Highway Slope Monitoring using 3D Laser Scanning at Different Seasons

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ABSTRACT

Maintaining safe transportation infrastructure networks such as roadways benefit from image surveillance. One promising technology is 3D LiDAR scanning of which the paper presents the Slope LiDAR embankment (SLidE) dataset. This paper highlights 3D LiDAR exploitation methods for expansive clay terrains across different seasons at a specific site along the Terry Road Exit from I-20 westbound in Jackson, Mississippi. The analysis helps to understand the impact of seasonal moisture variation on slope stability, with a particular focus on the implications of climate change. Expansive clays, known for their shrink-swell behavior in response to moisture changes, pose significant geotechnical challenges, especially under the evolving conditions brought about by extreme weather. By capturing dynamic soil behavior through seasonal 3D scanning, the results provide insights into these soils' volumetric changes and deformation patterns at the monitored location, underscoring the critical influence of moisture dynamics on soil and slope stability. The proposed LiDAR 3D scan processing methodology is designed to reduce the computational load of analyzing large datasets. Moreover, this work shares the SLidE dataset. SLidE serves as a valuable resource for researchers and practitioners in the field, enhancing data processing efficiency and enabling real-time monitoring and rapid response to potential geotechnical failures. Results indicate a notable trend where the slope, subject to expansive clay dynamics, tends to revert to its normal structural state during the fall/winter months.

Keywords: LiDAR, Slope Stability, Expansive Clays, Shrink-Swell Soils, Earthen Embankments, Geotechnical Failures

1. INTRODUCTION

Expansive clays, often referred to as shrink-swell soils, are characterized by their ability to undergo significant volume changes in response to moisture variation. Shrink-swell soils predominantly contain clay minerals, such as montmorillonite, that have the ability to absorb water, leading to an increase in volume, or *swell*, and lose water, resulting in a decrease in volume, or *shrink*[1]. The behavior of expansive soils during wet-dry cycles and their interaction with rainfall are critical factors that influence the stability of structures and infrastructures built upon ground soil[2]. In numerous regions across the USA, the surface soils are classified as *expansive clay*[3]. The construction of many embankments[4], levees, and earth dams, especially in states with an abundance of expansive clay like Texas, Louisiana, Mississippi, Alabama, and Colorado, rely heavily on these types of hard soils. Many embankments, such as along roads and highways, are designed with specific side slopes such as a 1:2 vertical-to-horizontal ratio (V|H), and are required to be maintained for safety. A review of embankments from the American Association of State Highway and Transportation Officials (AASHTO) is provided by Hassani[5] across different states and environments.

Clay soils are unfortunately susceptible to shallow slope failures within a short period of post-construction due to their inherent properties. The transition of expansive soils from a state of partial saturation to full saturation, particularly upon moisture increases, triggers *heaving*. An illustrative example is the Yazoo clay in Jackson, Mississippi, which undergoes a dramatic volume change ranging from 100% to 235% as it transitions from oven-dry to its liquid limit state, as noted by Lee[6]. Moreover, these soils demonstrate shrink behavior, marked by crack formation on the surface upon mois-

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ture loss, whether due to natural or anthropogenic factors. Expansive soils, with their moderate to high plasticity index and significant bearing capacity, exhibit variable strength characteristics as discussed by Kalantari[7]. Although such soils are encountered globally, their predominance in arid to semi-arid regions is notable, attributed to their clayey mineral composition which facilitates water absorption and consequent volume changes, as expounded by Bowels[8] and Murphy[9].

The National Risk Index classification of natural hazards in the U.S. delineates 18 primary categories[10], including *landslides*, based on their potential infrastructure damage or destruction, aligning with studies by Murphy[9] and Chen[11]. The challenges associated with expansive soils, particularly their role in economic losses due to infrastructure damage, underscore the need for heightened awareness and improved construction practices for roadways to enhance their longevity and economic viability.

