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A Road Map for Geotechnical Monitoring of Transportation Infrastructure Assets using Three-Dimensional Models Developed From Unmanned Aerial Data

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Abstract. Infrastructure forms the backbone of a nation's growth and economy. The smooth operation of those infrastructure assets depends on many factors including proper use of construction materials under different loading, environmental and durability assessments, and the frequency of monitoring after construction. The performance and maintenance of an infrastructure asset thus depend on the behavior of the system in a built geological environment. Proactive monitoring of infrastructure often leads to preventive maintenance. However, it is not economically feasible to use the current traditional monitoring techniques, especially considering the vastness of the infrastructure networks. In this study, unmanned aerial vehicle-close-range photogrammetry (UAV-CRP) technology is being proposed as a supplemental data collection tool to complement existing traditional monitoring techniques for geotechnical infrastructure. Two case studies covering a pavement structure built over rehabilitated subgrade rich with sulfates and stability of a rock slope adjacent to an old rail line were monitored aerially to understand their state of health conditions. The pavement site had a history of experiencing sulfate-induced heaving and was rehabilitated using extended mellowing after lime stabilization. The rail line under inspection was constructed more than a century ago and the stability of the weathered rock cut holds the key for safe operations on the rail line. The rock was highly weathered and considered to undergo circular failure. Aerial images were collected and processed to build three-dimensional models to evaluate and assess the condition of these geotechnical assets. This approach not only provides a comprehensive idea through dense point cloud models offering a real field like view of the asset conditions but also expected to result in significant savings in data collection time and costs.

Keywords: Infrastructure; Aerial Mapping; Photogrammetry; Pavements; Stabilization; Slopes.

1 Introduction

Transportation infrastructure plays a key role in the economic growth of a nation. It is often termed synonymous with the growth due to its vast network of assets spanning across the United States and providing access for movement of freight and passengers. The vast network of assets comprises pavements, railroads, bridges, embankments, and other structures [1, 2]. Oftentimes, the monitoring and maintenance of those infrastructure assets pose challenges to even developed countries. In 2017, the ASCE infrastructure report card had considered various factors influencing the infrastructure in the United States of America (USA) and provided a grade of “D+” [3]. This underlines the need for developing a sustainable and resilient transportation infrastructure to withstand the challenges experienced due to extreme weather events, varying and increasing traffic loading conditions, and other factors.

Highways are an integral part of the transportation infrastructure as they facilitate the truck transportation of approximately 74% of total commodities in the United States [4]. Their condition needs constant attention due to their exposure to varied geological conditions including problematic soils, various loading conditions, and a variety of weather conditions including extreme weather events such as prolonged droughts and hurricane-like events [5]. Nearly 94% of the paved roads in the United States have asphalt surfacing and the level of service offered to the road users heavily depends on the condition and potential movements of the underlying pavement layers. In the state of Texas, special attention has been given to pavement distresses such as unevenness caused due to expansive soils experiencing shrinkage related cracking, heave movements due to moisture ingress, and surficial soil erosions [6, 7]. There are also many soil embankments and rock cuts adjacent to the transportation infrastructure and need to be evaluated for stability to ensure the smooth operation of the infrastructure. The complexity and the steepness of the slopes often pose challenges to the traditional data collection methods used to collect two-dimensional information. The slope stability analysis performed using two-dimensional (2D) information is always conservative due to its inability to consider the end effects prevailing in the actual field conditions. Many studies have used a three-dimensional (3D) model extruded from a 2D section [8]. However, this 2D section may not be the most critical section when considering actual field conditions. Hence, there is a need for adopting new data collection methods that can offer actual field conditions that can be used for performing slope stability analysis. Proper planning of maintenance and rehabilitation (M&R) strategies can significantly lower the life-cycle costs and provide a consistent level-of-service for freight and passengers [4].

One of the effective ways to achieve a sustainable and resilient transportation infrastructure is by conducting proactive monitoring and preventive maintenance works that will contribute to the preservation of the infrastructure assets [9]. The current traditional infrastructure assessment methods including total station, terrestrial LiDAR, and profilers are both time-consuming and cost-intensive, thereby, creating a need for the development and application of new data collection methods [10].

Modern-day inspection tools have outperformed the conventional inspection and instrumentation methods by providing efficient, accurate, and innovative visualization of infrastructure condition data. The unmanned aerial vehicle is one such data collection platform where a variety of data collection sensors can be mounted to collect and process the data to obtain the infrastructure health condition. They are being used remotely to collect data that is post-processed to make judgments on the health condition of geo-infrastructure based on qualitative and quantitative inspection analyses. Unmanned aerial vehicle-close range photogrammetry technology (UAV-CRP) has been used for different aerial based infrastructure inspections [11, 12].

This paper covers previous studies on geotechnical aspects of transportation infrastructure including geomaterials, innovative stabilization methods, slope stability, various topics related to drones, and their application for infrastructure inspections. Subsequent sections discuss case studies on using unmanned aerial vehicles to solve issues related to transportation geotechnical fields. Based on the conducted studies, UAVs are expected to play a much bigger role in improving infrastructure performance, thereby, increasing the life of infrastructure assets.

2 Background

2.1 Stabilization techniques

Construction of infrastructure over problematic soils needs to be planned carefully as improper handling will increase the life cycle cost either by increasing the construction costs due to the use of transported material with superior characteristics or increasing the maintenance costs throughout the life of the infrastructure due to the use of locally available inferior material. Engineers/practitioners need to design the infrastructure judiciously by keeping the above scenarios in mind. Many infrastructure projects in various southern states across the USA, especially in Louisiana and Texas, are often built over those problematic soils. As suggested by numerous research studies, practitioners typically adopt stabilization of the problematic soils by adding chemical admixtures to enhance their soil characteristics [13, 14].

