DAM SAFETY 40TH ANNIVERSARY 1984 → 2024

Levee Structural Resilience Under Historical Rainfall and Flood Hydrograph using Transient Finite Element Analysis

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ABSTRACT

This study assesses the impacts of precipitation load and infiltration on levee structure, along with the flood hydrograph on a Levee section at the Mississippi east levee system at Norfolk North of Mississippi. With the emerging climate change impact, the trend in precipitation intensity, duration, and frequency has been changing considerably. Coupled flow deformation and safety analysis were performed on the levee section using Finite Element Method (FEM) software PLAXIS 2D. Historical rainfall and flood hydrograph was used as an infiltration and seepage loading. Transient analysis was performed to investigate the temporal effect considering the unsaturated soil behavior of the levee. The geometry and site condition of the levee were determined by using 2D Electrical Resistivity Imaging. With different infiltration conditions due to the historical rainfall, a factor of safety analysis was performed concurrently to determine the factor of safety of the levee slopes before and after the rainfall. This study gives insight into how a levee structure can be made climate-resilient utilizing the trend of historical analysis results. Incorporating historical precipitation loads and analyzing the stability condition will ensure the public safety of levees and help make the levees more resilient in different climate conditions.

I. INTRODUCTION

The Mississippi River's levee systems are important barriers that safeguard the alluvial valley's extensive and developed lands from the recurring threat of floods. These levees' effectiveness is very important in preventing the enormous economic and ecological damage that can result from flooding. Given this critical role, understanding the factors influencing levee stability is not just a technical necessity but is of societal importance. The combination of field investigation and Finite Element Method (FEM) analysis altogether brings out the actual scenario of the levee system. The effect of seasonal weather pattern along with rainfall and the changes in residual strength and changes in levee performance is an important factor to consider for the safety of the levee protected area. Levees and dams are provided to give protection to the people living on the floodplain area. The term called “Levee Paradox” highlights the importance of considering long-term and holistic approaches in flood management strategies. The "levee paradox" refers to a counterintuitive situation in flood management where the construction of levees to protect land from flooding can, over time, lead to increased flood risk and potentially more severe flooding events. This study focuses on assessing levee stability by correlating FEM and field investigation data with climate change patterns. The co-relation between field investigation and numerical analysis plays a significant role in addressing the levee paradox by providing enhanced understanding of levee vulnerabilities, data-driven levee management, informed urban planning, public awareness and preparedness, policy and investment and resiliency and adaptation. The main objective of this study can be summarized as conducting FEM analysis incorporating climate change patterns and developing a relationship between numerical analysis and field analysis. The study aims to understand how climate change impacts slope stability by integrating field measurements, climate analysis, and numerical modeling. By utilizing techniques such as Electrical Resistivity Imaging (ERI) and Finite Element Method (FEM) analysis, the research seeks to establish correlations between changing climate patterns, soil saturation levels, and slope stability. There have been several interior flooding incidents due to extreme rainfall in the New Orleans East Bank area. With a total of estimation 105000 acre-ft of water, the contribution of levee breach was 66% (1). Mississippi has faced many disastrous floods such as flood of 1927, The Great Flood of 1993 and so on (2). Levee breaches can occur due to various reasons. Some of the frequent reasons are overtopping, seepage and piping, erosion, slope instability due to soil saturation (3). Many studies have come to the conclusion that lack of resilience studies in dam and levee construction play a major part in these failures. Resilience studies help identify potential risks and vulnerabilities in systems, allowing for proactive measures to mitigate these risks (4).

Advancements in analytical methods have significantly improved Finite Element Method (FEM) analysis for levees and dams, particularly through enhanced geotechnical applications. Software like PLAXIS now allows for detailed simulations of soil-structure interactions, incorporating complex soil behavior under varying conditions. Rainfall-runoff calculations have been integrated into FEM models to simulate the hydrological impact on levees, providing a comprehensive understanding of how rainfall and runoff contribute to potential failures. Furthermore, the development of fragility frameworks has enhanced risk assessment by quantifying the probability of failure under different scenarios. These frameworks integrate FEM results with statistical methods to evaluate the vulnerability of levees and dams, offering a robust tool for designing resilient infrastructure.