The slow creeping failure of highway slopes made from geologic formations of Yazoo clay in Alabama, Louisiana, and Mississippi was primarily influenced by the interconnection between the soil's properties and environmental elements like moisture fluctuations and rainfall. Research has shown that repeated *wet-dry cycles* diminish the shear strength of Yazoo clay, transitioning it from a state of peak strength to significantly weakened conditions, especially when wet. The weakening is a key factor in a slope's slow failure process[12]. Additionally, the interaction of these wet-dry cycles with rainfall further compromises the slope stability by altering the clay's cohesion and void ratio, thus lowering the safety margin and enhancing failure risks[13].

Rainfall's role is also crucial, as it affects moisture depth within the slope, especially at its crest, leading to moisture variations that penetrate deep and gradually undermine the structure, contributing to its creeping movement[14]. Change in rainfall patterns, because of climate change, exerts significant influences on climate systems and soil dynamics, particularly in the case of Yazoo and other expansive clays. These clays, inherently responsive to moisture changes, experience volumetric transformations in response to fluctuations in soil moisture, a phenomenon closely connected with shifting precipitation patterns. The modification in precipitation regimes can intensify the swelling and shrinking tendencies of expansive clays, affecting the soil's structure and stability. Such variability promotes increased soil erosion, alters soil porosity, and modifies the mechanical properties of the soil, all of which have critical implications for the stability of constructions on these soils, possibly escalating geotechnical failures[15]. Furthermore, climate-driven changes in rainfall patterns influence the soil moisture environment, impacting organic matter decomposition rates, nutrient cycling processes, and microbial activities within expansive clays. These alterations may affect soil aggregation and structural integrity, thereby influencing erosion rates and soil fertility, posing implications for agricultural productivity and sustainability[16]. Additionally, the synergy between changed rainfall dynamics and expansive clays could modify water infiltration rates, runoff patterns, and groundwater recharge processes. Such modifications have far-reaching implications for water accessibility for flora and agricultural ventures, thereby impacting broader ecological systems and necessitating adjustments in land use and management strategies, especially in regions predominated by expansive clay soils[17]. Understanding these dynamics is essential for assessing the stability of structures built on such expansive clays.

The *shrink-swell behavior* of expansive clay is recognized as a substantial geologic hazard by Jones and Holz[18], and underscored by Wray and Meyer's[19] estimation of over 15 billion USD in annual losses. Despite various modeling attempts by researchers like Mitchell[20] and Lytton[21] to simulate the deformation behaviors of unsaturated soils, a definitive predictive model for expansive clays remains uncertain, highlighting the necessity for comprehensive field studies and sustained monitoring[22].

Addressing the challenges that Yazoo or other expansive clays play in slope stability could be significantly enhanced through continuous monitoring and early detection. It is hypothesized that LiDAR technology could play a pivotal role in the continuous tracking and incipient fault detection of earthen embankments made of Yazoo or other expansive clays. LiDAR's precision in capturing high-resolution topographical data could be invaluable in identifying early signs of slope instability and deformation, offering a proactive approach to mitigate larger failures[23]. LiDAR'sefficacy extends across varied terrains, even penetrating forest canopies to secure essential ground data, crucial for landslide risk assessment in such environments[24]. By generating detailed digital elevation models (DEMs), captured LiDAR data aids in analyzing key slope features—gradient, aspect, and curvature—vital for stability prediction and management[25]. Continuous LiDAR monitoring could track landscape changes over time, supporting the evaluation of stabilization measures and early failure warnings, thus playing a critical role in infrastructure safety and long-term terrain management. Ultimately, LiDAR's advanced capabilities could increase understanding and address the complexities of slope stability, significantly bolstering efforts to safeguard against geotechnical risks and enhance infrastructure resilience.