Traditional stabilizers like lime, cement, and unconventional stabilizers like liquid ionic soil stabilizer and other waste by-products are also being used for this purpose [15]. Traditional stabilizers improve the strength properties of expansive soils through the formation of pozzolanic components. The objectives of the stabilization procedures include targeting and improving one or more properties of the soil to align with the requirements of the related infrastructure assets. Some of the typical targeted soil properties include soil strength, compressibility, and stiffness, whereas, for expansive soils, swell-shrink behavior, and volume change are the most important [16]. They are typically accomplished through the formation of chemical gel for bonding between soil particles in addition to a decrease in affinity towards water.

Many previous studies have also reported cases where stabilization with traditional calcium-based stabilizers such as lime and cement, in sulfate-bearing subgrade soils, resulted in excessive swelling and shrinkage due to the formation of highly expansive minerals like ettringite and thaumasite [17–23]. Some of this distress might not be apparent in laboratory tests but can be identified through the inspection of the heave behavior in the real field conditions. Nevertheless, this underlines the importance of field monitoring of the behavior of conventional and unconventional materials and the stabilization techniques applied in constructing and supporting pavement infrastructure assets.

2.2 Slope stability issues

Recent advancements in high-performance computing facilities and analysis software have facilitated the analysis of complex slope stability problems. Limit equilibrium and finite element based numerical tools are the two most common stability analysis approaches adopted by researchers and practitioners. Both approaches have their advantages and limitations [24, 25]. In the past decades, various limit equilibrium method (LEM) based three-dimensional slope stability analysis methods have been developed by many researchers [26–28]. The rock slopes can be analyzed by 2D or 3D numerical modeling depending on several factors such as simulation time, parameters, and field conditions [25]. Cavounidis [29] reported that the factor of safety obtained from the 3D analysis was greater than the 2D analysis of normal slopes. The accuracy of the 2D analysis depends upon the nature of assumptions that are considered to reduce a three-dimensional problem into a two-dimensional approach. Several other researchers conducted pioneering works to illustrate the benefits of performing 3D slope stability studies. The present study in this paper showcases a case study where three-dimensional stability analysis was conducted on the actual slope geometry collected using cutting-edge technology.

2.3 Conventional monitoring techniques

The application of these unconventional construction materials or stabilization techniques or slope stability analysis needs to be inspected frequently to get an idea about their effectiveness in providing a longer life to the adjacent transportation infrastructure assets. Even though most of these geo-materials are used as underlying layers of various infrastructure assets like pavements, highway embankments, earthen dams, and other structures, their performance reflects on the surface of the asset. The stability of slopes also has a bearing on the performance of the infrastructure. Therefore, traditional inspection techniques comprising of profilers, surveying instruments, inclinometers, field instrumentation, and sometimes even visual inspections are regularly adopted to understand their performance and plan for more robust testing and slope stabilization at the identified problematic locations. These techniques are subjective and are influenced by the type of tools and experience of the operators, moreover, cause delays to the traffic while data collection. There is a need for identifying modern data collection tools to monitor the infrastructure condition in a safe, efficient, and effective manner. The following sections discuss the application of cutting-edge tools for remote data collection of infrastructure health monitoring.

2.4 Unmanned Aerial Vehicles based studies

Recent developments in remote data collection using unmanned aerial vehicles (UAVs) mounted with different sensors complemented by the robust image analyses algorithms provided an alternative to traditional data collection methods used for collecting surficial information of the transportation geotechnical assets. The Federal Aviation Administration (FAA) predicted that the drone market in the US will reach 2.7 million potential annual sales of commercial unmanned aerial vehicle systems (UAS) by 2020 [30]. This can be attributed to the constant evolution of data-collecting sensors, platforms, hardware, and image processing software to address safety, efficiency, and data quality requirements of various applications including infrastructure inspections. Unmanned aerial platforms, known by common acronyms of either UAVs or UASs, have emerged as potential data collection tools for transportation infrastructure inspection and health condition monitoring. A tremendous potential is identified in these cutting-edge data collection tools since they can collect, process, and analyze large amounts of infrastructure information in lesser time, cost, and workforce compared to the traditional methods.

There are two types of UAV systems classified based on their principle of working and are widely used for infrastructure applications: rotary- and fixed-wing UAV. The former works on the principle of using lift generated by the continuous rotation of its blades. This gives an ability to hover at a fixed place, besides, to take off and land vertically, like manned helicopters. The flexibility offered by the rotary UAVs tremendously helps in conducting localized inspections of infrastructure, which is not possible with the fixed-wing UAV. The latter works on the principle of generating lift by the forward motion and the shape of the aircraft's wings. This setup allows a fixed-wing UAV to fly at higher speeds for longer durations, similar to manned airplanes [31].

Close-range photogrammetry (CRP) is a subsidiary of photogrammetry, a science that measures distances using two or more images collected within a distance of 1000 ft. from the camera sensor [32]. The UAV platforms, which do not require an onboard pilot, offer an ideal, safe, and low-cost solution to conduct the close-range inspection of infrastructure. It is termed as unmanned aerial vehicle-close range photogrammetry (UAV-CRP) technology [10]. The many benefits of this pilotless technology include a potential reduction in labor costs, emissions, and provides access to hard-to-reach areas of infrastructure. Due to the semi-automation of the inspections, there is a considerable reduction in the exposure of the working personnel to hazardous environments. The growing use of UAVs has been found in many engineering applications such as aerial photography, surveillance and control of maritime traffic, construction surveillance, traffic safety, detection and control of coastal hazards, flood monitoring, terrain mapping, fire disasters, remote data acquisition of existing transportation infrastructure conditions, earthquake damage assessment, and post distress monitoring surveys [1, 10, 33–36].

