

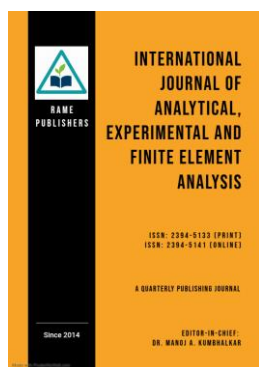


A Comprehensive Review of Remote Sensing Applications for Monitoring Soil Properties and Geotechnical Performance in Construction Projects

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Abstract: This review article discusses the novel application of remote sensing (RS) technology in geotechnical monitoring and soil property evaluation in modern construction. Although standard geotechnical tests are precise, they are frequently not able to consider spatial variability and provide real-time data on massive projects based on point sampling and manual inspection. To address these issues, this paper discusses various next-generation sensing systems, including satellite Interferometric Synthetic Aperture Radar (InSAR), aerial Light Detection and Ranging (LiDAR), and Unmanned Aerial Vehicles (UAVs) with hyperspectral and thermal sensors. Findings of the study indicate that such platforms have a significant enhancement of precision of monitoring of crucial geotechnical parameters (e.g., soil moisture, compaction, and soil deformation) and, consequently, enhance operational efficiency and cost-effectiveness. Moreover, it can be combined with Artificial Intelligence and Machine Learning methods to make accurate predictions of soil behaviour and landslides. The review indicates that the move towards Smart Geotechnics where remote sensing data are used alongside the traditional borehole sample and laboratory testing is vital in strengthening and maintaining the infrastructure. Remote sensing is a solution to the gap between historic geotechnical information and live monitoring, and a holistic approach to risk management and the best project results.

Keywords: soil, properties, remote sensing and review.

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1. Introduction

Construction projects have never been as complicated as they are today with the growing demand of infrastructures and the fast growing urbanization of our cities. Monitoring of soil properties and geotechnical performance is an important aspect of such projects because the success of any construction project is largely dependent on the nature of the soil. Traditional methods of testing these properties, including soil sampling and lab tests have been the staple of geotechnical investigations. However, they are slow, costly and have low spatial coverage particularly when it comes to large projects [1].

The advent of remote sensing technologies over the last few years has revolutionized monitoring of soil properties and geotechnical performance in construction projects. Remote sensing provides a non-destructive, cost-effective and efficient means of gathering real-time data across expansive regions using advanced technologies such as satellite data, drones, Light Detection and Ranging (LiDAR), hyperspectral sensors, and thermal infrared cameras. This allows real time monitoring which assists the engineers and project managers in determining the suitability of the soil to be utilized in construction, detecting risks and putting control measures to eliminate the risks [1].

Remote sensing methods offer several advantages against traditional methods, including the ability to get high-resolution information over large (and frequently

inaccessible) regions, in real-time. This is the information which can be utilized to supplement the traditional geotechnical tests, improving the accuracy of soil characterisation and geotechnical property modelling to various loading conditions. Moreover, remote sensing method may be used to observe the stability of soils, first signs of soil erosion, and subsidence or compaction issues, and even assess the environmental impact on soil quality during and after construction [2].

This paper will provide a review of remote sensing use in measuring soil properties and geotechnical performance in construction industry. This review will include the kind of remote sensing technologies that are used, their advantages and limitations. It will also talk about practical applications and case studies of their effective implementations in industrial regions, urban development and renewable energy projects. This review will demonstrate the groundbreaking effect of remote sensing in improving efficiency, accuracy and sustainability in construction endeavors with non-invasive, high-resolution data on the soil and geotechnical attributes [2].

As there is growing need to have sustainable and resilient infrastructure, remote sensing in geotechnical surveillance will always be relevant. Using these new technologies, the construction industry can enhance the decision-making process, speed up the process of resources to be allocated, and eventually, contribute to the development of safer, more resilient and sustainable construction projects [3].

The construction industry around the world is undergoing a paradigm shift in that sophisticated geospatial technologies and digital monitoring technologies are being integrated [17]. As infrastructure projects grow in size and complexity, the traditional methods of site characterization and monitoring infrastructure performance is more and more being complemented or even substituted by remote sensing (Rs) technologies [4]. These are contactless sensing technologies, including satellite images, Light Detection and Ranging, Interferometric Synthetic Aperture Radar, and Unmanned Aerial Vehicles, which allow continuously monitoring geotechnical assets at large scale, high-resolution and volume [5], [6].

One of the foundations of geotechnical engineering is characterized by soil properties, and discrete soil sampling techniques are typically unable to consider the spatial heterogeneity and time-varying nature of soil properties [7]. Remote sensing offers a promising alternative to this problem, as it enables the analysis of essential soil parameters, including moisture content, compaction, and nutrients of extensive areas [8], [9]. To illustrate, infrared and optical remote sensing via UAVs, and machine learning approaches have been a promising approach to map near-surface soil moisture content, which is important to highway embankment and slope stability [10].

Moreover, construction projects expose geotechnical systems to numerous environmental issues, including seasonal soil deformations and changes in groundwater [1]. Persistent Scatterer Interferometry and other techniques can be used to measure millimeter movements in the ground, which allows an early warning system of settlement or uplift on the linear transport infrastructure, e.g. roads and railways [12]. This amalgamation of such RS information streams with Building Information Modeling and artificial intelligence is also beneficial in predictive maintenance of geotechnical assets to facilitate proactive management of assets rather than reactive maintenance [13]. Despite the maturity of the technology, the issues of spatial resolution, data processing problems, and popular industry implementation standards should be considered, which means that an in-depth synthesis of the most recent studies and practices should be performed [14].

2. Background

The stability, safety and lifespan of structures in modern construction and engineering depends on the key factors that are the soil properties and geotechnical performance [14]. The stability and performance of foundations, embankments and slopes depend on soil properties, including moisture, compaction and bearing capacity [15]. Accurate control of geotechnical performance, such as ground settlement, heave and lateral displacement, is crucial to prevent disastrous infrastructure failures, particularly in massive civil infrastructure projects and urban development [15].

Traditional site investigation and soil monitoring in geo-technical rely heavily on point data collection and manual measurements [15]. There are a number of disadvantages to these traditional methods:

- Resource Intensive: Manual observations are lengthy, labour intensive and costly, and may need highly skilled technicians to be permanently on-site to observe soil properties [16].
- Spatial Resolution: Point measurements provide information at discrete points, but in many cases, this is not sufficiently resolved to capture the spatial differences in soil properties on the large construction sites [17].

- **Periodic Monitoring:** Traditional methods tend to be periodic and might not meet the sudden or seasonal changes in soil moisture or ground movements that may pose risks to infrastructure [17]. This space has been transformed by remote sensing through offering non-invasive, large-scale and continuous monitoring [18]. Construction practitioners are now able to retrieve high-quality geospatial information that seemed unattainable in the past by traditional means because of the use of satellite, airborne, and terrestrial sensors [18]. RS technologies make it possible to identify spatial and temporal patterns, providing a real-time monitoring opportunity, which enhances decision-making in the preconstruction and monitoring phases [18].

2.1. Purpose of the Study

This paper aims to provide an in-depth evaluation of the importance of remote sensing in monitoring soil characteristics and geotechnical behavior of very large infrastructure projects. This study aims to:

1. **Evaluate RS Platform Performance:** Evaluate the performance of different sensors in measuring important soil properties like moisture content and deformation.
2. **Assess Geotechnical Risk Reduction:** Assess the possibility of RS in landslides early warning systems, slope stability and management of infrastructure assets.
3. **Overcome Deployment Problems:** Understand the technical problems (e.g. spatial resolution, data processing) that do not allow RS to be more popular in the construction business.

2.2. Scope of the Paper

Important Remote Sensing Technologies Discussed. The new sensing technologies discussed in the review and their use in geotechnics are quite numerous:

- **Satellites and InSAR:** Persistent Scatterers Interferometry and Differential SAR Applications to monitor millimeter-scale deformations and seasonal soil heave/subsidence at the large scale.
- **UAVs:** The use of Unmanned Aerial Vehicles to regularly survey sites and collect data faster at inaccessible locations.
- **LiDAR:** Using laser scanning to create detailed terrain maps, terrain analysis and identification of structural deformations.
- **Thermal Infrared:** Assessment of surface moisture, and thermal anomalies that may indicate seepage or waterlogging.
- **Hyperspectral Imaging:** Informing about soil nutrients, health and composition based on spectral analysis.

2.3. Integration with Traditional Methods

The point on which this paper is going to dwell is that RS is not an alternative to the traditional geotechnical evaluation, but a complement. We talk about the application of RS data in combination with:

- **Field Sampling and Testing:** Field samples are subjected to laboratory tests to calibrate and validate RS models to increase accuracy.
- **Geotechnical Testing:** The approach to combining RS-based surface deformation measurements and borehole and piezometer measurements.
- **Building Information Modeling and Geographic Information Systems:** combining RS data with Building Information Modeling and Geographic Information Systems to create so-called digital twins of construction projects, which can be used to predictively maintain the object and manage the project life cycle.

3. Overview of Remote Sensing Technologies

3.1. Satellite Imagery

Multi- and hyperspectral sensors are used in satellites that are able to detect various wavelengths of electromagnetic spectrum. Data collected by multispectral sensors is recorded in large spectral bands (e.g., Red, Green, Blue, Near-

Infrared) are defined, whereas data collected by hyperspectral sensors is recorded with narrow spectral bands, which allows identifying the parts of the soil and chemical formations [19]. Applications: These sensors are crucial in measuring soil moisture, texture and surface temperature at large scales. Moreover, there are superior satellite technologies like Interferometric Synthetic Aperture Radar to track movements on the ground at millimeter-scale (subsidence or heave), which is essential in maintaining the stability of infrastructure [18], [19].