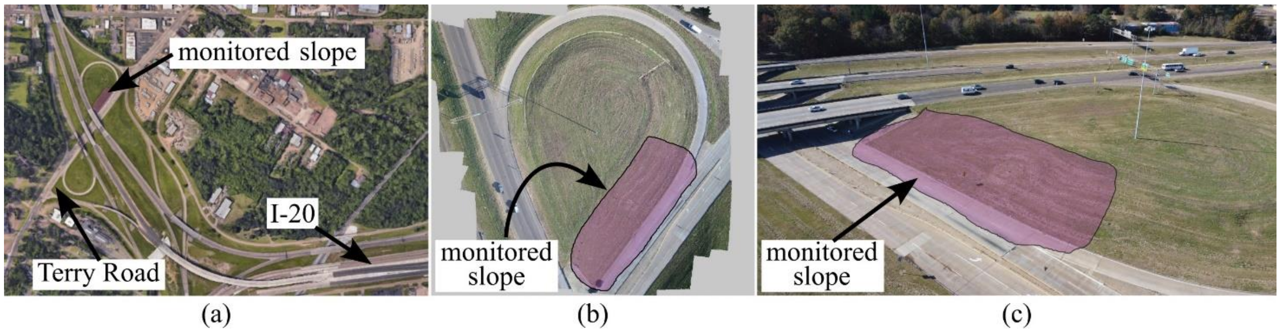

Figure 1: Monitored earthen embankment located at theI-20Ease exit onto Terry Road in Jackson Mississippi, showing: (a) a satellite view of the reference slope (base image credit Google Earth), (b) a composite image obtained from UAV flights at the test location, and; (c) a UAV image taken from the North-East side of the slope.

This paper presents an open-source *Slope LiDAR embankment (SLidE)*Terrestrial LiDAR dataset that tracks the movement in an embankment made from high-plasticity clay through time. The monitored embankment is located at the Terry Road Exit from I-20 westbound in Jackson, MS. The embankment slope surfaces were scanned at different time intervals between Summer 2021 and Fall 2023, capturing the slopes' changing conditions over time. The raw point clouds were refined through segmentation, eliminating undesirable points at the scan edges, as well as through the application of a ground extraction algorithm to remove vegetation and extraneous above-surface data points. The SLidE dataset is provided and hosted in a public repository[26]. The contributions of this work are twofold. First, the paper introduces and shares the SLidE dataset, which serves as a common dataset for researchers studying the monitoring of expansive clays in earthen embankments. Second, the paper introduces an exploratory data investigation into this dataset intended to serve as a baseline for future data processing undertaken on the SLidE dataset.

2. METHODOLOGY

This section presents the SLidE dataset and provides the formulation of methods for an introductory and exploratory data analysis of the embankment. It is hypothesized that profiles from scans captured at different time intervals can be compared to perform time-dependent surficial slope movement and deformation analyses. The SliDE data captures detailed seasonal variations in expansive clay behavior at a specific site and streamlines data analysis, as well as offers a comprehensive analysis for assessing risks associated with expansive soils.

2.1. SLidE Dataset

The SLidE Dataset consists of LiDAR scans of an earthen embankment situated along the I20E exit toward Terry Road (32°16'48.92"N, 90°12'44.03"W) in Jackson Mississippi, United States. This slope is depicted in Figure 2 and is a 15 ft. high slope with a grade that ranges from 3.5:1 (V|H) to 4:1(V|H). In the recent past, the slope encountered shallow landslides near the bridge, which were subsequently remediated using steel H-piles. Currently, the slope consists of reinforced and as-built sections made up predominantly of Yazoo clay[27].

