Advanced Techniques for Capturing Cracks in Clayey Soils: A Comprehensive Review

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Received: 4 April 2025 | Revised: 3 May 2025 | Accepted: 8 May 2025

ABSTRACT

Desiccation cracking in clay soils severely impacts the geotechnical engineering and environmental control by altering the soil strength, water infiltration, and structural stability. The application of traditional evaluation methods, such as observation and grid mapping, is commonly used to evaluate the fissures resulting from desiccation, tensile stress, and environmental factors. These techniques are inaccurate and not scalable. New advances in crack detection, including X-ray Computed Tomography (X-Ray CT), Ground-Penetrating Radar (GPR), Digital Image Correlation (DIC), and Machine Learning (ML), have enabled the performance of high-resolution, Non-Destructive Testing (NDT) of the surface and subsurface cracks. New techniques enhance the uses in slope stability assessment, soil liner integrity inspection, and water management. However, their potential shortcomings, such as expensive implementation and enormous computational needs, limit their extensive application. Emerging technologies, including the real-time inspection by Acoustic Emission (AE) techniques and neural networks, offer much potential. This study emphasizes the need for accessible tools to advance soil crack analysis and support sustainable geotechnical practices.

Keywords-desiccation cracking; clay soils; grid mapping; Ground-Penetrating Radar (GPR)

I. INTRODUCTION

Cracking in clayey soils is one of the biggest geotechnical engineering problems, which influences the strength, permeability, and structural stability of soils. The formation of cracks and the propagation of cracks affect many structures, such as embankments, foundations, and landfill liners, and thus their identification and measurement are of utmost importance for effective engineering designs [1]. Empirical relationships and visual observation have been employed to analyze the soil cracking, but they are not precise and scalable in case of underground or large-scale fractures. The technological advances have enabled sophisticated techniques, such as DIC, GPR, X-Ray CT, and image analysis with ML, which have made the crack detection in clayey soils with higher precision and speed possible. The prediction of soil behavior in terms of the cracking and compaction properties is a basic requirement of earthworks. Computer algorithms, integrating physical soil properties (e.g., grain size, plasticity) with ML techniques, such as Artificial Neural Networks (ANN) and Multiple Linear Regression (MLR), have been proved to be accurate predictors of the soil compaction parameters, Optimum Moisture Content (OMC), and Maximum Dry Density (MDD) [1].

These forecasting models supplement the first-order site assessments by reducing the amount of the required large-scale laboratory testing. In parallel, experimental studies have examined the dynamic soil behavior, such as stone column upgrading under seismic excitations, which influences the settlement behavior and foundation stability [2]. The detection of cracking is required for the assessment of deformation and geotechnical hazard prevention. Structural cracking failures are not only limited to structures in soil, but also to engineered structures, such as cylindrical shells and Ultra-High-Performance Concrete (UHPC) structures in which the vibration characteristics and structure durability are altered by the crack development [1, 2]. Emerging advanced imaging technologies and NDT devices, like fiber-optic sensing and AE monitoring, are being incorporated into crack detecting systems for real-time monitoring.

Despite all these advancements, some of the challenges are the high implementation costs, computational complexity, and flexibility to field conditions [1]. Consequently, tensile stresses surpass the soil's strength, resulting in the onset and spread of cracks [2]. The latter, significantly modify the physical and hydraulic characteristics of the soil, influencing its strength, stability, and permeability [3]. These alterations present considerable difficulties in fields, such as foundation engineering, slope stability, landfill liner systems, and irrigation management, where the soil integrity is essential [4]. Figure 1 shows the network of desiccation cracks in fine-grained soil [9].

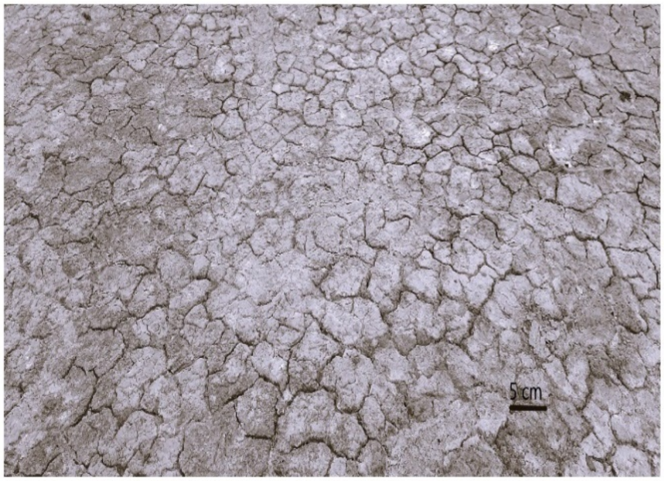

Fig. 1. Network of desiccation cracks in fine-grained soil.

Clayey soils are particularly susceptible to cracking due to their high plasticity and shrink-swell potential [5]. The network of fissures in these soils can serve as preferential pathways for water and solutes, raising the infiltration rates and facilitating the pollutant transport [4, 6]. In geotechnical applications, fissures undermine the structural integrity of embankments, dams, and liners, increasing the danger of failure [7]. Moreover, fissures expedite the soil erosion, resulting in land degradation in dry and semi-arid areas [8, 9]. Thus, the precise characterization of the cracks' form, size, depth, and connectivity is crucial for evaluating the soil behavior and managing the related risks [1]. The conventional techniques for crack analysis predominantly depended on visual inspection, manual measurements, and laboratory investigations [10]. These approaches have offered important insights into the cracking process but frequently lack precision and scalability [1]. The subjectivity in measurements, the labor-intensive processes, and the incapacity to document the complex crack networks are significant obstacles [7]. For example, the manual procedures for field-scale crack characterization tend to neglect the spatial variability [9]. Simultaneously, the laboratory investigations are limited by the controlled conditions that inadequately reflect the natural habitats [5].