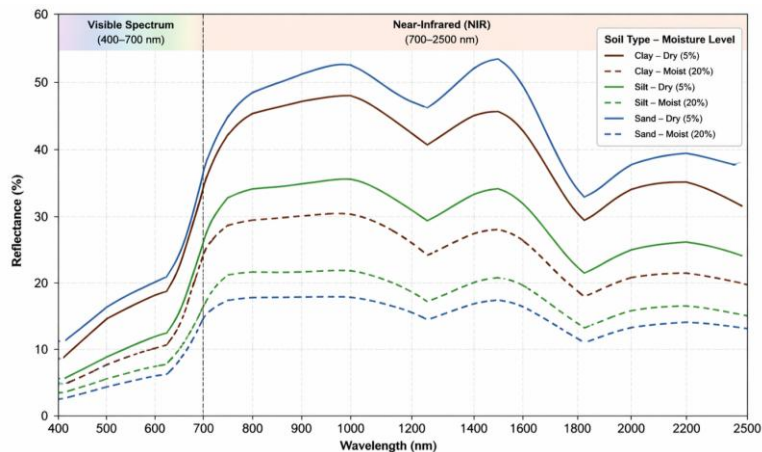


Figure 1. Spectral Reflectance Curves of the various soil types.

Figure 1 above illustrates the spectral reflectance of various soils, the textures of the soils (clay, silt and sand) and the moisture content of soils affect the reflectance of soils in the visible and near-infrared (NIR) spectrum. The wavelength (nm) between 400-2500 nm is the X-axis, where the visible spectrum (400-700 nm) is on the left and near-infrared spectrum (700-2500 nm) is on the right. The Y-axis is percentage of reflectance that ranges 0 to 60%. The lines indicate different types of soils and water content. As an example, the brown curves are the clay soils: one one is dry clay soils and the other is moist clay soils. The silt is given in green and the sand in blue with two lines each: dry and moist. The dry soils are solid lines and the moist soils are the dashed lines [19].

The plot exhibits a few absorption characteristics, which are the water absorption characteristics at 1400 nm and 1900 nm and the clay mineral absorption characteristic at 2200 nm. These characteristics are important since they show the effect of moisture and texture on the reflectance. As an illustration, wet soil absorbs more light and has less reflectance in certain wavelengths whereas dry soil, particularly those with rough textures, such as sand, reflect more light [19], [20].

The form of the reflectance curves shows that finer textures like clay are more likely to absorb more and reflect less light especially when wet whereas coarser textures like sand reflect more light and reflect higher when dry. This range of reflectance is useful to hyperspectral sensors to distinguish the characteristics of soils, including moisture and texture, which are of interest to remote sensing the environment and also in agriculture [19].

3.2. Drones and UAVs

Uncrewed Aerial Vehicles (UAVs) have emerged as a transformative technology in construction monitoring, offering high resolution images and timely data collection that are difficult to obtain from satellites due to cloud cover or revisit periods [21]. Applications: High-resolution optical and infrared cameras are mounted on drones to provide real-time monitoring of construction and soil conditions [21]. UAV data combined with machine learning can accurately classify near-surface soil moisture in sensitive locations such as highway embankments [23].

The aerial map of a construction site (Fig. 2) was captured using a UAV (Unmanned Aerial Vehicle). It is an orthomosaic top down map, providing a close-up of the construction site, with the arrangement of earthworks, equipment, and buildings. The map is also superimposed by a soil moisture heatmap, which shows the areas with varying moisture content, including low (dry) and high (wet), which allows locating hotspots of soil moisture. Contour lines are also drawn in the map indicating the elevation of the site, and it is possible to visualise the topography of the site and the changes in elevation. The right hand legend gives details of the different features of the site such as construction equipment, buildings, stockpiles, bare soil and site offices. The map shows details of the project, among which is the date

of capture (15 May 2024), the UAV employed to conduct the survey (DJI Matrice 300 RTK), the resolution of the image (2.5 cm per pixel), and the coordinate system (WGS 84 / UTM 37N).

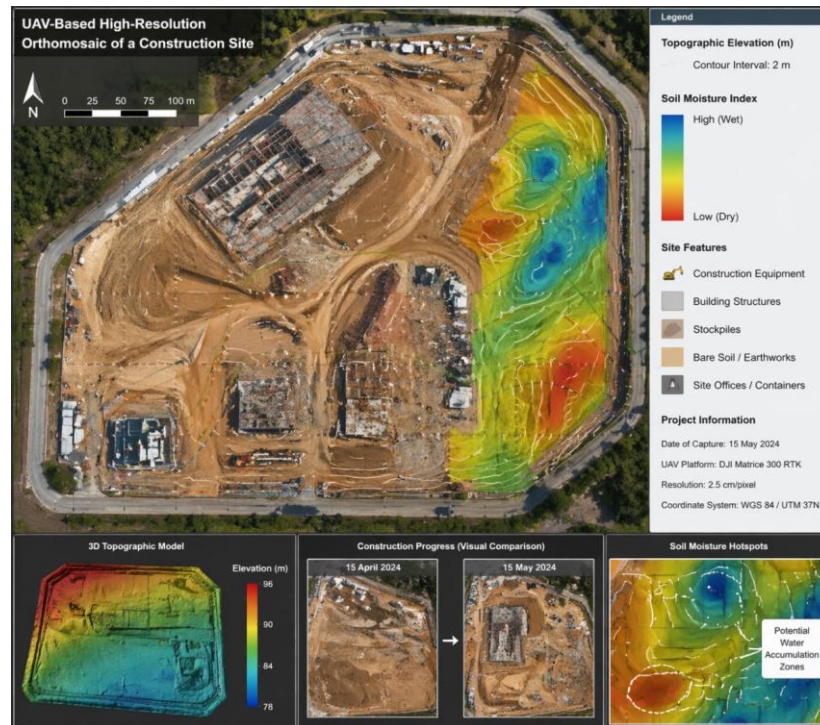


Figure 2. High-Resolution Orthomosaic of a Construction Site using UAV.

In the figure 2, you can also find some panels at its bottom. One of them is a topographic model (3D), which gives a 3D representation of the elevation. In another panel, the comparison of the site development of two dates (15 April 2024 and 15 May 2024) is displayed, indicating the progress of the site in one month. The final panel depicts the soil moisture hotspots, which possibly represent potential zones where water can accumulate and through which can impact construction and soil treatment.

3.3. LiDAR

LiDAR uses laser rays to measure distances and create finer details of the surface of the earth in three-dimensional forms, referred to as point clouds. LiDAR plays a vital role in geotechnical engineering since it is applied to trace topographic and structural changes of the surface of the ground. It is often applied in topography modeling, geology mapping and detection of small variations in the slope geometry that may cause landslides or structural instability [22].

Figure 3 is a more detailed 3D point cloud model of a slope failure with high-resolution LiDAR (Light Detection and Ranging) data that illustrates the different structural deformations and topographic features at the slope failure site. The image is a LiDAR-based digital terrain model (DEM) providing a high-resolution perspective of the terrain, especially the various parts of the slope failure, such as the crown crack, main scarp and toe area. The image has these features highlighted to indicate the locations of major structural deformations. The colours in the model show the differences in elevation with the warmer colours (reds and oranges) showing higher elevations and the cooler colours (blues and greens) showing lower elevations. This enables us to readily compare the steepest areas (at the crown crack) and the more flatter areas (toe region). The altitude data is necessary to analyze the movement of the slope failure, e.g., the influence of the deformation on the structure and stability of the slope. The LiDAR acquisition information is located at the upper-right corner and it indicates the specifics of the data acquisition. The data was collected May 12, 2024, using a RIEGL VUX-240 LiDAR sensor. The density of the point clouds is set at about 450 points per square meter which is quite detailed as an elevation data. To ensure consistency and accuracy to the elevation data, the data is referenced to the coordinate system UTM Zone 37N and vertical datum WGS 84 / EGMM36, both of which are commonly used geographic reference systems.

The figure 3, except the 3D model, has several insets to give more detail on the terrain information. The first inset displays the Digital Elevation Model (DEM) which is a 3D display of the terrain and demonstrates the height along the slope. The second inset, "Slope Gradient (Degrees), shows the gradient of the slope on its different regions, and shows the regions of steep gradient of the slope where the slope failure has occurred. It is on these areas that failure is more probable to happen thus this gradient map assists in comprehending how failure occurred.

The third inset is a cross-section of the slope, along the line A-A'. This profile shows the change of height of the slope as one moves up the slope through the crown crack to the main scarp and further to the toe. It aids visualisation of the extent of the failure and transformation of the slope profile as a result of the deformation. Such a profile assists in seeing the severity and scope of the failure, and its potential impact on the environment or infrastructure in the area. These types of LiDAR data are crucial to geotechnical and slope stability studies. It provides a high resolution model that can be applied to learn about slopes and predict future landslides or other slope failures. The exact topographic lines and deformation mapping can help engineers and geoscientists have a better understanding of the process of failures that is not possible to achieve with the help of ground-based surveys. Engineers and scientists are also able through the application of these technologies to not only track the development of the slope failures but also put in place improved measures of slope stabilisation, be it slope strengthening, drainage enhancement or even a measure of future potential failures [24].

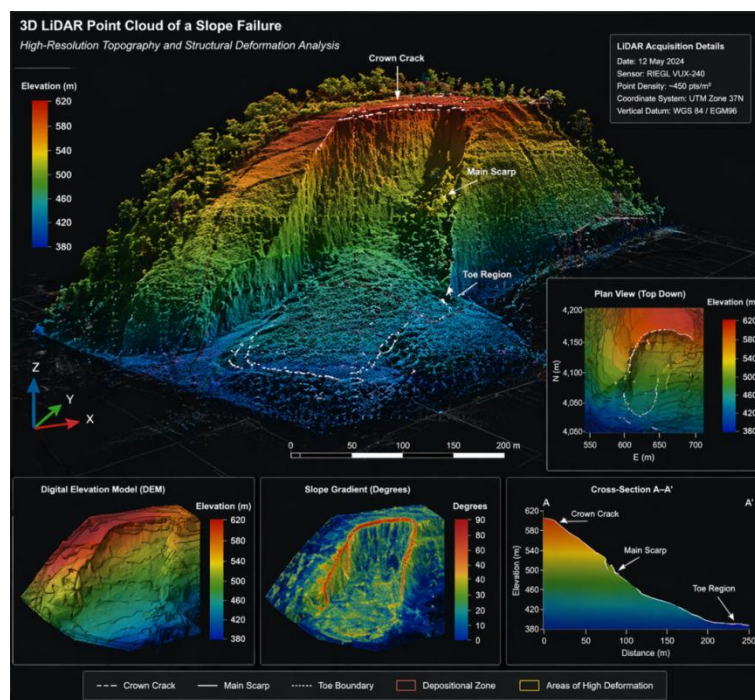


Figure 3. Slope Failure 3D LiDAR Point Cloud.