Some of the benefits of this technology pertaining to the infrastructure are discussed briefly in the following subsections.

Infrastructure Monitoring. In 2017, the American Society of Civil Engineers (ASCE) graded the infrastructure of the USA as "D". This underlines the need for adopting newer technologies with the capability to conduct proactive monitoring thereby paving way for preventive maintenance. The inspection of infrastructure assets is one of the fast-growing applications of unmanned aerial vehicles as evidenced by the fact that more than 35 state departments of transportation agencies across the USA are either in the research or implementation stage of this innovative technology for its application in regular inspection activities. Depending upon the need, various sensors such as visible range, near and far infrared, multispectral and hyperspectral cameras; normalized difference vegetation index (NDVI) cameras; and light detection and ranging (LiDAR) sensors are used for inspecting the infrastructure. The collected information is processed to obtain different characteristics and performance indicators of the infrastructure elements under focus.

Visualization. Interpretation of infrastructure data ranges from a simple graphical plot to an interactive three-dimensional view. In the transportation geotechnical fields, common types of data include surface and sub-surface exploration information of the site. These are collected using various in-situ as well as laboratory testing equipment. Laboratory information like material properties and behavior are used to interpret or validate the field behavior of the infrastructure assets influenced by various factors. Surface exploration involves a wide range of data collection equipment ranging from traditional surveying tools to contactless laser scanning devices. The data collected from aerial platforms offer a holistic view of the infrastructure conditions in a safe, quick, and efficient manner.

Recently, remote sensing and photogrammetry techniques are being used to visualize the field conditions through spatial models depicting the original conditions [37]. The data collected from the drones can be processed to obtain three-dimensional mapping products that will allow navigation through the models for better visualization of the infrastructure condition. These models also facilitate the inscription of material properties and other behaviors that are generated from either laboratory or in-situ sub-surface explorations. There are many opportunities in the transportation infrastructure fields to present the monitoring results in a rich and visual format. Three-dimensional visualization not only enhances the understanding but also improves the practical aspects of infrastructure design, construction, and rehabilitation involved during different stages of an infrastructure construction project. Project planning, design, construction, performance, resiliency, and service life assessment are the different phases of an infrastructure asset, as shown in Fig. 1.

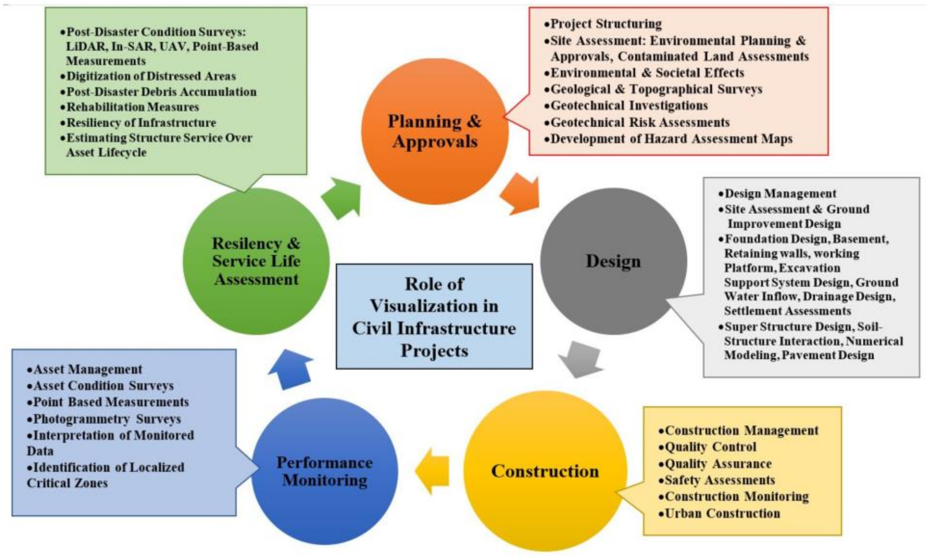


Fig. 1. Visualizing infrastructure assets during various phases throughout its lifetime

Cost benefits. The success of any new technology or methodology depends on its cost benefits. Aerial technology not only keeps the working personnel safe by keeping them away from interacting with the harsh field conditions but also conducts tasks efficiently with fewer boots on the ground and collection time compared to other traditional approaches. It needs minimal traffic restrictions due to reduced interaction with the traffic, thereby, resulting in lesser costs associated with freight and passenger traffic delays. Many previous studies have also reported that using UAVs will save more than 50% of time and cost compared to traditional approaches for health monitoring [10, 36].

The above-mentioned information has prompted this study to use unmanned aerial vehicles as a data collection tool for infrastructure monitoring. The below sections describe some of the key information required for selecting a drone, guidelines for safe drone flight, and two case studies to provide a well-needed direction for future infrastructure inspection studies based on UAVs.

2.5 Drone selection for infrastructure monitoring

Selecting the type of drone, suiting its application, is an important step in the inspection of geo-infrastructure. There are three different types of UAVs available in the market: rotary, fixed-wing, and vertical take-off and landing (VTOL). Since each of these types has its pros and cons, it is very important to know the major influencing factors that need to be considered while selecting a drone for infrastructure monitoring, as shown in Fig. 2. Most of them are interconnected with one another. Firstly, the payload, which comprises of the sensors and accessories necessary during the flight, needs to be identified since they vary for different inspections. For example, monitoring the asphalt laying process might require dual sensors, and hence a drone capable of accommodating a dual gimbal needs to be selected. Secondly, the accessories needed for the inspection should be capable of being mounted on the drone platform. For example, some inspections require a top gimbal or an additional sensor or precise navigation that cannot be possible by the inbuilt GPS of many drones. The availability of safety features, such as collision avoidance sensors and return-to-home features are of great value during close-range infrastructure inspections of unstable slopes. A global navigation satellite system (GNSS) controls the quality of data collected by the drone. The flight time per battery set limits the extent of inspection, hence drones with long battery life are selected for inspecting larger areas. Most geotechnical assets are suitable for inspection using rotary-wing UAV due to its ability to hover and conduct a localized inspection. Payloads like multi-spectral and hyperspectral cameras offer information about the unique spectral bands reflected by each soil mineral, therefore, help in site characterization. Monitoring the live progression of a landslide requires higher flight time per battery set, hence requires the appropriate selection of drone for such purposes. Slope monitoring needs to be conducted over a period of time using the same flight plan, so a drone with precise navigation capabilities will facilitate repeatable data collection at the same site.