This study addresses several critical gaps in current research and highlights the inadequacies of traditional methods. Traditional methods for assessing levee structural resilience often rely on simplified soil characterizations and static hydrological models, which do not capture the complexity of real-world conditions. These methods typically use borehole data and standard soil testing, which provide limited and often spatially sparse information about subsurface conditions. This approach fails to account for the inherent variability and heterogeneity of soil properties, leading to less accurate predictions of levee performance. Furthermore, traditional hydrological models generally assume uniform rainfall distribution and steady-state conditions, overlooking the temporal and spatial variations in rainfall intensity and runoff patterns that occur during extreme weather events. This simplification can result in significant underestimation of peak water levels and pressures exerted on the levee. ERI provides high-resolution, continuous profiles of subsurface resistivity, which can be correlated with soil moisture, porosity, and other geotechnical properties. This detailed characterization allows for the development of more accurate and realistic FEM models that better reflect the actual conditions within the levee. Additionally, by incorporating detailed rainfall-runoff calculations into the FEM analysis, this study accounts for the dynamic nature of extreme weather events. This approach enables the simulation of transient water flow and pressure conditions, providing a more comprehensive understanding of the levee's behavior under various stress scenarios. As a result, the combined use of ERI and advanced hydrological modeling leads to more reliable predictions of levee resilience and performance, addressing the key limitations of traditional methods.

Understanding the levee health condition under different extreme event scenarios helps `determining the overall condition of the levee. This study provides a great example of developing targeted maintenance and modification strategies based on identified weak points and critical areas within the levees. It also helps to identify the potential failure mechanisms as it indicates the internal erosion or development of failure surface. This study is required for every levee system, for the safety and security of people living near it. This holistic approach provides insights into the vulnerability of slopes to climate-induced hazards. The findings will inform strategies for mitigating risks, enhancing infrastructure resilience, and optimizing land-use planning in the face of evolving climatic conditions. Overall, the study aims to contribute to a better understanding of the complex interactions between climate change and slope stability dynamics.

II. LITERATURE REVIEW

Over time, a variety of numerical analysis approaches have been developed to establish methodologies for preventing accidents resulting from slope instability. The Finite Element Method (FEM) offers several significant advantages over traditional limit equilibrium methods in slope stability analysis. These include the ability to model strain hardening, softening, and progressive failure, providing more accurate predictions beyond initial failure; the capability to simulate stresses and strains within the slope under specific conditions, aiding in targeted field inspections for potential issues; and the proficiency to model staged construction of slopes, addressing time and strain-dependent consolidation problems (5). The principle of FEM is based on stress-strain relationship. Finite Element (FE) analysis can effectively simulate stress concentration issues and deformation compatibility, challenges that have proven problematic in Limit Equilibrium (LE) analysis (6).

ERI is a non-invasive geophysical technique used to map subsurface conditions by measuring electrical resistivity variation in the ground. Along with resistivity, ERI profile depends on pore-water conductivity, effective porosity, saturation, clay content. It is a useful tool to determine the depths of different soil layers. Studies conducted to verify the results of ERI has shown reasonable agreement between ERI profiles and soil interfaces (7). ERI has been used for various reasons over the years. It is a great tool for determining the hotspot zones of weak area or perched water which is an essential parameter for probable landslide area detection (8). It has also been used previously for the determination of seepage area in the dam and levee slopes. The investigation of a problematic slope profile due to seepage using electrical resistivity imaging (ERI) detects seepage zones at different depths, correlating well with physical mapping. ERI proved effective in identifying subsurface anomalies, offering a cost-effective and efficient alternative to conventional methods for assessing and mitigating slope instability (9). The stability of railway embankments is a critical aspect of infrastructure design and construction. Various methods and techniques have been developed to assess and improve the stability of these embankments (10). ERI has been used to determine the stability of railway embankments as well. ERI proved to be a cost-effective and efficient method, complementing conventional borehole techniques by extending surface information and identifying weak layers. This geophysical approach is suitable for sustainable ground investigation, reducing time and costs (11).

Although numerous factors influence slope stability, some of the most critical determinants include the properties of soil layers, the configuration of the slope, its geometric features, and the groundwater conditions. Climate change plays a significant role in affecting slope stability, primarily through increased periods of heavy rainfall. These intense rainfall events infiltrate the soil, reducing its cohesion and internal friction, collectively known as the soil's shear strength. As the shear strength reduces, the slope becomes more susceptible to sliding. When the forces driving the sliding movement exceed the reduced shear strength of the soil, a landslide occurs (12).

Finite Element Method and Limit Equilibrium Methods are the two most popular methods for assessing and predicting slope stability in challenging geological conditions. Numerical analysis plays a significant role in understanding slope failure mechanisms in soil slopes. FEM has been proven to be more efficient and has good precision on calculated values (13). FEM considers material’s behavior under stress and deformation over time, providing a more detailed understanding of the soil and rock mechanics whereas, LEM uses simplified assumptions about material strength and does not capture the progressive failure mechanisms that can lead to sudden slope failures. In order to improve resiliency studies on slope FEM analysis is a must (14). Numerical modeling depends on a variety of factors which includes essential geological structures. It has a direct impact on cohesion, internal friction angle, structural continuity, permeability properties and water conditions (15).

Most of the soil in Mississippi is expansive clay which is a high plastic soil. The high plastic clay soils absorb water and swell in volume and when moisture is removed from the soil through desiccation the volume of the soil shrinks. This shrink-swell behavior reduces the shear strength of soil making it vulnerable to sliding failure (16).