3.4. Thermal Infrared Sensors

Thermal sensors detect long-wave infrared emissions on the surface and these measurements are proportional to both the temperature and thermal characteristics of the surface. Water possesses high specific heat; thus, the change of temperature detected by such sensors is a good indicator of soil moisture [24]. These types of sensors can be applied in construction to identify possible geotechnical issues such as waterlogging, dam leakage or water-induced instabilities in embankments [25].

Fig 4 is a thermal map that demonstrates the changes in the soil moisture content in a construction site. The map is created based on the thermal infrared information that describes the change in temperature of the soil and the various colours show various levels of moisture saturation. Increased moisture saturation tends to be shown with warmer colours (like red and yellow) and decreased moisture areas are shown with cooler colours (like blue and green). The thermal map can be used to identify the high saturation areas that can either be signs of drainage problems or possible erosion. This assists engineers and site managers to focus on those areas where the moisture content may lead to issues, like improving

drainage or stabilising the ground. Monitoring of soil moisture variability using thermal infrared imaging technology can be done in real time and non-destructively, offers a more effective method of information gathering compared to traditional sampling techniques. These thermal maps may significantly aid in soil property management and avoid issues during construction leading to better geotechnical planning and preparation [25].

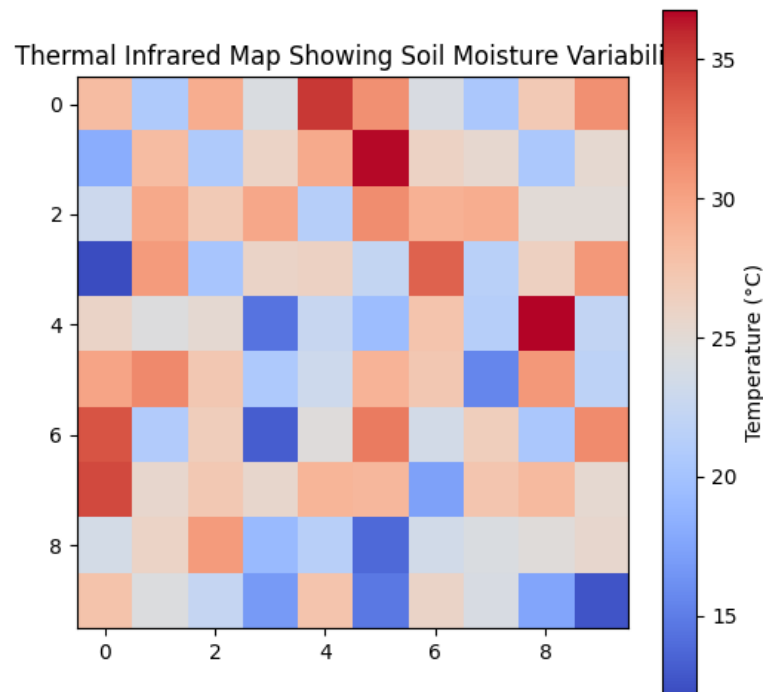


Figure 4. Thermal Infrared Map of Soil Moisture Change.

3.4.1 Advantages of Remote Sensing

The RS technologies offer a set of groundbreaking benefits compared to traditional geotechnical methods:

- **Non-Intrusive and Real-Time Data:** RS provides a non-contact type of measurements, allowing the research of geo-hazards (e.g. slope instability along the roadside to underground voids) without interfering with the soil [25]. It delivers real-time (or near-real-time) data, which is crucial in making real-time decisions about live construction operations [26].
- **Bulk Monitoring:** RS methods are able to scan an entire infrastructure network or a large project region, instead of just individual sample points (boreholes/CPT) in order to resolve spatial variability that is not known to point tests [27].
- **Access to Hazardous Areas:** RS can also be applied to monitor remote and/or hazardous locations, like unstable slopes or contaminated locations, where it would otherwise be too risky to deploy surveyors [26].
- **Cost-Effectiveness:** The initial cost of installing the advanced RS systems can be high, but it will result in significant cost-saving in the long-term perspective as it will remove the labor expenses, site visits and repair activities due to geotechnical issues that are not detected (Almohsen, 2024). RS-based predictive asset management allows conducting maintenance in time, and hence extends the life of the asset [27].

This table is a comparison of traditional methods (e.g., soil sampling and laboratory tests) with remote sensing (e.g., satellites, drones, LiDAR, thermal infrared) using a variety of metrics that are important in soil and geotechnical monitoring at construction sites.

Table 1. The comparison between the traditional monitoring and remote sensing monitoring.

Metric	Traditional Monitoring	Remote Sensing Monitoring
Data Density	Limited to small, discrete sample points	High-density, continuous data over large areas
Safety	Requires on-site personnel, which can be hazardous	Non-invasive and remote, minimizing health and safety risks
Speed of Acquisition	Time-consuming, results take days to weeks	Real-time or near real-time data acquisition
Spatial Coverage	Limited to sampled locations	Can cover vast, hard-to-reach, or inaccessible areas
Cost	Expensive due to labor, equipment, and testing fees	Can be cost-effective with large-scale data coverage over time
Data Accuracy	High accuracy in localized areas, limited by sample size	Accuracy depends on technology, but improving with new sensors
Scalability	Difficult to scale for large projects	Easily scalable for large construction sites or ongoing monitoring

The Traditional vs. Remote Sensing Monitoring comparison reveals the contrast between the traditional methods of soil monitoring, e.g., soil sampling, laboratory analysis, and the latest remote sensing technologies, e.g., satellite data, drones, LiDAR and thermal infrared. The table contains significant indicators of determining the soil properties and the geotechnical performance in different construction applications. The traditional monitoring offers low density, i.e. only presents data at the sample points whereas remote sensing offers high density, continuous data with high spatial coverage, offering a wider view of the site. In the context of safety, the conventional approaches are that the people are on site, which could be risky especially during construction works. However, remote sensing is not contact and can be performed remotely, minimizing the safety hazards.

The speed of acquisition is another benefit of remote sensing. Conventional monitoring systems may be slow where data acquisition and analysis takes days or weeks, compared to remote sensing which provides real-time or close real-time data thus making decisions faster. Traditional methods have limitations on the area covered as only the area where the samples are taken is covered with large portions of the construction site being missed. Remote sensing has the ability to observe large areas that cannot be accessed, this is handy when using in areas that are difficult to access or in large construction projects. Remote sensing may be cheaper, too. The traditional methods can be time consuming and costly in man power and equipment but remote sensing can be economical, especially in the long run, since it is applicable to a vast area. The methods of traditional measurements have high data accuracy at the local sample points, but are limited by the sample size. With the development of new technology, remote sensing accuracy is increasing, and it can accurately collect data [28].

Last but not least, is scalability. The conventional monitoring methods cannot be easily scaled-up, especially when the project is large and the number of samples is high. However, remote sensing is very scalable and can be applied in large construction sites, providing information in details over time and throughout the construction process. This comparison demonstrates the usefulness of remote sensing technologies to improve the efficiency, coverage and cost of monitoring of soil and geotechnical performance of construction projects.

4. Literature Review – Advanced Remote Sensing in Geotechnical Engineering

The recent rise of the literature in the area of geotechnical engineering has highlighted the move towards the concept of continuous and remote-sensing methods in lieu of the empirical and point-based ones. Such a shift is informed by the fact that it is extremely important to be more precise in the process of identifying the subsurface anomalies and reducing the risks of the large-scale infrastructural project that is not detected by the traditional borehole sampling [28]. However, recent research has revealed that the combination of satellite data, UAV sensors and model computations - including machine learning - is essential in the control of the uncertainties and heterogeneities of soil properties [28]. This literature review of six selected studies gives illustrations of how the technologies are already being used and are successful in diverse geotechnical and industrial applications.

4.1 Study 1 Hyperspectral Subgrade Soil Mapping with UAV.

The availability of water in the subgrade is crucial to road constructions stability. Kischel Lee and others examined the possibilities of Unmanned Aerial Vehicles (UAVs) with hyperspectral sensors to determine the moisture content of subgrade soils [29]. Spectral reflectance data were processed into models that accurately predicted moisture content variations across a construction site, rather than the time-intensive and labor-intensive method of drying samples of soil in an oven [29].

The figure 5 demonstrates how spectral reflectance of subgrade soil varies with the content of moisture at various wavelengths including the visible and near-infrared (NIR) ranges. The X-axis will be the wavelength in nanometers (nm) between 400 nm and 2500 nm and the Y-axis will be the percentage of light reflected by the soil.

The figure 5 indicates three lines that depict the reflectance of soil with varying contents of moisture: dry, moist and wet soil. The drier the soil, the higher the reflectance of the soil, especially on the near-infrared range. The reason is that water absorbs light particularly at some wavelengths leading to low reflectance. Specific wavelengths of essential absorption bands in the near-infrared region include 970 nm, 1200 nm, 1450 nm and 1900 nm. These bands are indicated in the graph since they are an indication of absorption features of water which are called the overtone and combination bands. The importance of these bands is that they are used to determine the percentage of water in the soil since the bands have specific troughs in the reflectance curve at these wavelength, indicating that the soil is higher in water content. This information is also vital in remote sensing and hyperspectral analysis because the latter can be employed in establishing the content of soil moisture. The reflectance at these bands can be used by engineers and scientists to get more information on the soil which is vital in many applications like crop management, civil engineering and environmental assessment.

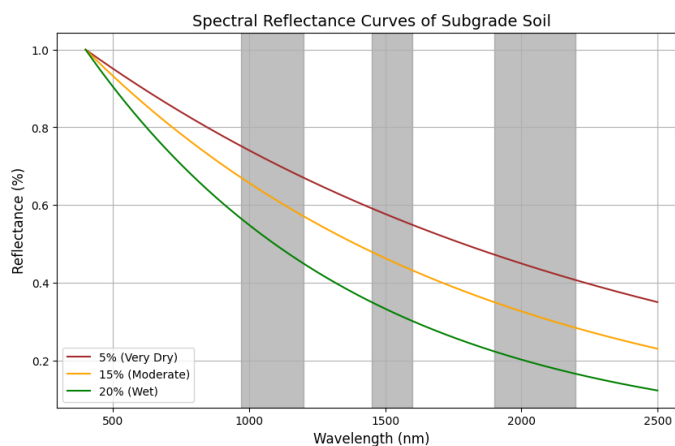


Figure 5. Spectral Reflectance Curve of Subgrade Soil..