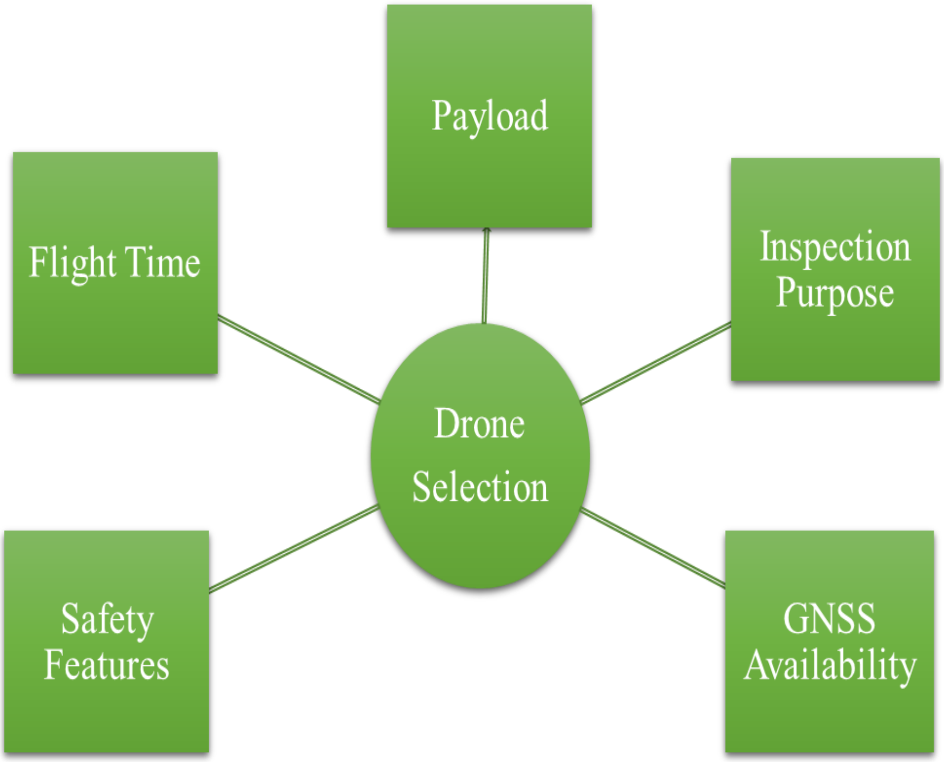


Fig. 2. Guidance for selecting an appropriate drone for geo-infrastructure applications

2.6 UAV Flight Safety guidelines

In 2016, the Federal Aviation Administration (FAA) in the United States had released a set of flight safety guidelines for the operation of small UAVs [38]. To date, these stand as mandatory guidelines to be followed by the FAA certified remote pilot in command (RPIC) for safely conducting the commercial operations using UAV platforms (weighing less than 55 lbs.) in the United States. Some of the highlights are provided below:

1. For commercial UAV operations, there should be at least one FAA certified pilot per UAV
2. Before conducting any commercial field operations, the UAV must be registered and the identification number needs to be attached visibly on the aerial platform
3. The FAA sectional charts are provided to identify the airspace class for the respective location. They also consist of details about other potential hazards such as intense glider activity, military exercise area, and many others for drone pilots to exercise caution
4. The aircraft must remain within visual line of sight (LOS) of the RPIC or a designee and yield right of way to a manned aircraft
5. Without a waiver, the drone can only fly during the day time under 400 feet above ground level and speed at or below 100 mph
6. The UAV must not be flown over people or moving vehicles which are not associated with the aerial operations
7. FAA must be reported, within 10 days, about any aerial operation that results in serious injury, loss of consciousness, or property damage of at least $500

There are also flight operations guidelines developed by some DOT agencies in the USA. For example, TxDOT’s unmanned aircraft system (UAS) flight operations and user’s manual (FOM) was developed as part of the study conducted by the authors to evaluate the applications of UAVs for infrastructure inspections. It includes various topics on flight crew requirements, flight planning rules, safety management system (SMS), project risk assessment (PRA), traffic control plans, various forms required for flight approval, health and safety plans, emergency procedures, the downed aircraft recovery plan (DARP), and accident reporting protocols. These flight operations manual guidelines were helpful to the authors in validating and conducting safe operations as part of two investigations performed for the Texas department of transportation.

3 Geo-Infrastructure Monitoring Case Studies

There are two types of aerial infrastructure inspections: qualitative and quantitative. The qualitative inspection provides a general overview of the infrastructure through an aerial perspective. The quantitative inspection provides a solution to make measurements of the infrastructure assets using remotely collected aerial data. The aerial data collection tasks performed as part of the infrastructure inspections conducted in this study are classified into pre-flight, mission flight, and post-flight tasks.

Firstly, pre-flight tasks include different activities related to the planning of the actual flight activities. They include mission objectives, preliminary reconnaissance based on web information, and identification of the airspace class prevailing at the site location under consideration. It is to be noted that the airspace restrictions may change depending upon the existing situations like weather, large crowd activity, and other events so it is a mandatory practice to check the FAA website before the aerial data collection to obtain information on any prevailing airspace restrictions. Aerial operation in airspace classes (A, B, C, D, and E), other than flying below 400 ft AGL in Class-G airspace, requires an FAA waiver.