Developing early warning criteria for rainfall-induced slope failure in high plasticity clay soils is an emerging topic. Seasonal fluctuations in soil hydraulic conductivity and shear strength increase vulnerability to failure. Susceptibility map and empirical thresholds based on rainfall intensity and duration development shows a success rate of over 70% in predicting failures. The findings highlight the importance of site-specific thresholds and suggest that these criteria can enhance regional slope failure warning systems (17). Highway slopes in expansive soil often fail due to the volume changes from seasonal variations, primarily caused by rainfall infiltration reducing matric suction and shear strength. A stabilization method using a modified moisture barrier (MMB) was tested on a failed highway slope, showing significant reductions in moisture fluctuations, lateral deformation, and vertical settlement compared to control sections. This method effectively minimized rainfall intrusion and maintained slope stability, proving more effective than traditional methods (18). Geotechnical characterization and numerical analyses of the Serchio River embankments in Tuscany, Italy, were conducted to understand the causes of the December 2009 failures, design repairs, and identify high-risk areas. Stability analyses using the bishop simplified method and FEM (PLAXIS Flow) showed low safety factors under steady state flow conditions, indicating the embankments' reliance on partial saturation for stability. The study concluded that permanent flow conditions are generally too cautious but likely contributed to the 2009 failures due to adverse factors like snowmelt and prolonged rainfall, necessitating targeted repairs and retrofitting (19).

III. METHODOLOGY

Geotechnical properties of soil differ drastically with the changes in weather conditions specially rainfall (20). A levee slope situated in Norfolk; Mississippi has been selected for this study. The highest average temperature of this area is 71.6 degrees Fahrenheit, and the lowest average temperature is 51.4 degrees. The average precipitation is about 44.87 millimeters (1.77 inches) and has 121.18 rainy days (33.2% of the time) annually (Weather and Climate). The levee is situated just beside mud lake of Mississippi river. Mud Lake is an oxbow lake located in northwestern DeSoto County, Mississippi, and in southwestern Shelby County, Tennessee. It was created by changes in the flow of the Mississippi River and borders Horn Lake to the east. The geology of this levee area is a mixture of clay and sand. The first layer from the ground surface is clay of low plasticity followed by high plasticity clay. After clay there is a small layer of SP-SM followed by CH and SP again. This borehole data was validated with ERI data.

Figure 1: Selected Study Area of Levee

To construct the FEM model, levee geometry, soil property data and weather data as boundary condition is required. Air temperature, solar radiation, dewpoint temperature, relative humidity, wet bulb temperature, dry bulb temperature, solar heat flux, net radiation, albedo, measured Alfalfa Ht and measured grass Ht weather data was obtained from NOAA (National Oceanic and Atmospheric Administration). This data was used in REF-ET software to determine the ETo (reference evapotranspiration). In this study, 1985 Hargreaves Temperature Method (Hargreaves and Samani) is used with daily timesteps to determine reference evapotranspiration (Eto). The Hargreaves method uses the following equation to determine Eto.

$$\mathrm{ETo} = 0.0023(\mathrm{Tmax}-\mathrm{Tmin})0.5\ (\mathrm{Tmean}+17.8)\mathrm{Ra}$$

ETo = grass reference ET, mm/d

Tmax = maximum daily air temperature (C)

Tmin = minimum daily air temperature (C)

Tmean = mean daily air temperature (C)

Ra = extraterrestrial radiation, mm/d

The slope geometry and soil properties were determined with the help of borehole and survey data of USACE. Soil geometry with different soil property layer was constructed in Plaxis 2D software. The software was set up as a plane strain with 15-Noded elements. Medium element distribution mesh was computed for the structure. Groundwater flow condition was given as input in the flow condition segment. Finally, different stage

Table 1

Soil Properties

Layer	**Soil Type**	**γ_{unsat} (pcf)**	**γ_{sat} (pcf)**	**Stiffness, E (psf)**	**Poisson's Ratio, v**	**Cohesion, c (psf)**	**Friction Angle, φ**	**Hydraulic conductivity in x direction, kx (ft/day)**	**Hydraulic conductivity in y direction, ky (ft/day)**
1	**Clay (Low Plasticity)**	116.0	116.5	131.3x10^3	0.25	1250	31	8.3x10^{-3}	8.3x10^{-3}
2	**Clay (High Plasticity)**	113.7	114	146.2x10^3	0.30	875	25	8.3x10^{-3}	8.3x10^{-3}
3	**Sand (poorly Graded) with Silt**	119	126	522.1x10^3	0.33	0	33	8.3x10^{-3}	8.3x10^{-3}
4	**Clay (Low Plasticity)**	120.0	120.3	375.9x10^3	0.25	1750	31	8.3x10^{-3}	8.3x10^{-3}
5	**Sand (Poorly Graded)**	114.0	121.2	731.0x10^3	0.20	0	32	8.3x10^{-3}	8.3x10^{-3}
6	**Sand (Poorly Graded) with Silt**	114.0	121.2	501.3 x10^3	0.33	0	32	8.3x10^{-3}	8.3x10^{-3}

construction was included with a 10-day interval with fully coupled deformation calculation type. Each of the stages were followed by safety phase incorporating precipitation and evapotranspiration to see the changes in factor of safety over time.