The spectral reflectance curve (figure 5 above) of a subgrade soil is used to show the reflectance values at different moisture content levels in the soil (very dry, dry, moist and wet). The wavelength of light is plotted against the X-axis where the visible (400-700 nm) is on the left and the near-infrared (NIR) range (700-2500 nm) on the right. The Y-axis is a percentage of reflectance or the quantity of light being reflected at any wavelength.

The graph has a number of lines, which represent the various levels of soil moisture. The less reflectance, the greater the moisture content of the soil particularly in the NIR range. This is because of the absorptive characteristics of water which is more effective in the NIR. The curves have different moisture content, a very dry soil (red), a wet soil (purple) and the middle moisture content is represented by the orange, green and blue color.

The figure also indicates the presence of major absorption bands in the NIR region which are important to estimate the moisture content of the soil. They are the bands that are produced at specific wavelengths (970 nm, 1200 nm, 1450 nm, 1940 nm and 2200 nm). Hyperspectral sensors consider these bands important since they can be utilized to determine the presence of moisture in the soil by measuring the absorption of light by the water. The absorption bands are marked in the figure, and it can be seen that the locations of the absorption bands are where the reflectance diminishes significantly with an increase in moisture.

Such spectral data can be useful in remote sensing and soil research where engineers and scientists can use it to estimate the water content of the soil and how it affects the activities of farmers, land use or construction projects. The figure demonstrates the relationship between soil moisture and reflectance, and can be used to visualise the application of hyperspectral sensors in monitoring soil.

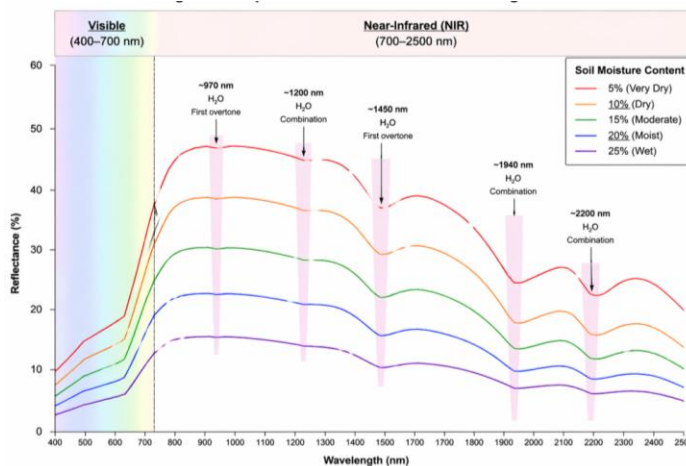


Figure 6. Spectral Reflectance Curve of Subgrade Soil.

Figure 7 presents in detail a spatial map of the water content of a section of a highway subgrade, using the information obtained via an Unmanned Aerial Vehicle (UAV). This heatmap map will show the distribution of the moisture content in the subgrade so that engineers could visually differentiate the areas with different moisture content and take the required steps. The color ramp of the heatmap is between warm color (red, yellow) and cool color (blue, green) to illustrate the high and low water content respectively. The warm colors in the map are areas that could be weak or unstable and could require to be stabilized or drained so as to improve the performance of the subgrade. The cool colors reflect the potentially stable or dry areas, which are unlikely to become a serious problem to the construction and foundation performance. The right hand legend provides a clear picture on the percentage of volumetric water content in the range 5-35. It enables the engineers to locate the moisture content in the various areas of the highway subgrade, and to make knowledgeable decisions regarding how to manage any existing problems in these areas. The high-resolution of the heatmap allows a more detailed inspection, and thus, it is a useful tool not only as a real-time moisture sensor but also to inform specific soil stabilization actions to be taken at the appropriate sites to improve the performance of the highway subgrade. The figure shows the importance of UAV data in high-resolution soil moisture mapping, and subsequently, improved infrastructure maintenance and construction.

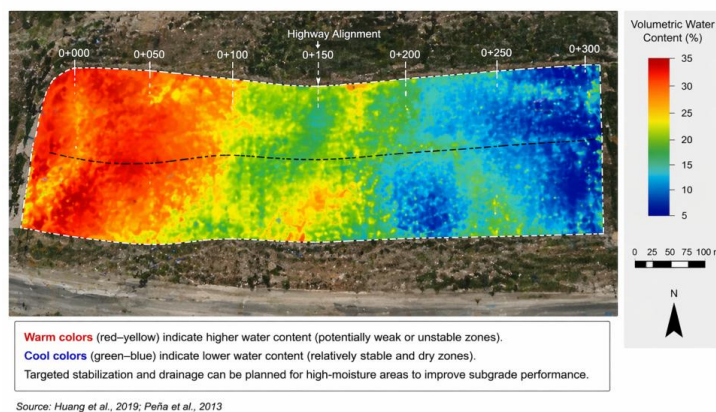


Figure 7. Spatial Water Content Distribution Map.

4.2. Study 2: Smart Compaction of Soilrock Mixture Subgrades.

Soil-rock mixtures can prove to be difficult to test on quality of compaction depending on the variance of the compaction mixture. Mei Shi et al. have created a smart compaction system (with real-time moisture-CMV composite

control and edge computing) [30]. This method allows determining the subgrade stiffness and moisture content in real-time during the rolling process, with the whole project area meeting the design requirements without using a significant number of spot tests [30]. The figure 8 depicts the design of a smart compaction system that seeks to improve construction by improving the quality of compaction. It begins with a set of sensors on the compactor (roller) that collect data as the compaction process is conducted. These include vibration sensors, accelerators, temperature sensors and GNSS (Global Navigation Satellite System) to measure vibration, acceleration, temperature and position of the compactor. This data is sent to an edge computing unit, attached to the roller.

The edge computing unit will handle the processing of the data in real-time, say, signal processing, compaction measurements, and compaction quality analysis. It identifies any differences or places where extra compaction is necessary. This data is then displayed on the operator display in the compactor cabin to provide the operator with a feedback on the compaction. This involves a compaction map, number of passes and whether the compaction has achieved the desired values. It also issues warnings on areas that require advancements. It also records the compaction information to the device and through wireless connectivity; the information is stored in the cloud. This will enable further analysis and remote access to the data to review and evaluate performance. Trends and performance are analyzed using this data and reports generated providing an insight on compaction efficiency and quality. Project managers and engineers can use this information to decide and monitor progress and improve on the quality of compaction to ensure that the construction project meets compaction standards. With this system architecture the compaction process can be monitored and enhanced enhancing the process efficiency and quality and reducing human error.

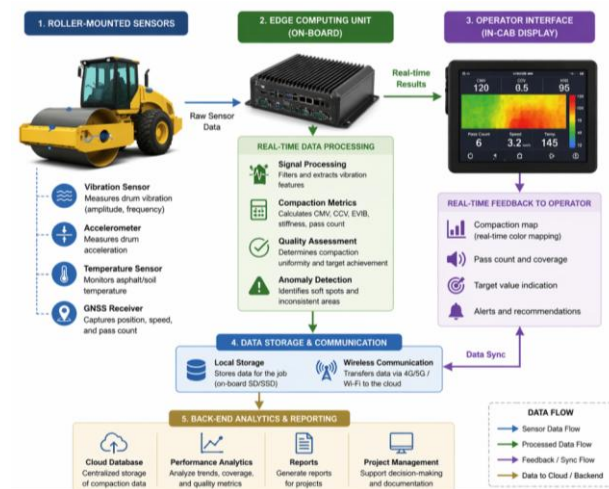


Figure 8. Smart Compaction System Architecture.

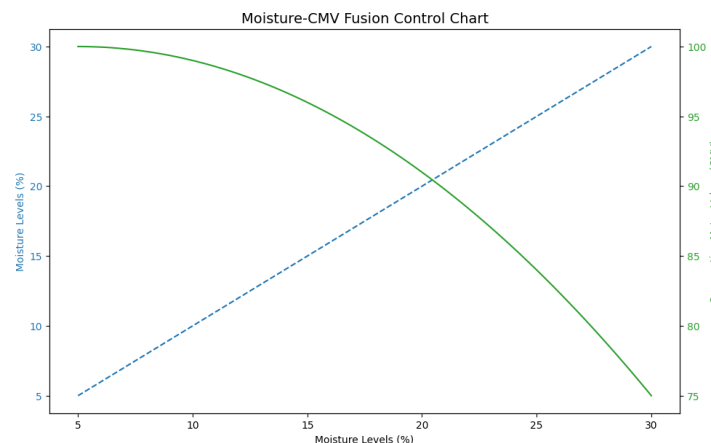


Figure 9. Moisture-CMV Fusion Control Chart.

The Moisture-CMV Fusion Control Chart, which is illustrated in figure 9, is a dual axis graph that explains the relationship between moisture and Compaction Meter Values (CMV). This chart shows the interaction between the two

factors in subgrade soil compaction. The chart presents the moisture level on the left y-axis, 5-30%. The rising water content is signified by the blue line (dashed) which rises to the right. This is the amount of moisture in the soil at the time of compaction. The Compaction Meter Values (CMV) is illustrated by the solid green line on the right y-axis. Moisture level has a negative correlation with CMV. The CMV starts taking a higher initial value (around 100) at lower moisture levels and then declines with the rise in moisture levels. This dual axis plot graphically illustrates the influence of moisture on the compaction process where more moisture resulted in less effective compaction evidenced by the decreasing CMV. Combining these datasets, engineers will be able to better determine the quality of compaction of the soil and modify their methods to guarantee that the subgrade is stabilized properly [31].