Secondly, the tasks under mission flights include setting up and inspecting the equipment, physical reconnaissance of the inspection area, contacting the closest air traffic control (ATC) towers to inform about the day's aerial tasks, setting up of necessary signage, and preparing the flight plan with necessary longitudinal and lateral overlap. These activities are the same for both qualitative and quantitative inspections, except the latter requiring an additional task of marking and collecting the information of ground points before executing the flight plan. The ground control markers need to be distributed uniformly across the site and large enough to ensure their visibility in the imagery collected from the operating flight altitude. Often, manual and automated flights are conducted for qualitative and quantitative inspections, respectively. However, manual flights with the help of a camera intervalometer are also conducted for quantitative inspections of infrastructure assets located in complex terrains.

Lastly, the tasks under post-flight operations include the retrieval of imagery, debriefing, and performing a quick quality check at the site. If needed, the areas with poor quality images can be flown again and this facility greatly helps in avoiding the need to schedule another day of data collection due to any discrepancies in the collected data, when found at a later point. Later, the retrieved data is geotagged using either GPS or GNSS RTK or GNSS PPK data, depending on their availability. Data processing and analysis depends upon the type of inspection. For qualitative inspections, frames can be extracted from high definition videos at the desired frequency, and the metadata can also be extracted to use it in conjunction with the visual images. For quantitative inspections, the georeferenced images are subjected to batch processing steps like aligning and stitching of images, building dense point cloud, rendering of mesh & texture, and ortho-rectifying the images. Some of the 3D outputs generated by the above batch processing include a fully navigable digital elevation model (DEM), sparse and dense point clouds, mesh, and orthomosaics. These data outputs are further used for different purposes like contour generation, building information modeling (BIM), visualization, analysis using artificial intelligence techniques, and 3D printing to understand the condition of the given infrastructure assets.

Following the above procedures, two case study data were collected, processed, and analyzed as follows

3.1 Pavement geotechnics

In North Texas, the presence of expansive soils and its volumetric change due to water absorption is known to cause distresses to adjacent infrastructure assets. Many stabilizer treatments, predominantly calcium-based, have emerged in the past decades to address the expansive nature of the soil. Many of those studies were successful in arresting the expansive nature of the clay dominated by montmorillonite mineral. However, some of the treated areas, where sulfate mineral was present in soil subgrade, were found to be effective during the initial period but started to show distresses of even higher magnitude over a period. It was found that the sulfate reacted with the calcium, available in lime or cement stabilizers, alumina and silica in soils, and formed ‘Ettringite’, an expansive mineral. This led to heaving distress failures on many pavements in the North Texas area. Many researchers have identified that Ettringite is the main culprit for inducing heaving distress on pavements laid over sulfate soils treated with lime or cement stabilizers [7]. Different studies were also conducted to study the sulfate content in clay soils, factors impacting sulfate-induced heave, use of an innovative bender element to indirectly assess sulfate heaving, and other sulfate heaving related issues [7]. This underlines the need for regular monitoring of pavement to validate and observe the performance of pavements with treated subgrade and base materials.

In this study, a site that experienced sulfate heaving before and was treated through extended mellowing combined with other treatments was selected for performance evaluation of the treatment using aerial inspection. More details on the data collection and processing can be found in studies conducted by the authors [10, 11]. The three-dimensional model of a highway processed from the collected aerial images was able to visualize and help in quickly identifying the problematic regions. The dense point cloud and digital elevation models obtained from the aerial images were used to overlay contours on the pavement and identify the presence of any abrupt change in the elevation profile of the pavement. Any abrupt change in the contours can be an indication of the presence of sulfate-induced heave.

The 3D mapping products were leveraged to visualize the pavement surface in different views including the top, 3D, and profile views, shown in Fig. 3. The top left corner indicates the top view of the area and the 3D view of the area enclosed within the orange rectangle laid over the top view is shown at the top right corner of Fig. 3. A profile section of the pavement at the location indicated by the white rectangles in both the top and 3D views is shown at the bottom of Fig. 3. Since there was no visible distress on the pavement surface, the 3D and the profile views have shown the planar surface of the pavement throughout its length.

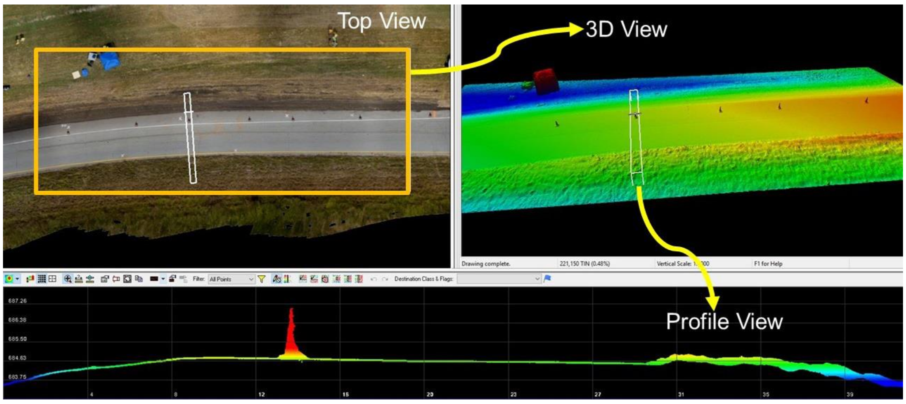


Fig. 3. Different views of the pavement condition

In addition to the dense point cloud, the digital elevation model was also provided to give a quick idea about the elevation information of the pavement and its surrounding areas (Fig. 4). Typical sulfate heaving could vary between 0.10 m to 0.25 m (4 in. to 10 in.) and any changes in the elevation profile within the magnitude of those limits could indicate either occurrence or onset of sulfate-induced heaving. Hence, half-foot contours were provided in Fig. 5, to quickly identify the presence of sulfate-induced heaving after the rehabilitation of the pavement was performed. The contours of the pavement are fairly following the design slope and there is no visible abrupt change in the elevation of the pavement. Hence, it can be concluded that the pavement did not undergo sulfate-heaving distress after stabilizing the soil with high sulfates.

