. Four specific rainfall durations 5 mins, 10 mins, 15 mins and 30 mins of rainfall were selected to represent short-duration, high-intensity rainfall events that are critical for urban drainage and flood management. The annual maximum rainfall data were extracted from the datasets. Various statistical distributions are available to fit distributions to estimate rainfall intensities corresponding to various return periods, including the 1,000-year return period, while exercising caution due to the uncertainties associated with extrapolating beyond the observed data range. The calculated rainfall depths were finally plotted against their respective durations for each return period to develop the DDF curves, with each curve representing a different return period and illustrating the relationship between intensity, duration, and frequency.

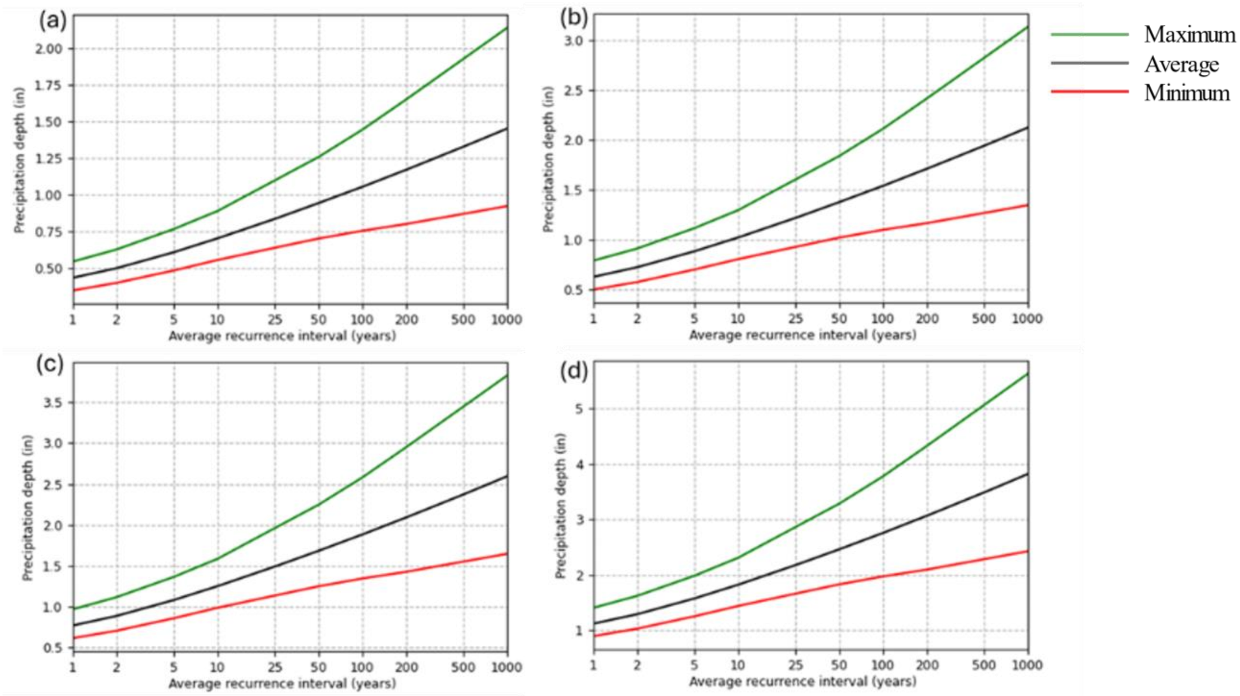


Figure 5: Rainfall Return Period (a) 5 mins, (b) 10 mins, (c) 15 mins, (d) 30 mins

The Net Infiltration Value (NIV) was estimated using evapotranspiration (ETo from REF-ET), precipitation, and runoff calculated via the Curve Number (CN) method, which accounts for land use, soil, and hydrological conditions. ETo, representing short grass evapotranspiration, was preferred due to field grass cover and determined using ASCE, FAO-Penman, and Hargreaves methods.