4.3. Study 3: Multiple-source Remote Sensing of Mining Deformation.

It is very important to detect the ground deformation early in mining and other large excavation sites to prevent catastrophic accidents. Liuru Hu et al. demonstrated that it was possible to update active deformation inventory maps with the help of InSAR and LiDAR data [32]. The multi-source data enables engineers to trace millimeter-scale surface variations over extensive regions, which can offer an early warning system of slope failure and subsidence that can influence infrastructure [32]. Figure 10 shows an InSAR Line-of-Sight (LOS) velocity map, and it shows the rate of ground displacement velocity in a mining region. This high-resolution satellite image is a colour-scale image to show the velocity of the displacement, with the negative values (coloured red and yellow) corresponding to the displacement of the ground towards the satellite (subsidence) and the positive values (coloured blue and green) to the displacement of the ground away the satellite (uplift). A color ramp, which begins with the stable areas (green) down to the areas of high displacement (bright colors, including red) that indicate a high risk of subsidence is also shown on this map. Figure 10 shows outlines of areas in the mining region flagged as high subsidence risk areas that should be further explored and mitigated with the dashed outlines. These are areas that are susceptible to ground movements, and where more research is needed.

A map is also provided at the bottom of the figure to provide some form of context as to where the mining region is located within a larger geographic region. Other important data that are found in the map is the LOS direction, heading and incidence angle that are used to identify the position of the satellite and its viewing angle. The time period of data (January 2021 - January 2023), source (Sentinel-1A) and the processing method (SBAS-InSAR) are also included, to provide a clue about the data collection and processing. Overall, this map allows one to have a good sense of the ground movement in the mining area, the areas of concern regarding subsidence, which is paramount in guiding engineering and safety considerations of mining operations.

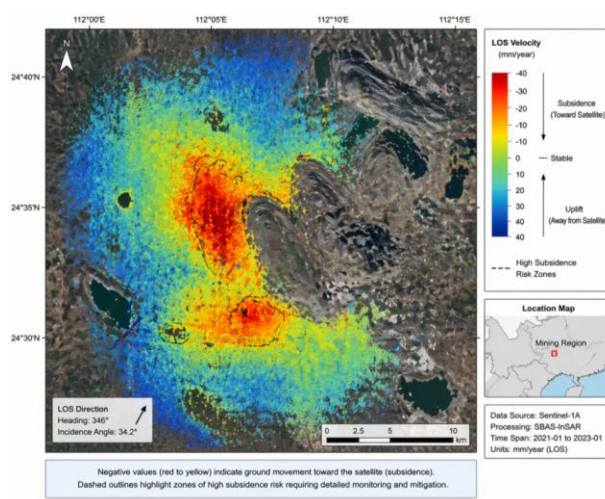


Figure 10. InSAR-Derived Line-of-Sight Velocity Map

A cross-sectional LiDAR deformation profile of mining slope is shown in figure 11, which compares the historical heights of the slope with the modern values, to visualize the physical volumes of the area and structural displacement of the terrain. The original topography of history before any major alternation happened is indicated by the historical elevation, whereas the modern day elevation of the slope is indicated by the current elevation. The deformation or loss of

volume is depicted by the difference between the two profiles, indicating where the ground has been deformed or even moved vertically [33].

This deformation plays a critical role in the stability of the slope because it gives useful information on what might cause some risks in the slope such as slope failure or subsidence that may impact on the mining activities or the structures around the slope. Through such elevation variations, engineers and geologists can determine the extent of deformation and take decisions on what to do to stabilize the slope or to avoid further losses. In this kind of cross-sectional analysis, LiDAR data are used to enable a fine level of tracking topographical change, which is a high-resolution instrument to examine and control the slope stability [33].

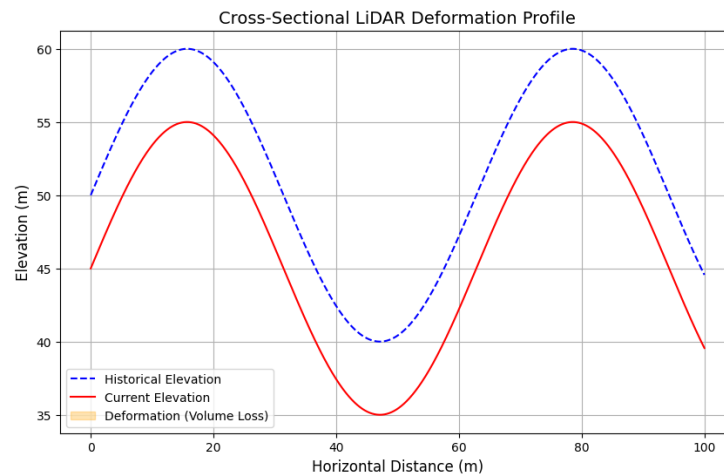


Figure 11. Cross-Sectional LiDAR Deformation Profile.

4.4. Case Study 4: City Foundation Risk, Machine Learning.

Cities tend to be constructed on loose soils and near complicated infrastructure. Ali Akbar Firoozi explored the application of Machine Learning to geotechnical risk assessment by training the model based on the historical subsurface data with subsurface monitoring data [34]. The articles demonstrated how the ML could take hundreds of variables into account: soil characteristics, groundwater, and utilities are present, to predict potential foundation failure, resulting in improved projects compared to the traditional qualitative judgements [34].

A machine learning (ML) risk prediction flowchart as illustrated in figure 11 demonstrates the process of predicting the degree of soil risk based on multi-source geotechnical information. It begins with the data inputs, which includes the collection of different geotechnical data, including the InSAR displacement, LiDAR deformation, compaction, moisture content, soil property, environmental data and soil risk labels. To predict the risk, this information is required to know the present condition of the soil. The second step is the preprocessing of data whereby data is cleaned by dealing with missing values and outliers. It is spatially and temporally consistent to preserve the temporal and spatial integrity of the data. It normalises the data to have the features on a similar scale and encodes categorical data. After preprocessing, the data is prepared to undergo feature engineering, whereby statistical and geotechnical features are extracted out of the data. The correlated features are removed, and the dataset is in some cases, downsized using algorithms like Principal Component Analysis (PCA). Once feature engineering is done, the data is separated into training, validation and test sets. The training set (70 percent of the features) is used to train the model on the patterns and relationships among the features. The rest of the data (30% validation and 30% test) is used to test the model and quantify its performance on new data.

In the model training step, a machine learning algorithm (e.g., Random Forest, XGBoost, or neural network) is selected. The training set is fitted to the model and hyperparameter optimization is performed to optimize the model. Once the model has been trained, it is then tested to determine its performance with the help of different measures, including accuracy, precision, recall, F1-score and ROC-AUC. It is also validated through cross-validation. When the performance of the model is satisfactory, it proceeds to the prediction stage whereby it is used on new sites to determine the risk level of the soil. The model classifies the soil into low, medium and high risk, which could be applied by engineers and geoscientists to evaluate and control soil risk.

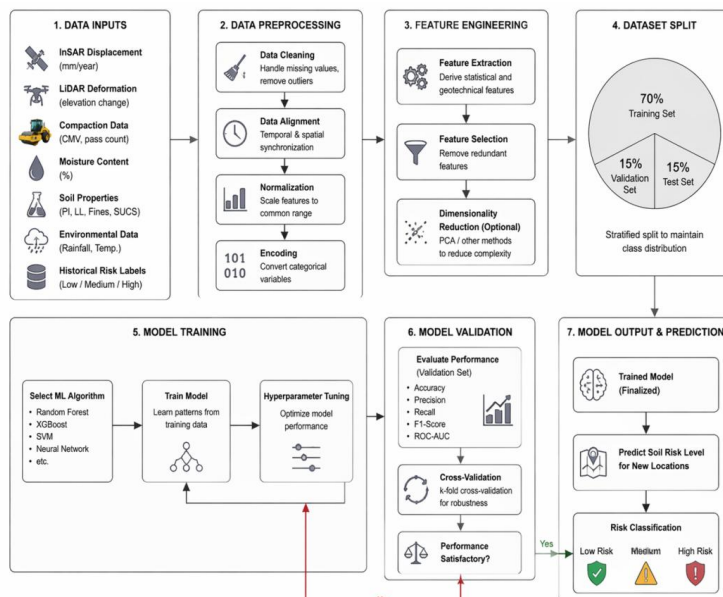


Figure 12. Machine Learning Risk Prediction Flowchart

In this figure 13, a scatter plot is drawn of the predicted values of the foundation settlements against the observed values of the foundation settlements observed during construction. The settlement that has been predicted is the X-axis and the observed settlement is the Y-axis. The settlements of the foundations observed and predicted are represented by the points on the plot.

The distribution of the information points presents the tendency of the high level of correlation between the predicted and measured values. This is indicated by a red dashed line that is the line of perfect correlation, at which the settlement that is predicted equals the observed settlement. The nearer the points on the data to this line, the more the predictions of the model are good. Most of the points are near the red dashed line although there are minor differences. These variations are minor differences between the values of settlement which are predicted and the value of settlement which is observed and which can be anticipated due to a number of reasons, such as the inaccuracies in measurements or some other factors can affect the real settlement in practice, such as temperatures, presence of moisture, etc. Summing up, the plot reveals that the machine learning model used to forecast the foundation settlement has a decent accuracy level, and the estimated values are closely related to the measured values.

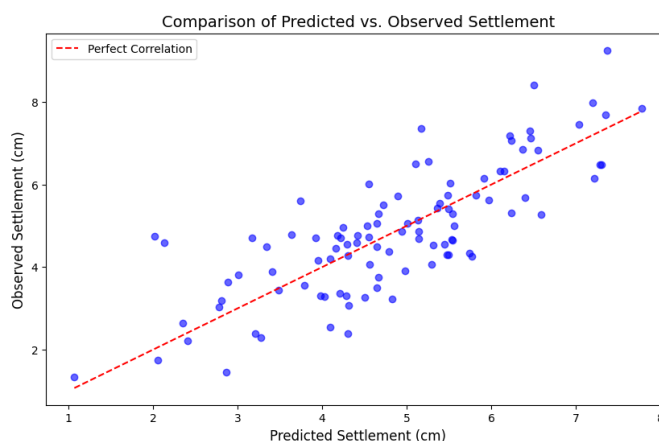


Figure 13. Comparison of Predicted vs. Observed Settlement

4.5. Case study 5: Early detection of landslides using IR thermography

One of the challenges in geotechnical engineering is to detect landslide-prone slopes prior to failure. Valerio Vivaldi et al used remote monitoring via airborne photogrammetry and IR thermography for landslide detection [35]. They observed

that IR thermography can identify thermal anomalies associated with groundwater seepage and moisture gradients, which can be early signs of slope failure. This remote sensing technique enables the quick survey of remote areas where conventional sensors cannot be installed [35].