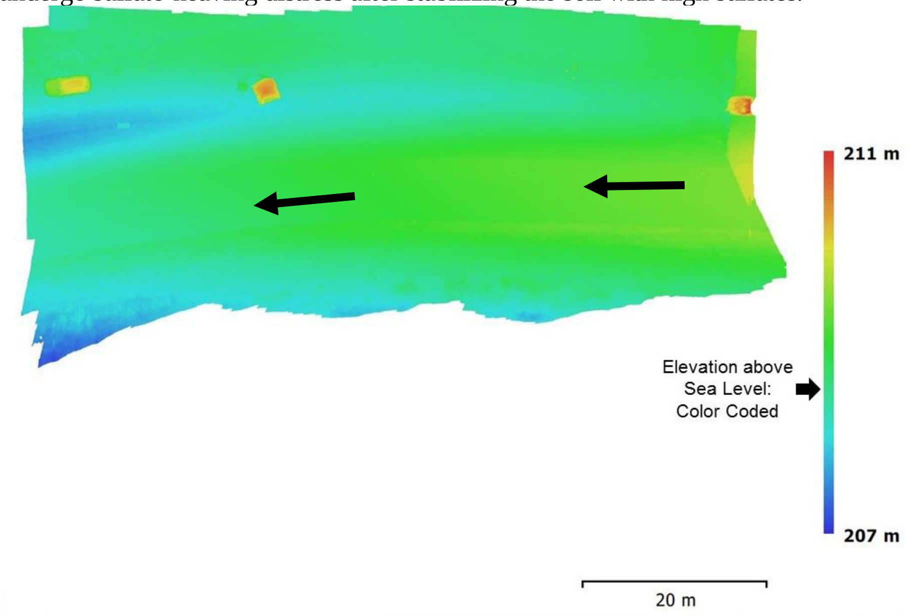


Fig. 4. DEM of the pavement and surrounding areas

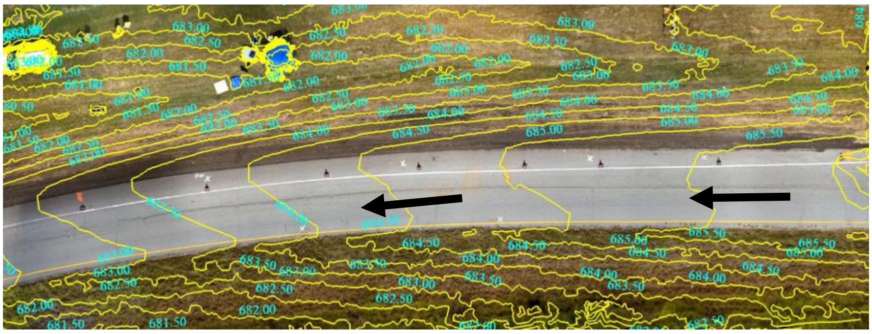


Fig. 5. Half-foot contours of the pavement and surrounding areas

3.2 Railway rock-cut slope stability

The stability of rock slopes adjacent to infrastructure assets is always considered to be crucial as failure can be destructive in terms of human and property losses. Geotechnical researchers and practitioners have been studying different slope failure modes to perform rock slope stability analyses depending upon the type of rock formation. Planar, wedge, circular, toppling, and buckling failures are some of the common failure types. The stability of rock slopes is mainly influenced positively by rock strength and negatively by rock discontinuities. Many slope stability methods proposed by different researchers have their limitations and advantages [25].

Most of the traditional data collection methods are inadequate to collect the data on the steep rock slopes. Therefore, a data collection technology that requires less time, cost, and fewer workforce is needed. This study discusses the use of UAVs to remotely capture and collect the slope geometry data using photogrammetry and then perform 3-dimensional stability analysis. The collected aerial images were processed to obtain three-dimensional mapping products presenting comprehensive information of the complex slope surface geometry. The three-dimensional model of the slope model was used for a comparison of both two- and three-dimensional stability analyses.

Three-dimensional slope stability analysis

The rock-cut is in highly weathered condition since the rail line passing through the rock-cut was constructed more than a century ago. The rock slope was considered as an equivalent continuum undergoing circular failure and analyzed using Morgenstern and Price's 2D and 3D stability analyses methods [41, 42]. Due to the non-linear behavior of rock mass failure envelope, generalized Hoek-Brown (HK) criterion was used to represent the true failure envelope of the limestone. The rock material properties considered are unit weight of 24 kN/m^3, intact compact strength value of 30 MPa, geological strength index (GSI) of 25, intact rock constant (m_i) of 8 and disturbance index (D) value of 0.7 [40]. This study used the Morgenstern and Price (M-P) method that considers both force as well as moment equilibrium to account for the effect of all inter-slice forces in the slope stability calculations. It satisfies all conditions of equilibrium and can analyze complex failure surfaces.