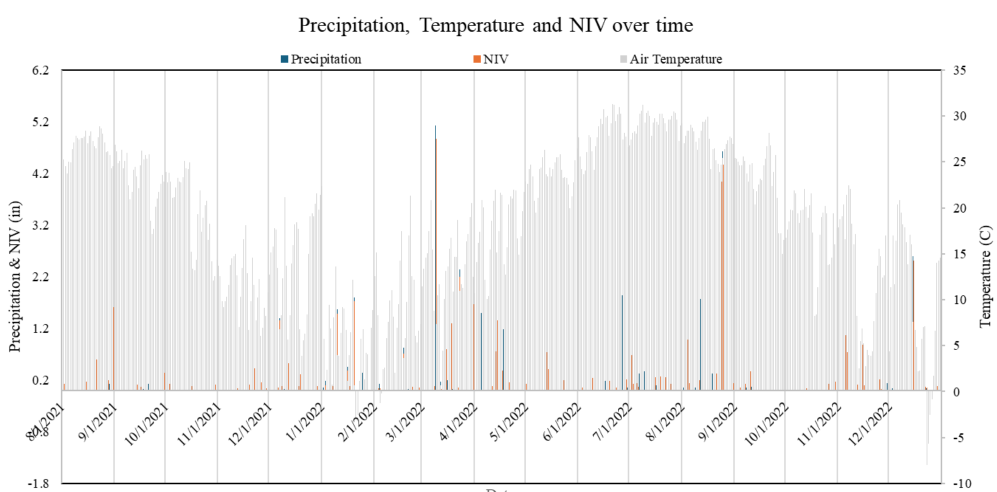
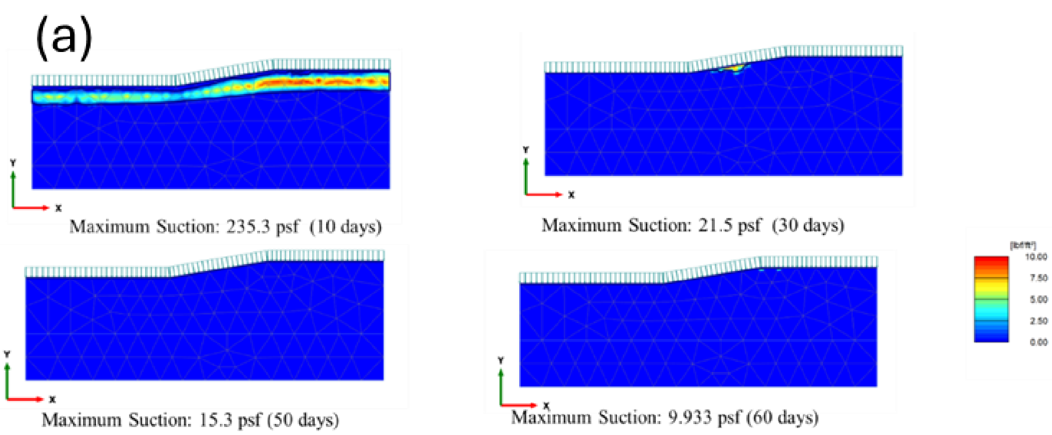


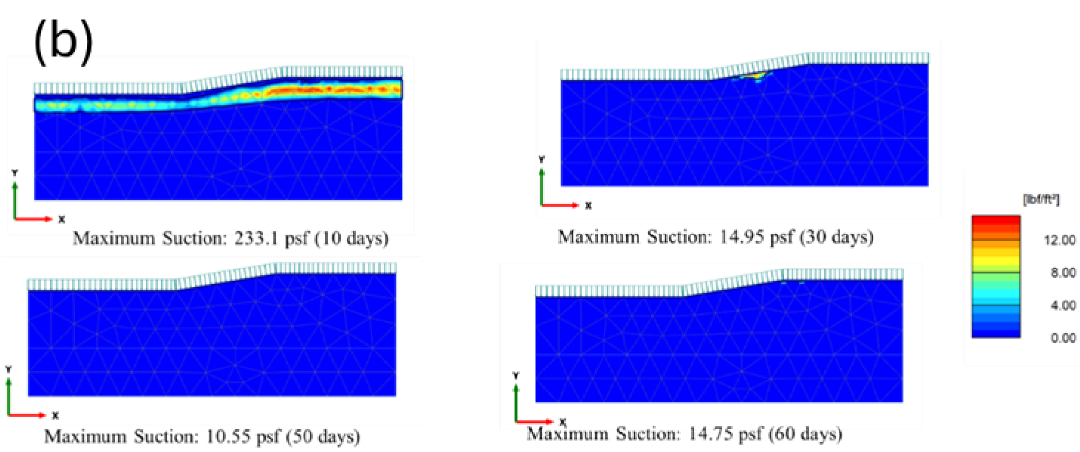
Figure 6: NIV with the variation of precipitation