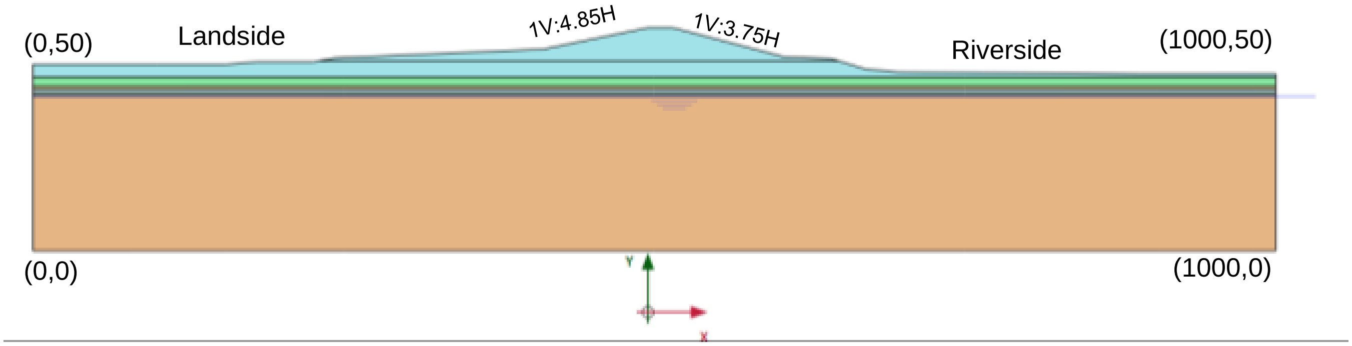

Figure 2: Geometry of the Levee section

The outline of the methodology has been provided in figure 3. The methodology begins with comprehensive data collection, focusing on weather data and the levee's geometry and soil properties. Weather data is processed through REF-ET software to calculate evapotranspiration rates, which are crucial for understanding soil moisture dynamics. Concurrently, the levee's physical characteristics are used to develop a detailed model geometry. Boundary conditions are established to accurately simulate real-world scenarios. All this information is then input into Plaxis 2D software to perform stability analyses, yielding a factor of safety. These results are used to develop a resiliency curve, providing insights into the levee's stability and resilience under various conditions.

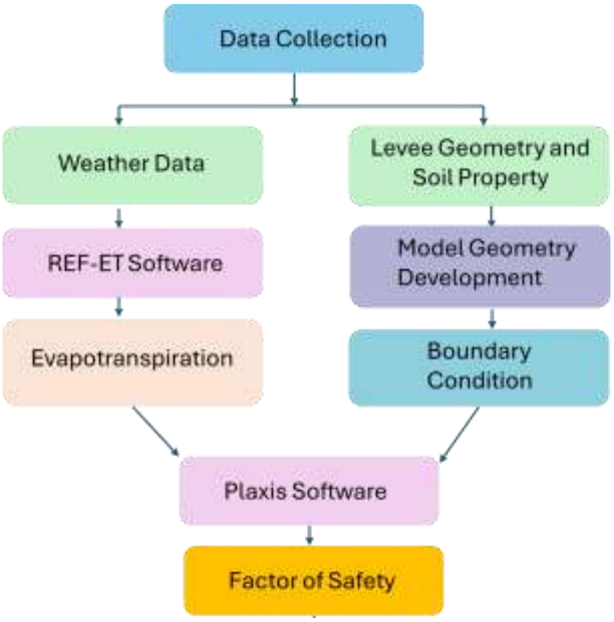

Figure 3: Methodology flow chart

After conducting the Plaxis analysis, factor of safety, stress distribution, pore water pressure, displacement and deformation, stress-strain relationship of each phase is analyzed.