The three-dimensional slope geometry data from the three-dimensional dense point cloud model was used in conjunction with the rock material properties to conduct a three-dimensional stability analysis based on the Morgenstern and Price (M-P) method and identified the critical slip surface. The factor of safety (FOS) of the multiple surfaces considered on the rock slope was computed and overlaid as a surface safety map on the rock slope, as shown in Fig. 6. The colored legend on the right describes the average factor of safety prevailing at the respective location. Using the Morgenstern-Price method, the 3-dimensional global minimum FOS of the rock-cut was found to be 1.2 corresponding to the critical global slip surface. Also, slip surfaces with FOS < 1.4, indicated in yellow around the global critical slip surface in red, are provided in Fig. 7. Altogether, the present study gives an idea about a novel approach of integrating the 3-dimensional rock geometry collected from close range photogrammetry technique and material properties to analyze the rock slope stability.

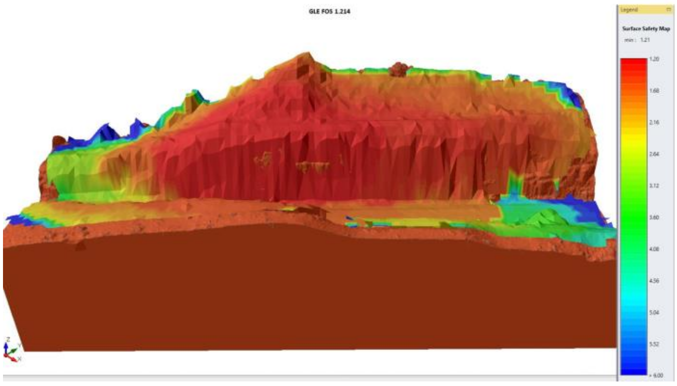


Fig. 6. Surface Safety Map obtained from Morgenstern-Price method overlaid on the Rock Cut Model

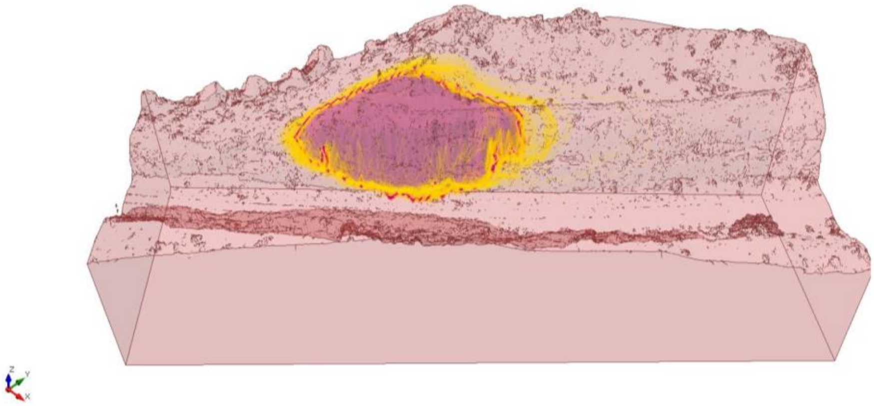
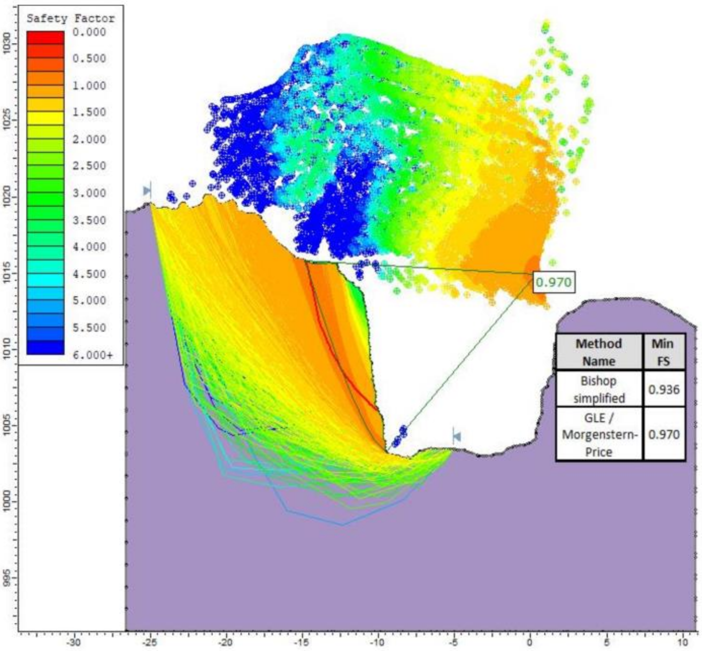


Fig. 7. Stability Analysis: Critical slip surface and surfaces with FOS less than 1.4

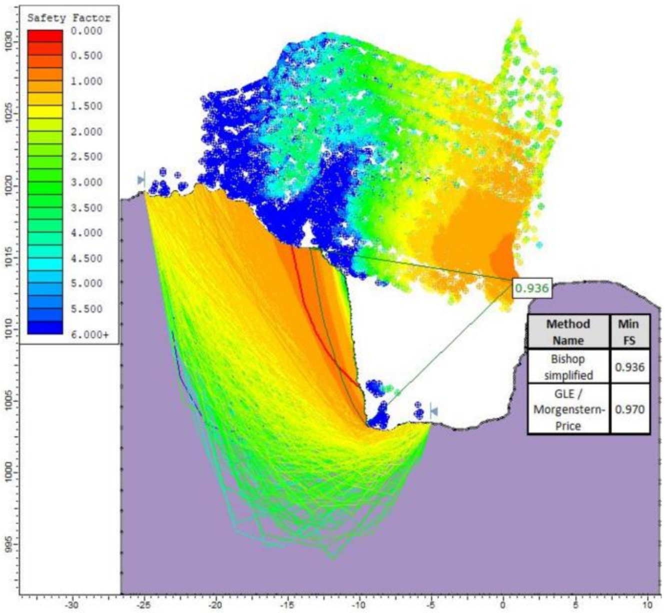
Two-dimensional slope stability analysis

Two-dimensional planar sections were created by slicing and distributing them across the slope area covering the 3D global critical slip surface. The 2D sections obtained were analyzed using commercial software for 2D LEM based slope stability analysis to identify stability using 2D analysis. For consistency purposes, MP’s two-dimensional stability analysis method was used to analyze these planar rock slope sections. Cuckoo search technique was used for locating critical non-circular slip surfaces for the 2D section. The 2D stability analysis using Bishop’s and MP’s methods yielded a critical FOS of 0.94 and 0.97, respectively. The corresponding centers for the non-circular slip surfaces identified for the 2D section can be observed around the center of the 2D critical slip surface of each section, shown in Fig. 8. The color of the slip surface and the center of the slip surface matches with the FOS safety. The slip surfaces corresponding to the factor of safety values ranging between 0 and 1.4 can be observed in Fig. 9.