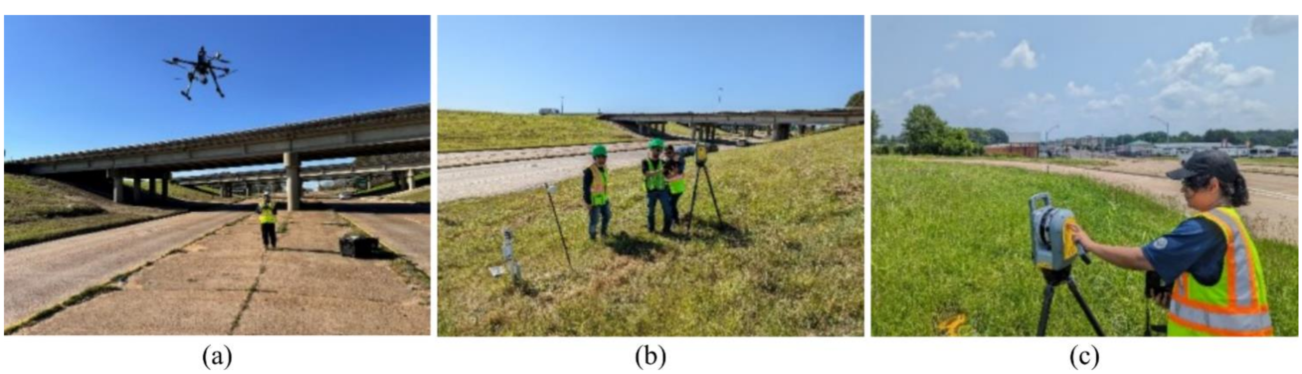

Figure 2: Field data collection, showing the data collection crew: (a) operating the UAV used to obtain aerial footage of the slope; (b) LiDAR set up on the slope, and; (c) LiDAR scanner during operation.

Figure 3: LiDAR point cloud surface topography of the monitored embankment for the size scans from 2021-2023.

Dense point cloud data from the LiDAR scan were collected to develop a 3D surface and generate topography of the slope surface. Field scan data was collected multiple times over several years. The LiDAR scans were acquired at 5 stations on the slope to gather overlapping point cloud data, as shown in Figure 2 highlighting the field data collection. The LiDAR data acquisition and analysis involved the use of Terrestrial LiDAR equipment (Trimble X7) to perform 3D laser scanning on embankment slope surfaces. A total of five to six scanning stations were employed, resulting in the collection of multiple-point clouds with approximately 20 million points. The field collected data was digitally post-processed using Trimble RealWorks software to generate a single-point cloud which reduces the point clout to approximately 12 million points. This unified point cloud includes various infrastructural features from the surrounding area that were within the LiDAR scanner's field of view, such as the northbound sector of the adjacent highway and bridge immediately southwest to the slope. The raw point cloud data for each LiDAR scan is further processed using the Recap software tool from Autodesk[28]. The manual data assessment with the Recap tool was used to remove anything unrelated to the physical slope itself, including waystations, road signs, foliage, and personnel.

The dataset is distributed in the compressed 'LAZ' format as a standard. The LAZ format is a compressed version of the LAS format which was designed for the interchange of 3-dimensional point cloud data[29]. LAS is considered the industry standard for LiDAR data adopted by the American Society for Photogrammetry and Remote Sensing (ASPRS). To obtain the data in LAZ format, it was exported from Autodesk-ReCap to the e57 file standard; a format supporting data conversions to more intuitive and spatially effective file formats. The conversion from e57 format to the LAZ format was performed using a tool called e57tolas from the LASTools software collection[30]. Individual conversions were made for each point cloud in an effort to preserve the metadata containing the original point-source IDs from the initial LiDAR scan file format. Some of the point clouds that are available in the associated public repository[26] are shown in Figure 3.

2.2. Exploratory Data Analysis

This section outlines the steps and analytical techniques employed in processing the SLidE dataset. Analyzing the LiDAR 3D point cloud data seeks to assess the structural integrity of the embankment. The primary objective was to segment the point cloud into distinct regions and subsequently analyze these regions to identify potential structural vulnerabilities. The procedural steps, data analysis techniques, and the rationale behind the chosen methodologies include these steps:

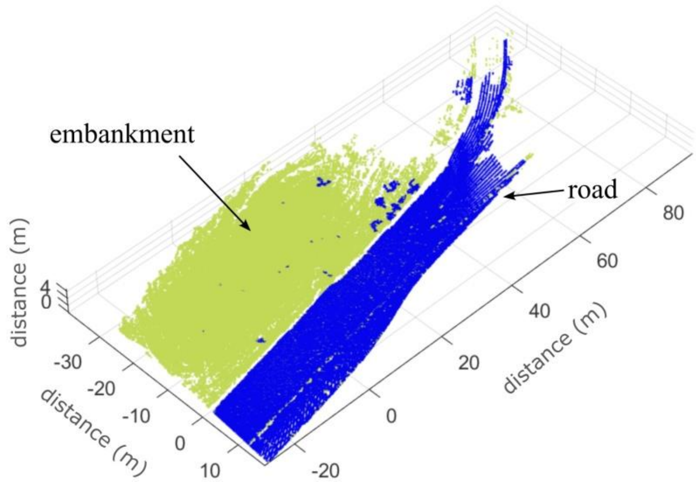

Figure 4: Segmentation of road and embankment through analysis of normal vectors and curvature values of each point in the point cloud, distinguishing between the road (blue) and bank (green) regions.