The figure 14 shows an infrared thermogram of a landslide scarp, as taken by thermal sensors. The picture illustrates temperature differences on the slope face, with a color bar that indicates the temperature from cooler (blue and purple) to warmer (yellow and red) zones. Colder areas, shown in purple and blue, are indicative of higher moisture content in the slope face, implying high soil moisture content. These areas are identified as failure zones, which means they are at greater risk of potential failure and instability as a result of excess moisture. Conversely, warmer regions (in yellow and red) represent drier and more stable materials that are less likely to fail. The cooler zones are encircled by a dashed line, marking them as areas where increased water may destabilise the soil. The image also shows a temperature scale, ranging from 5°C to 30°C, to give an idea of the temperature variations. This thermogram can be used to monitor and evaluate the likelihood of landslide, as the presence of water plays a significant role in soil stability.

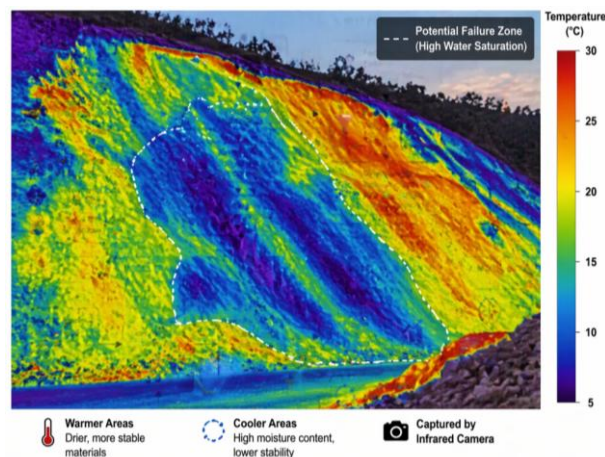


Figure 14. IR Thermogram of a running Landslide Scarp.

The figure 15 above is a plot of a 3D photogrammetric model of slope instability and resembles a digital surface model obtained through aerial imaging. The figure depicts a surface where there are simulated tension cracks and topographical variations indicating the initial appearance of landslide. It is depicted as a 3D model in which the slope is depicted as a smooth sine-wave-like surface, with some random fluctuations to model cracks and deformations. These are the creation of tension cracks, which are characteristic of slope instability and landslides. The rough variations in the smooth surface, which may result in slope failure, are the tension cracks of this model. The topographical changes, which are the differences in the elevation of the slope, can be viewed and analyzed in the 3D representation and the possible areas of the further instability can be determined. This model assists in identifying and monitoring of the possible early landslide activity and may provide engineers and geologists with understanding of the stability of a slope and that mitigation measures may be necessary [36].

3D Photogrammetric Model of Slope Instability

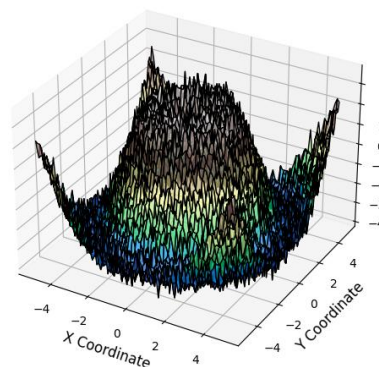


Figure 15. Slope Instability 3D Photogrammetric Model.

4.6. Study 6: Spoil Sites Identification and Hazard Assessment.

Construction waste and spoil sites are naturally geotechnically dangerous, and there is a risk of a collision and debris flows. Wei Xiao and Weiping Tian have suggested remote sensing methods to identify and assess hazards of these sites [44]. They also relied on spectral identification and topographical analysis to categorize the stability of various spoil heaps, their effects on the environment as a consistent means of addressing construction wastes in hilly regions [44]. The above flowchart (figure 16) is the Spectral Identification Flowchart of Spoil Sites that shows the steps that were taken to analyze the remote sensing images to identify the types of construction waste and terrain. It shows the processes beginning with the Remote Sensing Imagery Acquisition, followed by the Preprocessing to correct and filter the imagery. This is followed by the Spectral Band Selection, and then Classification of Terrain and Waste Type. The final step is the Post-Processing and Analysis that is applied to enhance the results and obtain some useful information to identify the spoil sites.

This simple flow diagram shows the logical steps to the analysis of geospatial data to differentiate between various types of terranes and categorize the construction waste, which is crucial in spoil management.

Spectral Identification Flowchart for Spoil Sites

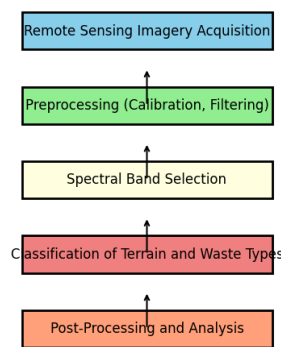


Figure 16. Spectral Identification Flowchart for Spoil Sites

Figure 17 is a 3D photogrammetric model of slope instability, developed from images taken from the air, to produce a digital surface model (DSM). The model represents the slope surface, with particular attention given to areas of tension cracks and topographical changes. These are signs of incipient landslides. The terrain is depicted in three dimensions, where the changes in altitude across the slope are presented. The tension cracks are visible as discontinuities in the surface, which are sites of potential instability in the slope. These cracks are typically an early warning sign of landslides because they are areas where the terrain has been stretched or pulled apart. As well as the cracks, the model shows changes in the topography that can be used to infer the stability of the slope. Such changes may reveal areas of settlement or uplift that may indicate the onset of landslides. This 3D model is essential for assessing slope stability, as it allows engineers and geologists to detect and examine potential risks. The early identification of landslides in this model enables more effective risk reduction of slope failure [37].

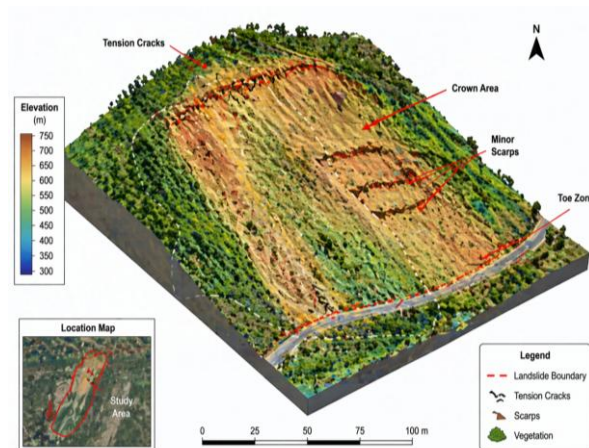


Figure 17. Spoil Site Hazard Zoning Map.

Such studies show that the application of remote sensing as a secondary survey method in geotechnical monitoring has changed as it is now becoming part of the risk management and quality assurance in construction. With the high-resolution data and intelligent processing methods, engineers can now perform site characterization on a new level that cannot be provided by traditional methods. All these papers point to the fact that despite the concerns of data integration and environmental impacts, a more sustainable and economic solution of infrastructure development is found in the transition to the so-called Smart Geotechnics. UAVs and machine learning combined with satellites allow the sector to be flexible to the environment of the built world.

4.7. Case Studies and Applications

The utility of remote sensing and other monitoring technologies can easily be seen in the context of their application to important industrial and other infrastructure assets. Whereas in the past monitoring has been done through manual inspection or use of point-sensors, in modern projects, a system-of-systems approach has been taken. This method integrates thermal imaging, wireless sensors and satellite data to track intricate thermal and structural dynamics in real-time [25], [38]. Utilizing numerous examples of case studies, starting with thermal control of heavy industrial equipment in India up to load-balancing of urban utilities in New York, one can see that remote monitoring has become not just an option, but also part and parcel of operational resilience. These illustrations demonstrate how the synergy of high-tech materials (e.g., nanofluids, phase-change materials) and remote sensing data allow a novel predictive maintenance and safety that previously was unfeasible [39]. Remote sensing and monitoring technologies in infrastructure and industrial projects have revolutionized the administration of intricate systems, including geotechnical design to gigantic energy systems. These applications are moving towards in-service monitoring in real-time instead of point sampling and periodic inspections, enhancing safety and efficiency.

4.8 Real-World Examples

4.8.1 Case Study 1: Steel Plant in India.

The electrical infrastructure is relevant in industrial systems, like the Indian steel plants. The most important use is the use of nanofluid cooling systems to monitor and cool transformers. Traditional transformer oils (e.g., UTR 40) may be exposed to high thermal loads and degrade due to humidity, leading to malfunction of the system [39]. The higher efficiency in heat removal has been attained in these plants by the introduction of magnetic nanofluids (e.g., MNF/UTR 40) made of Fe₃O₄ nanoparticles that experience a liquid-vapor phase change to dissipate heat ([17], [40]). The high-resolution thermography is commonly used to monitor these plants remotely and is capable of 3D surface temperature mapping of the transformer tank [40]. And industrial wireless sensor networks allow the remote continuous regulation of the cooling system, which ensures stability in severe conditions that thermal power plants and steel plants have [41].

4.8.2 Example 2: Utility grid of New York City.

The utility grid of the city of New York shows peak loads which are extremely high particularly during the cooling season in summer. The grid has fitted the cooling systems to be hybrid with the use of Phase Change Materials (PCMs) to store thermal energy. This allows shifting of peak loads the energy is stored in the times of low demand and to be released in the times of high demand [40]. In New York City, techno-economic tools have shown that PCM storage combined with residential and commercial heat pumps can reduce peak electric load by up to 53% [41]. This is necessary as it provides energy security since there is less use of costly peaker plants and the strain on the underground utility is reduced. These systems can be assessed based on machine learning algorithms, which integrate maps of the underground utilities along with load data to inform energy distribution [42].

4.8.3 Case Study 3: Wind Farm in UK.

Thermal control of large generators is important in the management of variable loads in offshore wind farms such as in the UK. The transition to larger (8 - 10 MW) direct-drive generators necessitates the use of direct liquid cooling and enhanced insulation in order to manage the intense heat loads in small nacelles [40], [41]. Direct liquid-cooled generators are much smaller in diameter, and thus, cause reduced mass and cost of offshore structures. Low-temperature superconductivity and cryogenic cooling have also been employed in some innovative designs as this decreases the complexity and levelized cost of energy through the use of a closed-loop cycle. These systems are not visible in the

nacelle and with remote health monitoring, it can operate without maintenance over long distances, which is a necessity in the North Sea environment [41].