The Net Infiltration Value (NIV) was calculated by subtracting runoff and evapotranspiration from total precipitation, indicating the water available for soil infiltration and groundwater recharge.

Figure 6 represents the variation of NIV with precipitation and temperature. For higher temperature the gap between precipitation and NIV increases, indicating increased evapotranspiration due to the temperature.

The rainfall analysis identified 2003 as the year with the highest maximum rainfall. Using PLAXIS 2D, simulations for 100- and 500-year rainfall return periods were conducted for various durations (5, 10, 15, and 30 minutes). The numerical model was calibrated using field conditions, including groundwater table depth, friction, cohesion, and shear strength, based on previous MDOT studies. Stability, deformation, and coupled flow-deformation analyses were performed on calibrated models of slopes 1 and 2, incorporating soil properties and geometric parameters. As a result, each model analysis underwent a total of 26 phase runs, beginning on December 1st, 2019, and ending on March 31, 2020. The analysis's rainfall phases were all followed in order. From numerical analysis, displacement of both of the slopes and suction was determined for 100 years and 500 years with 5 mins, 10 mins, 15 mins, 30 mins, 1 hour, 6 hours, 12 hours and 24 hours. Displacement result shows the gradual changes in the slope and suction shows how the soil gets saturated over time. From numerical analysis the deformation occurred at 10, 30, 50 and 60 days are shown here.