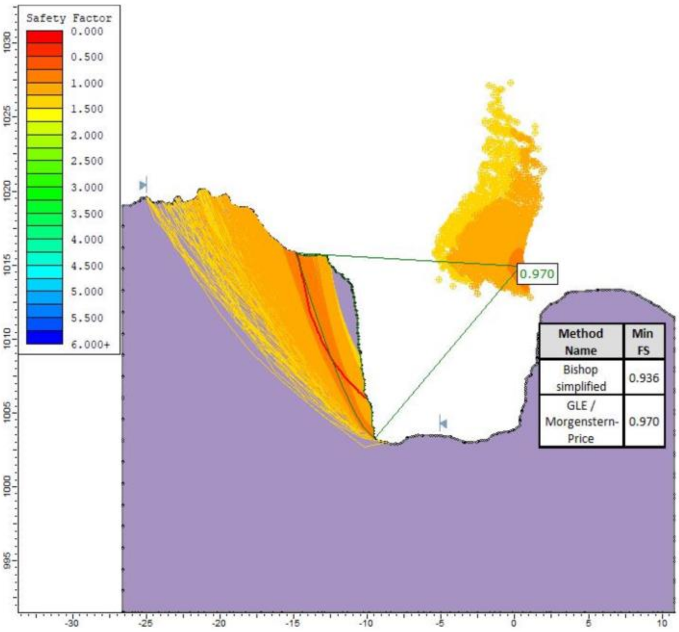
Method Name	Min FS
Bishop simplified	0.936
GLE / Morgenstern-Price	0.970

(a)

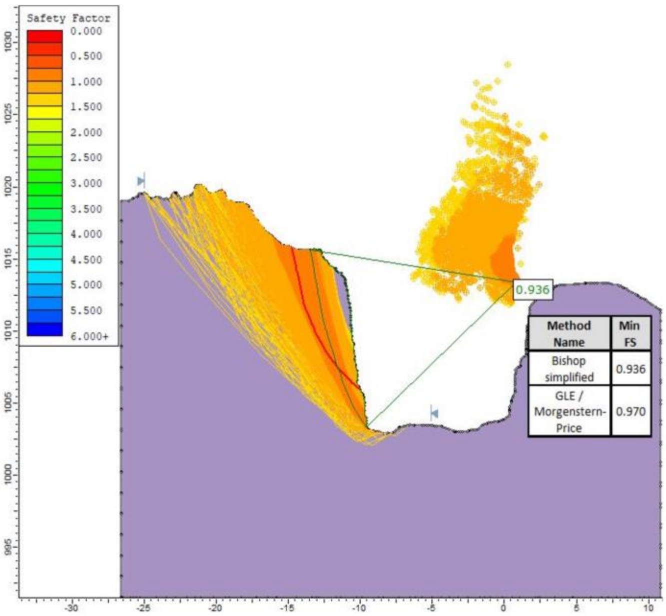


(b)

Fig. 8. Two-dimensional Slope Stability Analysis of Rock Slope (a) Morgenstern-Price's method (b) Bishop's Method



(a)



Method Name	Min FS
Bishop simplified	0.936
GLE / Morgenstern-Price	0.970

(b)

Fig. 9. Slip surfaces with FOS less than the allowable limit (a) Morgenstern-Price's method (b) Bishop's Method

It can be observed that 2D FOS from Bishop's method is conservative compared to the MP method. Also, the 2D FOS of the MP method is conservative compared to 3D FOS. Overall, the study offered a unique way of integrating the rock-cut surface profiles from UAV based photogrammetry technique and then analyzing their slope stability assessments. More studies are needed to further advance the implementation of these approaches which could play a major role in stability assessments of slopes undergoing circular failure.

4 Conclusions

This study outlined the different topics needed to be understood to select and conduct an aerial inspection of infrastructure. Two geotechnical case studies were monitored quantitatively by collecting and processing aerial images into three-dimensional mapping products. Pavement site with problematic history due to the sulfate-induced heaving was monitored to validate the effectiveness of the extended mellowing treatment. Dense point cloud, DEM, and contours have indicated that the pavement did not undergo heaving. Another case includes a rock-cut adjacent to an old railway line that was obsolete for many years. For getting the railway line back to working condition, the stability of rock slopes was monitored using aerial platforms to access those steep rock slopes. Two- and three-dimensional slope stability analyses were conducted on three-dimensional slope geometry and compared to understand the conservativeness of the 2D analysis. This also highlights the need for considering three-dimensional stability analysis to make realistic stability analysis and reduce the project costs. Also, the critical areas that need to be further strengthened to increase the safety factor above the allowable limit were identified by considering the 3D end effects. Overall, aerial photogrammetry can be considered as a supplemental tool to traditional data collection methods and expected to provide benefits in terms of data collection time, cost, and workforce required to execute a task. Moreover, it also provides a holistic idea about the condition of the infrastructure asset by providing a real-field like view through its navigable 3D models.

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