4.8.4 Combination with Geotechnical Data.

Remote sensing data are most effectively utilized by combining it with traditional geotechnical engineering. Whereas soil sampling and lab test result provide accurate, point information, they might not be representative of a variable construction site. InSAR, LiDAR, and hyperspectral imaging with the help of UAV can also be used as supplementary tools allowing remote sensing [27].

Smart geotechnics involves the utilization of Internet of Things sensors on top of more traditional borehole sensors to allow real-time monitoring of important infrastructure components like foundations and tunnels [43]. This remote sensing data are amalgamated into a digital platform, which helps engineers cross-calibrate satellite-created deformation maps with sensors. This combination enhances the predictive model quality, and engineers can identify possible geohazards or settlement issues that could go unnoticed by standard site investigations [43].

4.8.5 Remote Sensing Effectiveness.

Remote sensing has led to actual improvement in the performance of the project and savings.

- Precision of Risk Prediction through AI and ML: AI and machine learning using remote sensing data has transformed risk prediction. The foundation analysis of New York City, an example, machine learning (ML) models trained on historical soil samples and utility maps have been able to identify areas where the evaluation was inaccurate, thereby preventing project delays and costs [40]. Similarly, neural networks like Convolutional Neural Networks are used to categorize soils and define the landslide probability.
- Mitigation of Risk and Costs: Risk-prone regions (e.g., landslides) that were not identified during the traditional surveys can be identified and controlled using remote sensing and timely evacuations and additional reinforcement.
- Operational Efficiency: Geotechnical processes based on data-driven solutions eliminate uncertainties and natural variability of soils [43]. It allows more sustainable and resilient designs because engineers will be able to revise their designs according to the real geotechnical responses obtained by remote sensors [43].

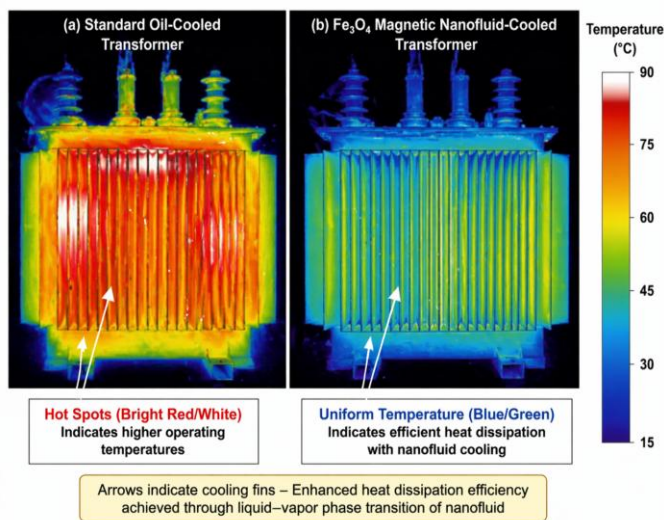


Figure 18. Thermal Imaging of Nanofluid-Cooled Transformers

Two side by side thermal (infrared) images. The left hand picture is a typical transformer tank with oil cooling the tank and the hot spots are marked in bright red/white. The right figure displays a transformer that uses Fe₃O₄ magnetic nanofluids, which exhibit a less uneven temperature distribution (marked in blues and greens) [25]. The arrows must point to the cooling fins, and the increased heat dissipation as a result of the phase change (liquid to vapor) of the nanofluid/

Source Reference: Adapted from Pişlaru-Dănescu et al. on the use of magnetic nanofluids (Pişlaru-Dănescu et al., 2017).

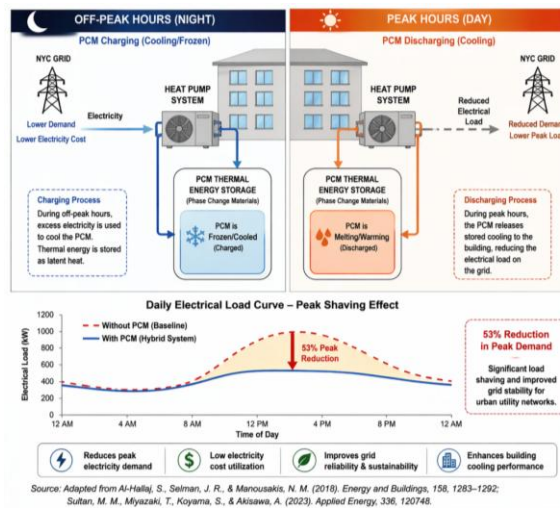


Figure 19. Hybrid PCM Cooling System of Urban utility grids.

An illustration of a basic layout of a residential or commercial heat pump system that is linked to a Thermal Energy Storage system and Phase Change materials (PCMs). The scheme must illustrate the energy flow: during the off-peak (night) operation, PCM is charged (freezes/cooling it); during the peak (day) operation, PCM is discharged to enable cooling, which decreases the electrical load on the NYC grid. The 53 per cent decrease in peak demand would be an alternative graph of a shaved peak on a daily load curve [44].

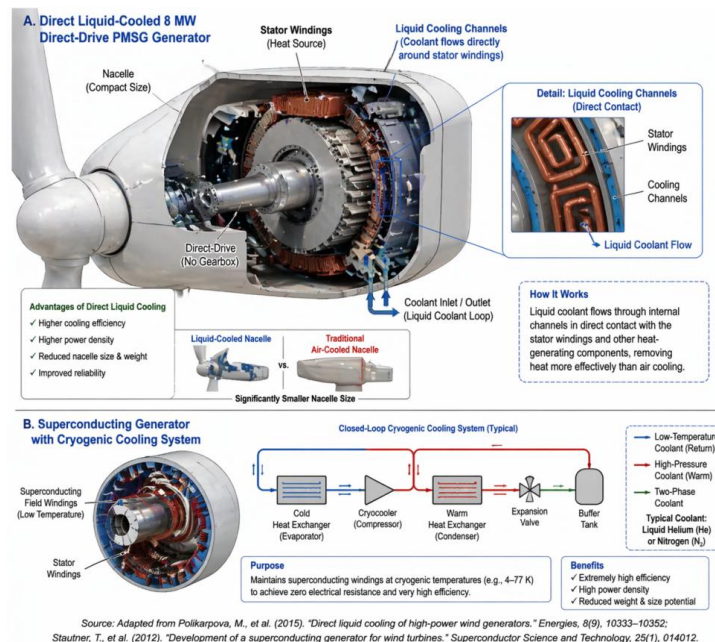


Figure 19. Cutaway View of a Direct Liquid-Cooled Wind Turbine Generator. Source Reference: Adapted by Sultan et al. and Al-Hallaj et al. (Al -Hallaj et al., 2018; Sultan et al., 2023).

A three-dimensional cutaway view of a high-power (e.g. 8 MW) permanent-magnet-driven synchronous generator that does not have a winding. Notably, the generator must indicate the windings in the stator and the cooling routes where the liquid coolant circulates on the hot parts [40]. This allows a much smaller nacelle than air-cooled generators. When it comes to superconducting models, a schematic would be used to illustrate the closed-loop cryogenic cooling system required [40].

Sources used: Adapted by Polikarpova et al. and Stautner et al. (Polikarpova et al., 2015; Stautner et al., 2012).

Finally, the movement towards remote-sensing-based systems in various industries (heavy machinery, down to renewable energy) is a game-changer with respect to performance and safety. These technologies are successful due to their capability to provide a continuous stream of quality information that can be processed by AI and machine learning to forecast and prevent failure [41]. Ranging on a downward scale (such as 53% peak electricity reduction, through smart cooling) to directly liquid-cooled offshore wind generators (physical size reduction), the results are consistent in showing an improved performance of the project and a reduction in costs [42]. Furthermore, as remote sensing data continues to be incorporated into traditional geotechnical methodologies, the geotechnical sector is becoming smarter and smarter geotechnics where infrastructure is not only strong but also smart [43]. Finally, these cases prove that the interplay of digital information and physical engineering is necessary to manage the modern construction and industrial projects in a sustainable way [10], [11].

5. Challenges and Limitations

Despite the revolutionary potential of remote sensing in geotechnical monitoring, its use is limited by a number of challenges. These obstacles span from the financial costs associated with sophisticated sensor systems to technical issues related to resolution and regulatory challenges associated with flying systems.

5.1 Cost and Complexity

The development of a remote-sensing-based method in place of the traditional geotechnical surveys is costly to initiate. High-resolution satellite imagery (sub-meter) remains expensive and the computational resources to store and process such large volumes of data usually involve extra investments in more efficient hardware and software [3], [4]. When it comes to the Unmanned Aerial Systems (UAS), financial aspects are not limited to the purchase of the system: significant amounts of money are required to maintain the system, as well as the size of the payload and the legal qualification of the pilot and the aircraft [1], [3]. Lastly, the advanced level of integrating these technologies with the current process of building is usually compensated by the unwillingness of the industry to embrace it because of the technical expertise required [26], [41].

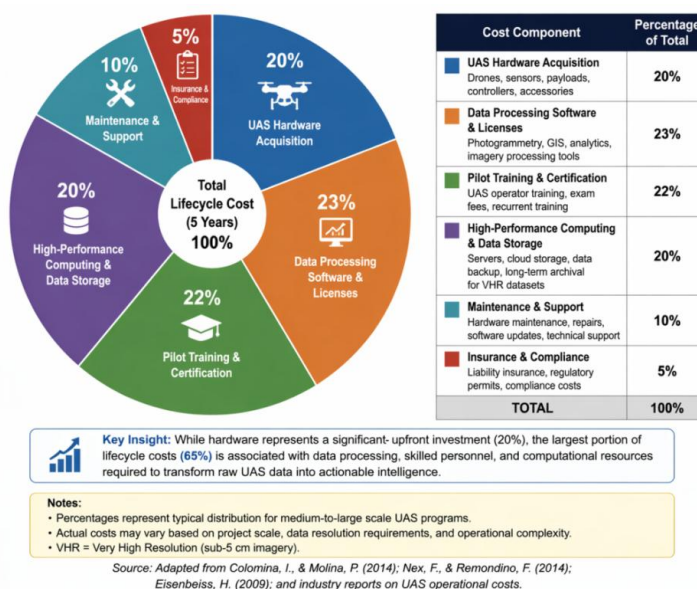


Figure 20. Lifecycle Costs Breakdown of the UAS Integration.