IV. RESULTS

The precipitation data for the period from January 1, 2023, to May 28, 2024, was obtained from the NOAA. The trend of this precipitation data is illustrated in Figure 4, represented by the green bars, which show the daily precipitation levels in inches. Concurrently, the gage height data, indicated by the blue line, is plotted to reflect the elevation at RM 719 over the same period. The graph clearly demonstrates the relationship between precipitation events and changes in gage height. Notably, higher precipitation levels correspond with increases in gage height,

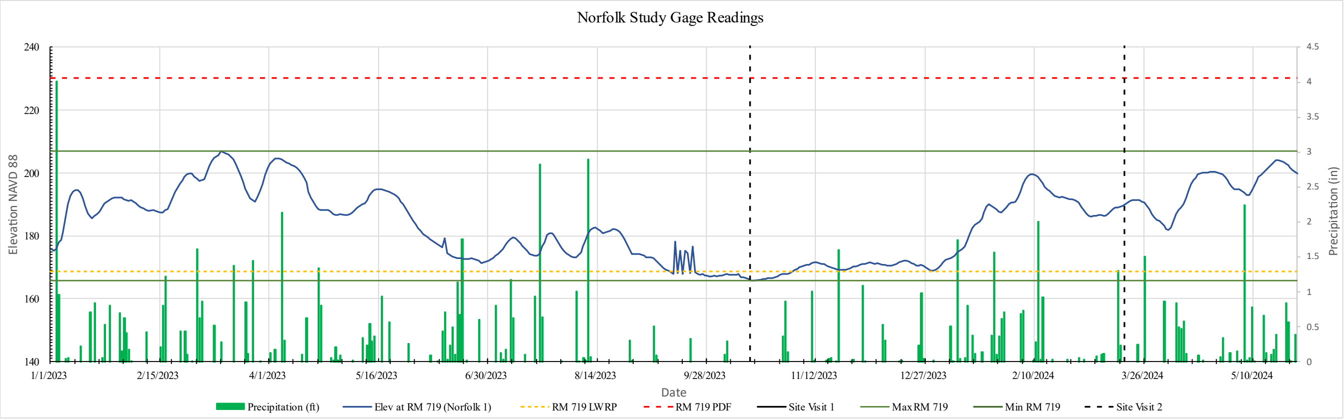

Figure 4: Norfolk Study Gages with Precipitation Reading

as seen during peak rainfall periods in mid-May 2023 and early August 2023. This correlation highlights the direct impact of precipitation on water levels at RM 719. Additionally, the graph includes critical reference lines such as the low water reference point (LWRP), maximum and minimum recorded elevations, and the probable flood level (PDF). Two vertical dashed lines mark significant site visits on September 28, 2023, and March 26, 2024, for on-site assessments. The stage elevation validates the NOAA precipitation data. Rainfall is the main factor in contributing to the increased elevation level. This precipitation data was given as boundary condition for the Finite

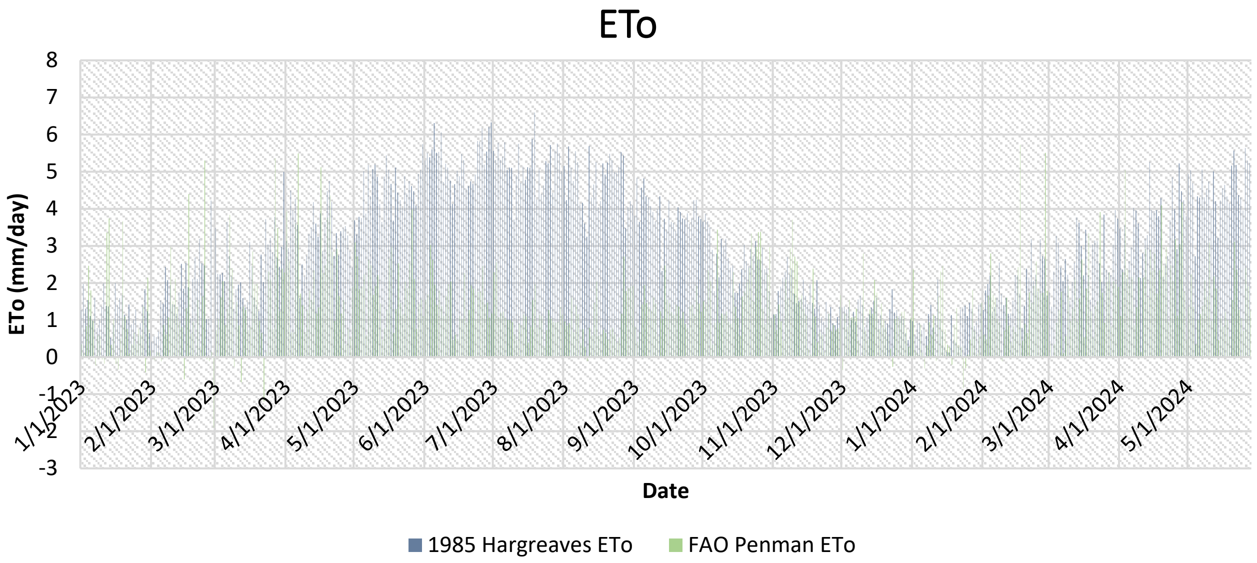

Figure 5: ETo 1985 Hargreaves method and FAO Penman Method using REF-ET software

Element Method (FEM) analysis. In this plot, 1985 Hargreaves ETo shown more evapotranspiration than FAO Penman ETo. 1985 Hargreaves ETo relies primarily on temperature and extraterrestrial radiation, using a simplified empirical approach. In contrast, the FAO Penman-Monteith method is more detailed and physically based, incorporating temperature, radiation, wind speed, and humidity. This comprehensive inclusion of climatic variables in the FAO Penman-Monteith method often results in more moderated ETo estimates, making the Hargreaves method more sensitive to temperature variations and potentially leading to higher ETo values. For this study, FAO Penman-Monteith method has been selected for the study.