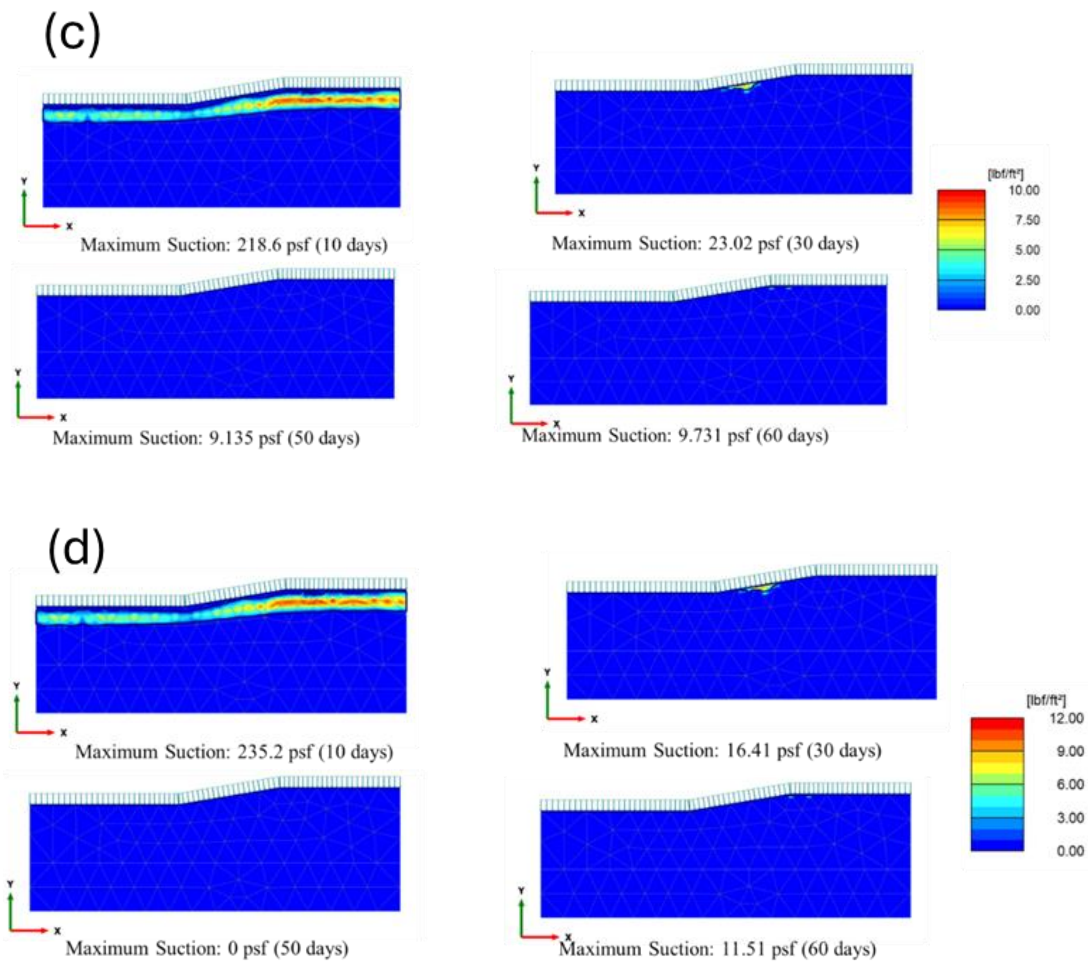
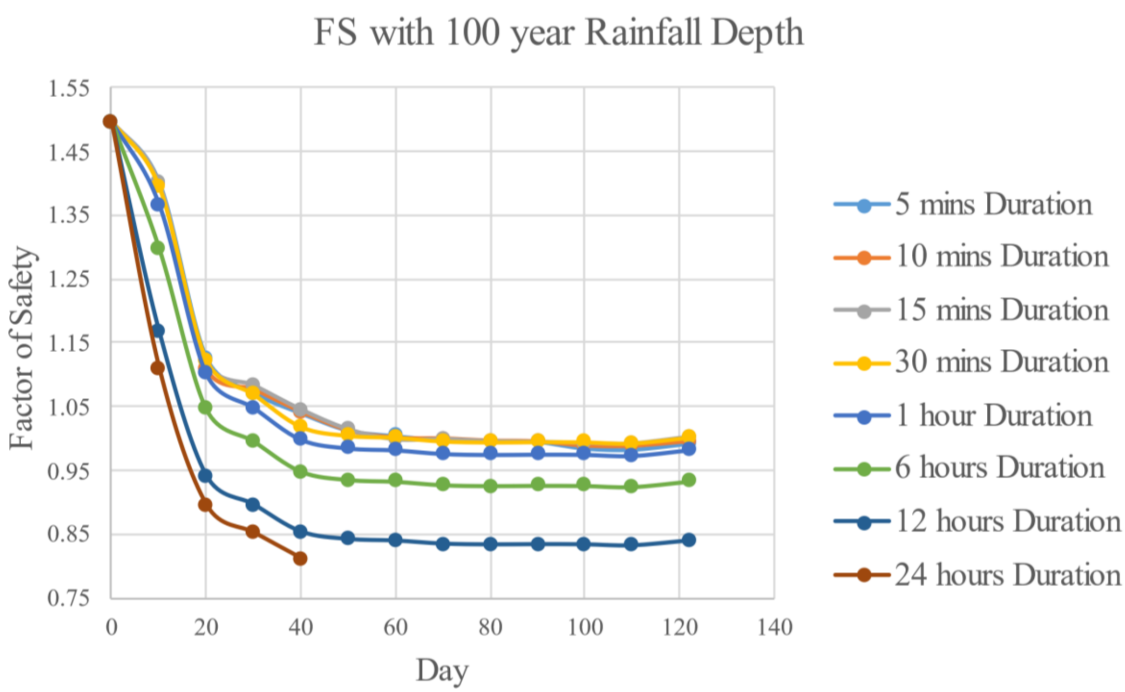