5.2 Accuracy and Resolution

One of the weaknesses of remote sensing data is temporal and spatial resolutions [41]. As an example, whereas airborne optical data can solve data on the centimeter scale, certain passive microwave data obtained with satellites can only solve data on a tens of kilometers scale. Such restrictions play a role in the construction field where the exact analysis of soil properties is required. The primary limitation to geotechnical applications is that most remote sensing systems can only help retrieve the top or near-top information of soil, which does not penetrate the deeper layers where

most of the structural problems occur. Spectral signatures can be obscured by vegetation, lichens and uneven topography in complex soil conditions, which leads to lower or biased data [40].



Figure 21. Ground-Level vs. Satellite Resolution.

5.3 Data Integration and Interpretation

Combining various remote sensing data with conventional geotechnical data (e.g., boreholes and laboratory findings) is not technically easy. The VHR data has the "Big Data" trait that adds to the computing load, potentially slowing real-time analysis [28]. Currently, these new methods are not highly trusted in the construction sector because there are no comprehensive systems of scientific advancement, which can involve satellite or UAVs data in traditional engineering frameworks [40]. Thus, we must develop superior software and AI-based solutions to check and process the remote sensing data to align with the standards of high geotechnical safety [30], [17].

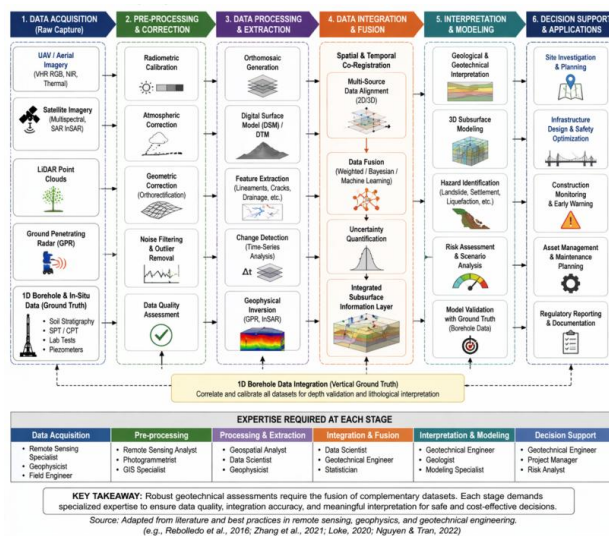


Figure 22. Data Fusion Workflow in Geotechnical Engineering.

5.4 Environmental and Technical Barriers

Weather is very important in remote sensing. Optical sensors on satellites and aerial platforms are very sensitive to weather conditions, clouds and snows- which may render the images useless. Data Availability: In one study, the PlanetScope satellite data was only available 14.5% and 7% of the time with cloud cover and snow, respectively.

Regulatory Barriers: There are also regulations as a hindrance. The most commonly known limitation of UAVs usage in the construction industry is the presence of no-fly zones, as well as the privacy concerns and legal regulations on autonomous flying [40].

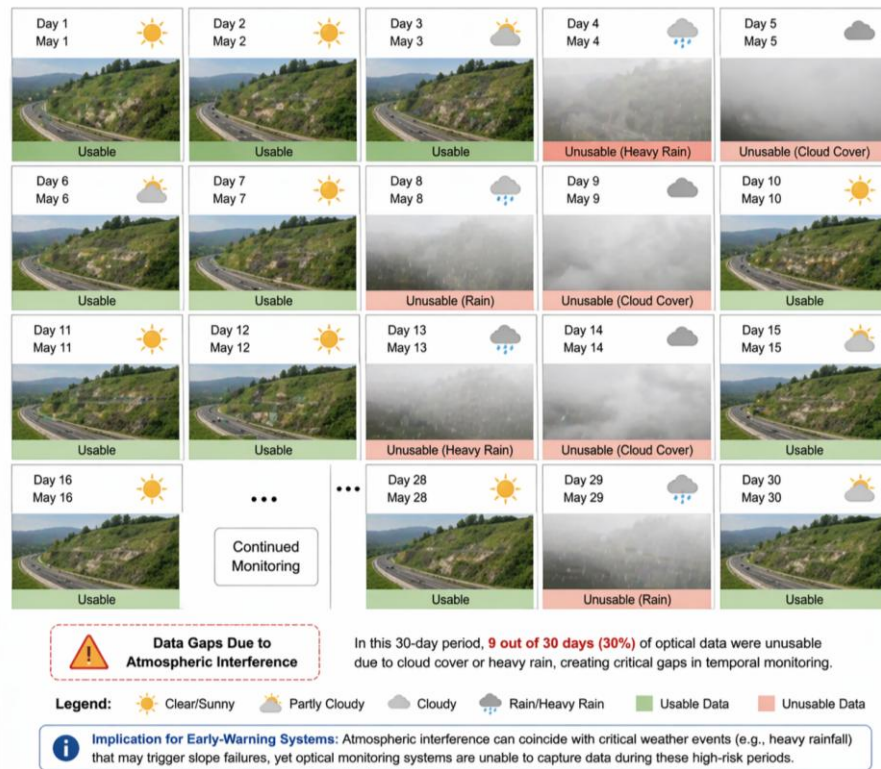


Figure 23. Impact of Atmospheric Interference on Optical Monitoring.

Finally, remote sensing has provided engineers with a cornucopia of spatial information due to technological advances, yet the price, resolution and integration challenges remain daunting. The industry must overcome significant regulatory and environmental limitations to be able to completely substitute traditional geotechnical surveying approaches. However, with the artificial intelligence-based analysis of the data and the development of cheaper sensor networks, remote sensing can become more than a niche survey tool and become a component of the resilient management of construction projects [1].

6. Future Directions

The future of better monitoring of geotechnical and industrial performance is the implementation of thermal control systems and smart data. These technologies offer a game changer to address the urgent demand of having efficient systems, yet offer detailed and real time information regarding the structural and thermal integrity. Both efficient cooling and geotechnical monitoring are being done with the use of heat pipe technology. Vertical ground heat-transfer units are also being installed in boreholes and used to complement the cooling of oil-filled transformers in times of overload in the electrical industry [17]. The heat pipe removes the heat and moves it to the adjacent soil with the help of these below-ground units; it forms a substantial heat sink [40]. Meanwhile, energy geostructures are in action to enable buildings to either give or take heat by use of pipes that are built into the concrete base including heat exchanger piles and retaining walls [44]. This thermal stress should be measured because thermal cycles may cause radial stresses and surplus pore water pressures that influence the shaft resistance and stability of the foundation [40].

In the near future, micro-channel cooling will revolutionize monitoring and performance in transformers used in high-power and challenging conditions. Micro-channels enhance the heat exchange significantly, and direct liquid cooling can be performed in small nacelles or transformer tanks, where air-cooling is not always possible [17]. Micro-channel cooling and industrial wireless sensor networks [17] are used to create a high-reliability thermal monitoring system in noisy industrial environments, namely thermal power plants. This allows online identification of "hotspots" and

acceleration measures of the age of the asset, and with high confidence in the health of its health assessment even in harsh operating conditions [35], [38].

Remote sensing is becoming a predictive, and not descriptive, discipline with the use of AI and machine learning.

- **Real-Time Monitoring and Soil Behavior:** LiDAR and satellite data are now being recognized using machine learning algorithms [3], [4]. In the case of geotechnical engineering projects, AI models may forecast soil behavior (e.g. settlement, landslide) using past subsurface data (in combination with real-time sensor data).
- **Enhancing Thermal Management:** Thermal management is also enhanced by the use of ML strategies. The analysis of the modules of IoT-based monitoring (e.g., oil level, gas formation and temperature) can help to predict the remaining life of transformers and warn about self-diagnosis, using AI techniques (Dhanraj et al., 2020; Zhan et al., 2014). It can also help to conduct real-time risk evaluation and create digital twins to simulate thermal management systems in various load configurations [10], [38], [35].

Research Gaps

Nonetheless, these advances have left certain key gaps in the research on the application of these technologies:

1. **Absence of Standardised Methods:** There are no standardised methods to fuse high-resolution remote sensing data (InSAR or UAV) with traditional geotechnical borehole and laboratory data at the moment [9], [10]. Consistent data collection and processing methods are needed to increase data accessibility and render the results explainable to engineers.
2. **Dynamic Cooling Systems:** Despite the promising nature of energy foundations, more dynamic cooling systems will be required to serve variable loads and intermittent energy storage in soils [40]. Studies should be performed in order to learn the long-term thermo-mechanical behaviour of such systems to prevent accidentally destabilizing the structure on a long-term basis [44].
3. **Data Quality and Availability:** There is a lack of data on disasters and scientific methods of regional hazard assessment in Regional assessments [44]. To overcome the gap between tradition and innovation to create geotechnical safety algorithms, data scientists and civil engineers must collaborate to address the gap between the two fields.

7. Conclusion

To conclude, it is possible to say that the way to complete integrated remote sensing in geotechnical and industrial applications is characterized by the balance between the opportunities of the technology and the real limitations. Although the cost, resolution limits, and regulatory barriers stand at the way to the mass implementation, the efficiency of these technologies in enhancing safety and operational efficiency cannot be neglected. The advent of AI and machine learning is a significant trigger that has turned raw remote sensing data into predictive feedback that can be used to mitigate risks in real-time and manage thermal functions optimally. Finally, the industry requires filling the research gaps, including the necessity of adaptive cooling solutions and uniform frameworks of data integration, which will be the future of the industry. The multidisciplinary approach, which combines the accuracy of classical geotechnical engineering and scalability of remote sensing and AI, would enable project managers to establish a new level of structural sustainability and safety. As these technologies become more cost-effective and mature, they will stop being a niche technology and turn into the backbone of the modern construction and infrastructure management.

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Conflicts of Interest

The author declares no conflicts of interest.

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