After simulation the scenario in Plaxis software, the saturation profile of the levee was compared with the ERI profile. The ERI and Plaxis simulation was compared for October, March and June.

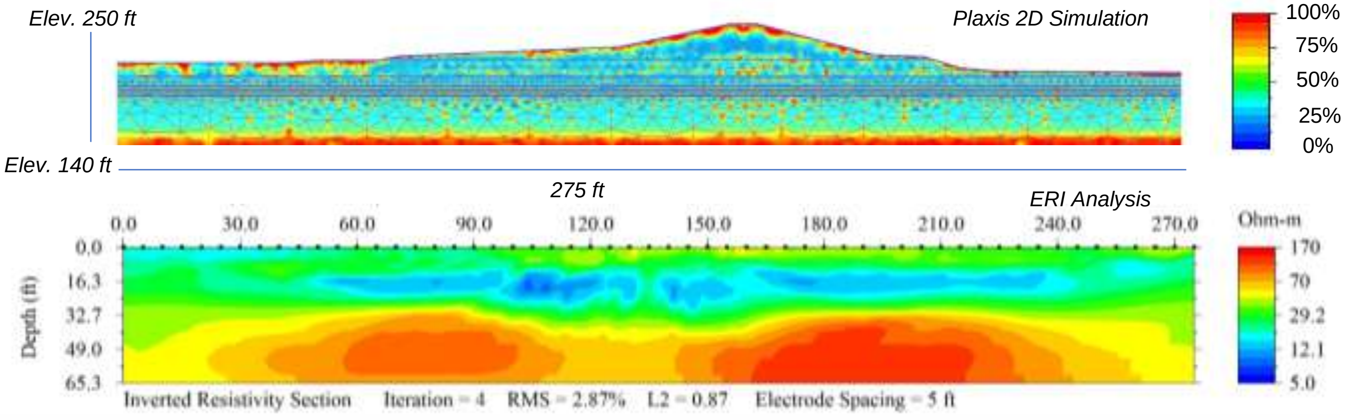

Figure 6: October 2023 Plaxis 2D simulation result and ERI analysis

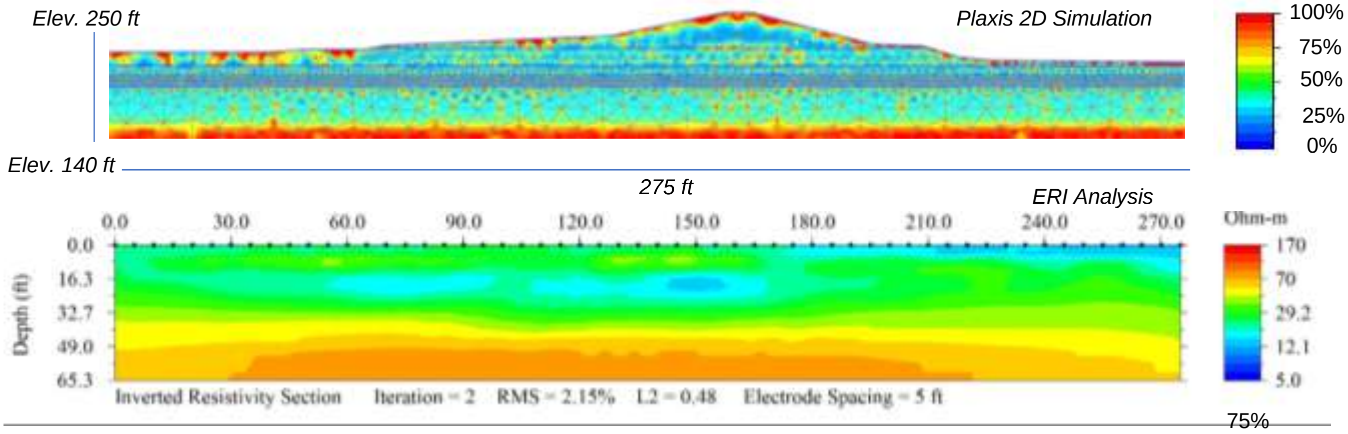

Figure 7: March 2024 Plaxis 2D simulation result and ERI analysis

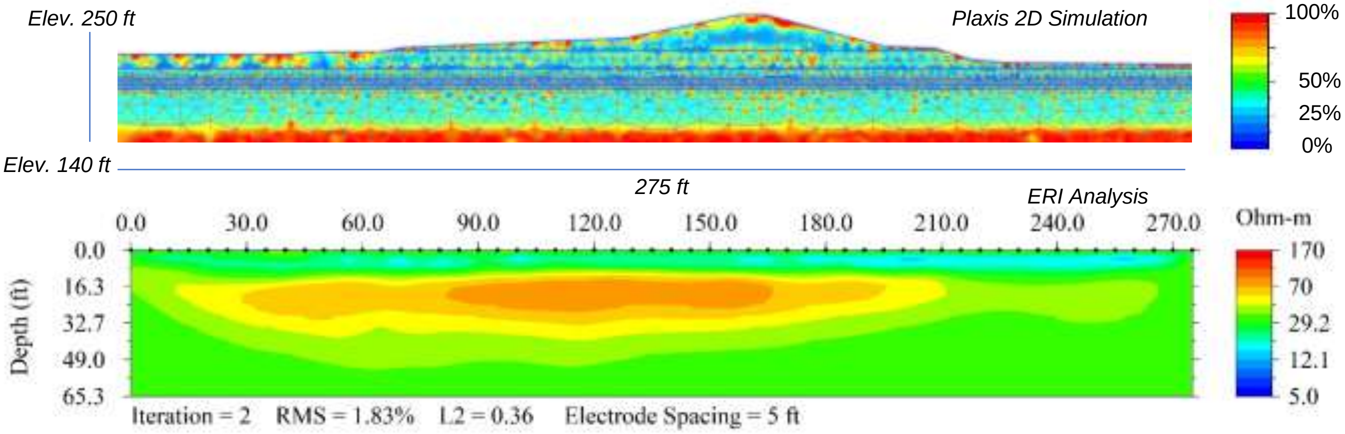

Figure 8: June 2024 Plaxis 2D simulation result and ERI analysis

Both the Electrical Resistivity Imaging (ERI) and Plaxis results provide a detailed view of the subsurface characteristics of the levee, highlighting similar features such as variations in material properties and moisture content. The ERI image distinguishes different layers based on resistivity values, with higher resistivity indicating drier or denser materials and lower resistivity suggesting more saturated or less dense zones. Similarly, the Plaxis model visualizes the subsurface conditions in terms of stress and deformation, identifying areas of potential weakness or high stress. Both methods reveal critical zones within the levee that require attention, demonstrating their complementary roles in assessing the structural integrity and resilience of the levee under various environmental conditions. For October, both ERI and Plaxis saturation results show the perched water zone below surface which reduces in the month of June. The saturation of different layers of soil can also be noticed from the figures.

The changes in factor of safety with precipitation has been presented in figure 9 to identify any potential patterns or anomalies in structural safety relative to precipitation. The plot also helps in pinpointing any months where significant deviations in FS could indicate emerging risks. For example, consistently observing the FS values helps in monitoring for any downward trends that might correlate with increasing rainfall, which could signal potential instability. This type of analysis is crucial for civil engineers and geotechnical analysts who aim to predict and mitigate risks associated with periods of high precipitation. By understanding the relationship between rainfall and FS, they can make informed decisions on necessary reinforcements to ensure the continued stability and safety of the structures. Such insights are essential for planning and maintaining infrastructure resilience against weather-related impacts, ultimately contributing to safer and more reliable engineering practices.