- *Step 1: Data Segmentation and Preparation*. The initial phase of the study involved segmenting the 3D point cloud data into two main regions: the road and the bank. The segmentation was achieved by analyzing the normal vectors and curvature values of each point within the 3D point cloud. By employing geometric features, points were classified accurately into two visually distinct regions, marked by green (embankment) and blue (road), shown in Figure 4. Figure 4 shows a segmentation result for the October 2021 earthen embankment scan. Following segmentation, the focus was shifted exclusively to the bank region, filtering out the road data to streamline subsequent analyses.
- *Step 2: Curvature Histogram Analysis.* For the analysis of the bank region, the analysis first computes the local Gaussian curvature within the bank region for each 3D point using its local neighbors; and then generates a 100-dimensional histogram array for all these curvatures. The histograms served as a visual signature for the bank's entire surface, encapsulating the geometric variability and intricacies of the bank's structure. To assess the similarity/difference between different banks, the Wasserstein distance, also known as the *earth mover's distance*, assesses the difference in each pair of curvature histograms. The Wasserstein distance metric provided a quantitative measure of similarity, allowing for the comparison of structural features across different bank regions.
- *Step 3: Principle Component Analysis.* A principle component analysis (PCA) was conducted on the curvature embedding to further understand the structural variance within the bank regions. Unlike the previous Wasserstein distance for each pair of banks, which can only yield pair-wise differences among the banks, PCA reduces the dimensionality of the curvature data to two principal components, facilitating a global and more intuitive visualization and analysis of the data's underlying structure. The PCA results offered insights into the primary modes of variation in the curvature data, aiding in the identification of patterns that may not have been apparent in the original high-dimensional space.

3. RESULTS AND DISCUSSION

The exploratory data analysis reveals insights into changes in the embankment over time (i.e., deformation patterns). Our investigation was aimed at capturing the dynamic behavior of these expansive clays as they respond to seasonal moisture variations. First, the Wasserstein distance—a measure for quantifying the similarity between two probability distributions—was used to analyze the difference in the six collected point clouds and are presented in Table 1. At a global level, the Wasserstein distance describes the embankment's varying degrees of deformation and structural changes across different seasons. This variation in distances points to significant structural changes over time. The average Wasserstein distance for each scan is 152. Every distance associated with the June 2023 scan has a pronounced Wasserstein distance of over 269. Inferring a large change in the deformation of the embankment during this time. This could likely be attributed to the cumulative effects of moisture levels at the time of the scan. However, the September 2023 scan reverts back to Wasserstein distances between 18 and 98 which are below the dataset's average of 152. This reversal to the mean suggests that any changes detected during the June 2023 scan were seasonal in nature and possibly not the direct result of a geotechnical failure.

Table 1: Similarity matrix by Wasserstein distance between the six collected point clouds.

	2021- June	2021- Oct.	2022- Feb.	2022- Nov.	2023- June	2023- Sept.
2021- June	0	24	111	91	381	98
2021- October		0	112	91	378	98
2022- February			0	29	269	19
2022- November				0	290	18
2023-June					0	282
2023- September						0

Further information on the embankment's structural variances can be achieved through interpreting the PCA of the curvature embedding, as depicted in Figure 5. By reducing the curvature data's dimensionality to two principal components, the PCA facilitated a more global and intuitive analysis of the data's underlying structural patterns. The analysis revealed a clustering of the scans done in the fall/winter months with the June 2021 and 2023 scans being those with the greatest distance from the cluster of scans taken during the fall and winter seasons. Importantly, the red arrows added to Figure 5 show the progression of the PCA components through time, again suggesting that the slope reverted back to normality following June 2023.