Figure 7: Matric Suction for 100 years and 500 years rainfall in McRaven Road (a) displacements for 100 years rainfall with 15 mins duration, (b) displacement for 100 year rainfall with 30 mins duration, (c) displacements for 500 years rainfall with 15 mins duration, (d) displacement for 500 year rainfall with 30 mins duration

From numerical analysis it is visible that the matric suction reduces as duration of rainfall increases. The presence of moisture in soil reduces matric suction. As duration of precipitation increases, the desiccated crack on the surface infiltrates more water in the soil resulting in less matric suction. (Ma & Liu, 2021). This increases stress within the soil, leading to greater slope instability (Sun et al., 2015). Shorter rainfall durations lead to higher intensity, causing rapid infiltration and pore pressure buildup, which reduces soil shear strength and increases deformation (Borja & White, 2010).

The changes in factor of safety with 100 years and 500 years rainfall return period with different durations were calculated during the finite element analysis. These results are presented in figure 8. The factor of safety reduces as the rainwater sits longer on the slope. For rate of FS reduction is higher for 500 year rainfall than 100 year rainfall return period as the precipitation intensity is higher for 500-year rainfall.

(a)



(b)

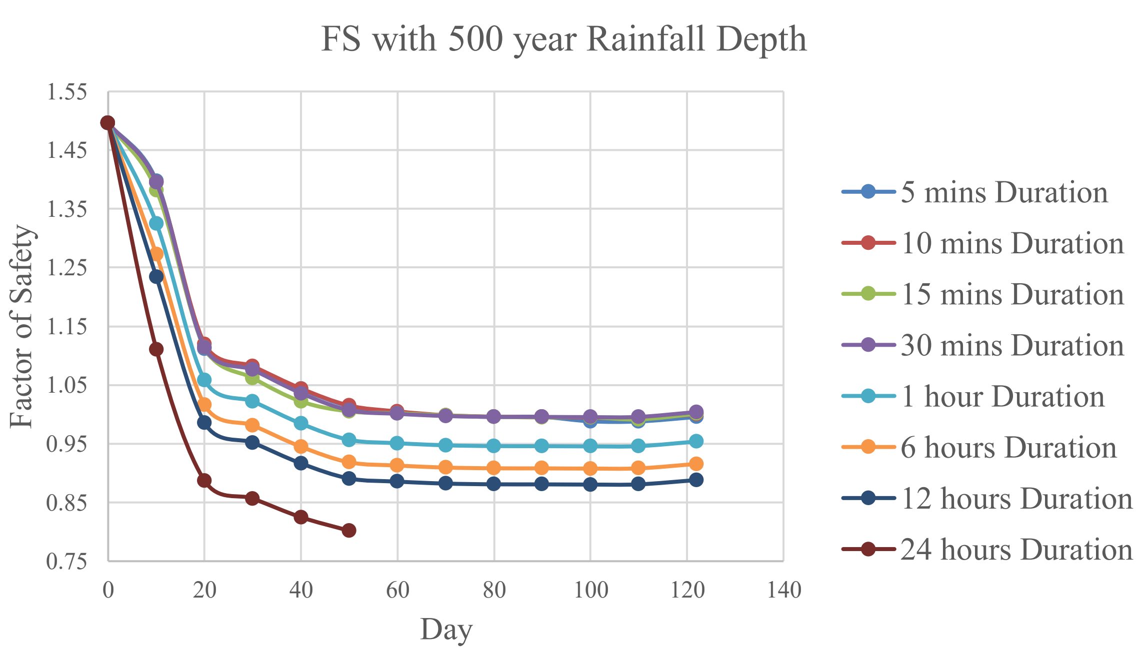


Figure 8: Change of FS with (a) 100-years and (b) 500-years rainfall return period at various duration

Fragility curves for McRaven Road and Terry Road highlight differing vulnerabilities to rainfall-induced damage. McRaven Road shows a steep increase in damage probability with small rainfall increments, indicating high vulnerability. These curves visually represent damage probabilities at various rainfall depths, aiding in risk assessment and mitigation planning (Mander, n.d.).