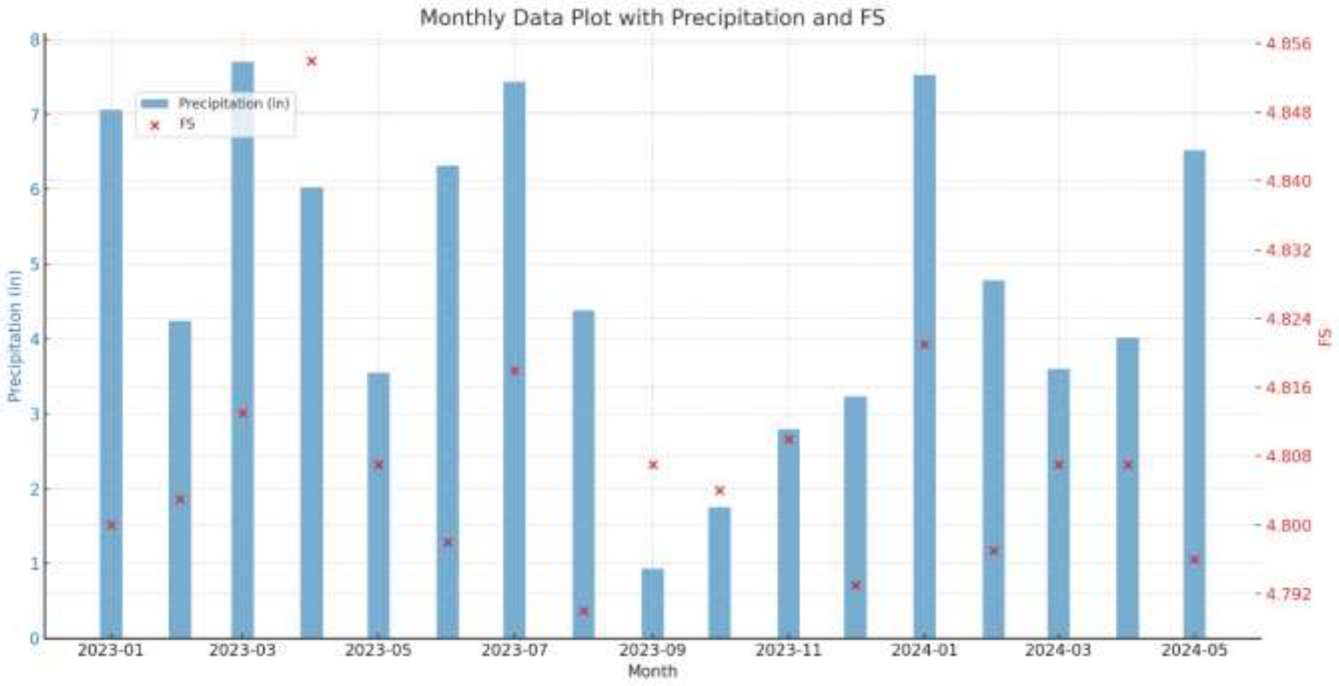

Figure 9: Changes in factor of safety with Precipitation

The plot illustrates the relationship between monthly precipitation (in inches) and the Factor of Safety (FS) over a span of 17 months from January 2023 to May 2024. Precipitation data is represented by blue bars, with the height of each bar indicating the amount of rainfall for the corresponding month. The Factor of Safety (FS), which is a critical measure for assessing the stability of slopes, embankments, or other structures, is depicted as red points. Analyzing the plot, it is visible that significant precipitation events, such as those in January 2023 (approximately 7.06 inches), March 2023 (7.7 inches), July 2023 (7.44 inches), January 2024 (7.53 inches), and May 2024 (6.52 inches), are captured by taller blue bars. These months of low rainfall increases the FS values which is seen during the high precipitation bars. And during the low precipitation time factor of safety shows decrease as it takes time to infiltrate rainfall in the soil from the initial phases. but remain relatively stable around 4.8, as indicated by the red points.

V. DISCUSSIONS

This study provides a detailed analysis of the impacts of precipitation load and infiltration on the structural resilience of a levee section at the Mississippi east levee system in Norfolk, North of Mississippi. By incorporating historical rainfall and flood hydrograph data into transient Finite Element Method (FEM) analysis, the temporal effects of unsaturated soil behavior have been captured and their implications for levee stability. The results indicate a clear correlation between precipitation events and changes in the Factor of Safety (FS). High precipitation months, such as January 2023 (7.06 inches), March 2023 (7.7 inches), July 2023 (7.44 inches), January 2024 (7.53 inches), and May 2024 (6.52 inches), exhibit relatively stable FS values around 4.8. This stability suggests that the levee structures are designed to withstand significant rainfall events without immediate compromise to their structural integrity. However, during periods of lower precipitation, a decrease in FS is observed. This decrease can be attributed to the initial phase of rainfall infiltration of the previous high intensity rainfall into the soil, which temporarily reduces the soil’s shear strength before stabilizing. The use of Electrical Resistivity Imaging (ERI) alongside FEM simulations has proven instrumental in validating the soil saturation profiles and identifying critical zones within the levee that require attention. The comparison of ERI and Plaxis simulation results for October 2023, March 2024, and June 2024 reveals consistent patterns in subsurface characteristics, including variations in material properties and moisture content. Both methods have successfully highlighted areas of potential weakness or high stress, underscoring their complementary roles in assessing levee resilience. Furthermore, the study highlights the importance of incorporating detailed rainfall-runoff calculations into FEM analysis to simulate the hydrological impacts on levees accurately. The integration of evapotranspiration data, derived using the FAO Penman-Monteith method, adds another layer of realism to the simulations, ensuring that soil moisture dynamics are well-represented.

VI. CONCLUSION

This study underscores the critical relationship between precipitation and the Factor of Safety (FS) in levee stability. High precipitation months demonstrated relatively stable FS values around 4.8, indicating that the levees can withstand significant rainfall events. Conversely, periods of low precipitation showed a temporary decrease in FS due to initial rainfall infiltration. The integration of Finite Element Method (FEM) simulations and Electrical Resistivity Imaging (ERI) provided a comprehensive understanding of subsurface conditions and their impact on levee integrity. These findings are essential for developing proactive reinforcement strategies, ensuring the resilience and safety of levee systems against evolving climatic conditions.

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