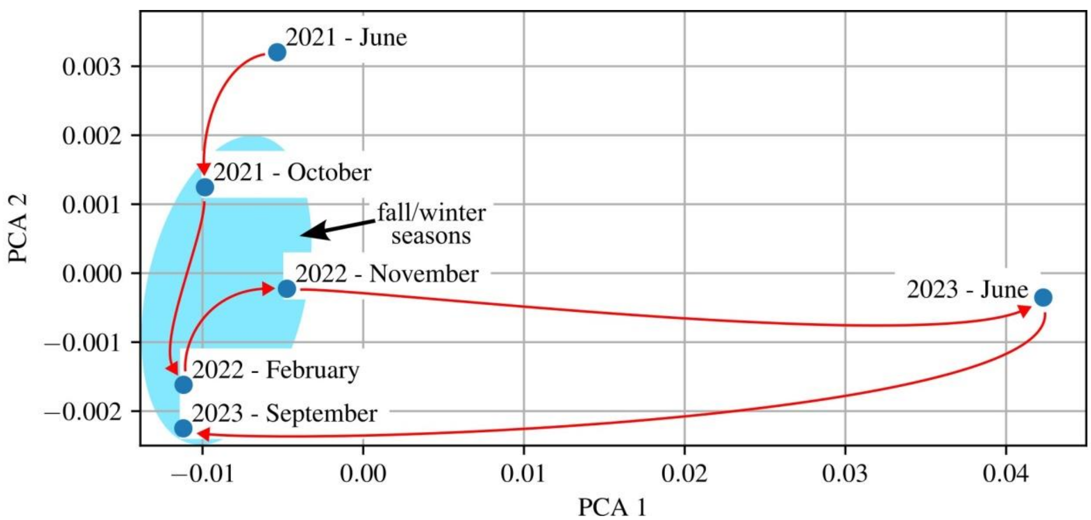

Figure 5: Results for the curvature embedding via PCA with two principal components.

The analysis using Wasserstein distances and PCA provides insight into the temporal variations within the embankment structure through time and across different seasons. The observed variations underscore the sensitivity of expansive clays to probable changes in moisture with changes in seasons. Importantly, these data-driven approaches seem to infer that the changes in the monitored slope are reversible with the seasons. Future efforts include using the models and the seasonal variation knowledge to coordinate the dynamic coordination of the simulation and measurement data as highlighted from the dynamic data-driven applications systems[31] concept for structural health monitoring[32].

4. CONCLUSION

Investigation into the stability of embankments composed of high-plasticity clays, facilitated by LiDAR technology was demonstrated in the paper. The open-source *Slope LiDAR embankment* (SLidE) dataset represents a valuable resource for the research community, offering a baseline for future studies and data processing efforts. As climate change continues to alter precipitation patterns and moisture dynamics, the need for adaptive construction practices and infrastructure management strategies becomes increasingly urgent. LiDAR scanning provides a novel approach to capture changes in expansive clays, offering a high-resolution perspective on the deformation patterns that occur over time. The provided preliminary analysis from SLidE details the probable effect of varying seasons within the embankment. The results suggest resilience to seasonal moisture changes that could inform more effective management and mitigation strategies for geotechnical stability. These insights are crucial for developing resilient construction practices and infrastructure management strategies in areas prone to the challenges posed by expansive clays. Geotechnical engineering and slope stability monitoring provide adaptive strategies for slope analysis in the face of climate change-induced shifts in precipitation patterns and moisture dynamics.

The potential impact of environmental conditions on the structural integrity of embankments built on expansive clays is of concern. The findings show the potential impact of continuous monitoring and early detection of potential geotechnical failures through the use of LiDAR technology in infrastructure safety and management. In future work, we plan to expand our dataset by collecting additional LiDAR scans alongside moisture content and inclinometer data to enhance our understanding of the complex interplay between soil moisture variations and slope stability, aiming for a more comprehensive assessment of geotechnical risks associated with expansive clays.

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