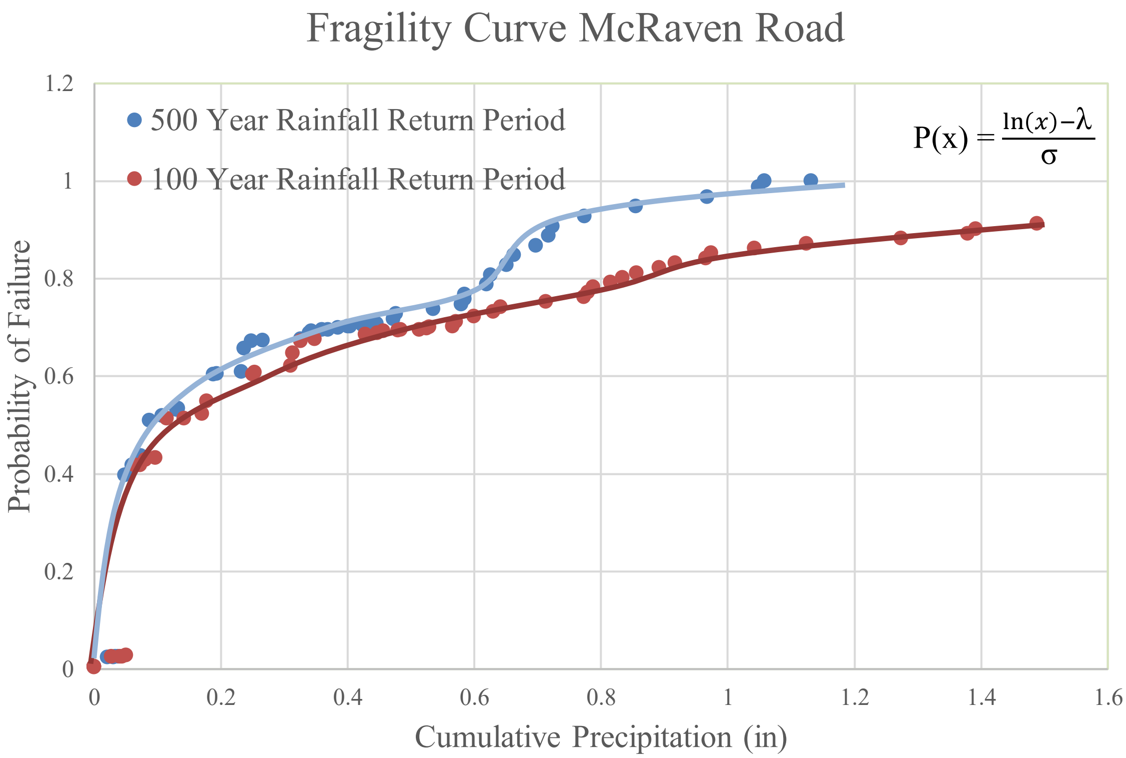


Figure 9: Risk Assessment Curve for McRaven Road

The fragility curve for McRaven Road reveals that the probability of slope failure increases significantly with cumulative precipitation, particularly under 500-year return periods. This underscores the road's heightened vulnerability to extreme rainfall events, emphasizing the need for targeted mitigation measures.

Conclusion

This study examines rainfall-induced slope instability in Mississippi, with a focus on McRaven Road. Long-term data from NOAA revealed significant rainfall trends, showing that extreme events exceeding 3 inches in a day pose serious risks, especially on expansive Yazoo clay. Simulations using PLAXIS 2D highlighted that intense rainfall leads to greater slope deformation and higher failure probabilities. Fragility curves showed that McRaven Road is more vulnerable to flooding, with damage escalating quickly. These findings provide valuable insights for designing better infrastructure, managing risks, and developing mitigation strategies for areas prone to extreme rainfall.

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