The emergence of sophisticated imaging technology and computational techniques has transformed the examination of fractures in clayey soils [1]. The high-resolution cameras and drone systems now provide precise crack mapping at both laboratory and field scales [11]. Techniques in image processing, such as edge detection and segmentation, enable automatic detection and crack measurement [12]. Additionally, 3D imaging techniques, such as photogrammetry and LiDAR, elucidate the crack depth and volumetric characteristics, enhancing the comprehension of the soil cracking behavior [13]. Advancements in Artificial Intelligence (AI) and ML have significantly improved the crack analysis. AI algorithms can analyze extensive datasets, detect intricate fracture patterns, and determine the relationships between the crack characteristics and soil behavior [14]. Furthermore, NDT techniques, including thermal imaging and AE, have proven to be effective instruments for identifying the subsurface fractures and tracking the crack progression in real time [15].

Table I depicts the results of various techniques for identifying the desiccation cracking in field soil. The results indicate that the U-CrackNet framework outperforms all other models in crack recognition, accurately capturing both the overall structure and fine details of the cracks. Unlike other methods, it effectively avoids excessive noise and localized omissions, ensuring superior segmentation performance [21].

This review aims to synthesize existing information and critically assess the available techniques for crack detection and analysis in light of the significant improvements in this field [1, 11]. This paper thoroughly examines both conventional and contemporary techniques for detecting and analyzing cracks in clayey soils. It covers basic ideas, applications, and limitations of several approaches, emphasizing their evolution [10].

TABLE I. OVERALL PERFORMANCE OF THE COMPARED METHODS UNDER DIFFERENT METRICS ACCORDING TO [21]

Methods	Overall performance %					
	Precision	Recall	Dice	Jaccard	Average overlap metric	Standard deviation of the overlap metric
TBM	57.11	85.91	67.09	51.94	65.51	12.97
SAM	87.12	68.02	75.53	61.37	73.01	9.56
Pseudo mask	87.06	90.14	88.47	79.44	86.28	4.1
U-Net	93.99	51.72	66.59	50.34	65.66	17.55
Swin-UNet	80.93	49.03	60.82	44.17	58.74	14.17
UNet++	97.33	75.93	85.21	74.39	83.22	9.14
Attention Res-UNet	97.54	72.26	82.88	70.95	80.91	10.66
U-CrackNet	85.81	86.61	86.07	75.78	83.57	4.51

The review also delineates significant obstacles, including the absence of standardized protocols, financial impediments related to sophisticated technology, and the necessity for field-scalable methodologies [12]. Additionally, exploring the current trends and future directions in crack analysis include the potential for IoT-enabled systems and real-time monitoring [14]. The current paper aims to provide a comprehensive overview of the current status of crack analysis, guiding future research initiatives and aiding in developing creative methods for comprehending and alleviating the soil cracking occurrences.

II. MECHANISMS AND INFLUENCING FACTORS OF SOIL CRACK FORMATION

The formation of cracks in clayey soils is a complex process influenced by numerous intrinsic and extrinsic factors. Comprehending these principles is crucial for forecasting the soil behavior and alleviating the detrimental impacts of cracking in geotechnical and environmental contexts.

A. Desiccation-Induced Shrinkage

Desiccation-induced shrinkage is a primary process of fracture development in clayey soils. As water evaporates from the soil matrix during desiccation, the soil undergoes a volume reduction due to the contraction of clay particles. The shrinkage magnitude is influenced by parameters, like the mineralogy of the clay, its initial water content, and the drying rate [1, 5].

- Mechanism: during desiccation, the capillary forces in the pore water become more severe, producing tensile stresses inside the soil matrix. Cracks commence and extend when these stresses surpass the soil's tensile strength [4].
- Shrinkage-swelling behavior: clay soils, especially those rich in montmorillonite, demonstrate a considerable shrink-swell capacity owing to their expansive characteristics. This behavior increases the probability of fissuring during the drying phases [13, 16].

B. Formation of Tensile Stresses

Cracking occurs when the soil's internal tensile stresses exceed its tensile strength. These stresses result from the interaction within the soil particles during volumetric contraction.

- Stress concentration: the differences in drying rates across the soil surface cause unequal stress distribution, resulting in stress concentration zones, where cracks are more prone to develop [7].
- Boundary constraints: boundary features in the field, such as hard sublayers or structural reinforcement, might constrain the soil movement, elevate the tensile stress and facilitate the crack development [3].

C. Propagation and Patterns of Cracks

Upon the initiation, cracks extend through the soil due to the stress redistribution. The soil texture, moisture gradient, and desiccation conditions affect the fracture propagation.

- Primary and secondary cracks: primary cracks, which are the initial fractures, develop first and are generally larger and deeper. As drying progresses, secondary fissures emerge, linking the initial fissures and creating a network [1].
- Pattern formation: crack networks frequently display distinctive patterns, including polygonal or orthogonal configurations, influenced by the soil characteristics and environmental conditions [4].

III. FACTORS AFFECTING THE CRACK DEVELOPMENT

A. Soil Properties

- Clay content and mineralogy: soils with rich clay content and expansive minerals are more susceptible to cracking owing to their significant shrinkage potential [10].
- Moisture content: the initial water content affects the shrinkage rate and the resultant crack patterns. An increased moisture content generally results in more extensive and significant cracks [1].
- Soil structure: aggregated soils demonstrate a distinct cracking behavior relative to homogeneous soils since aggregates can impede or alter the fracture propagation [3].

B. Environmental Factors

- The drying rate influences the tensile stresses and cracking; rapid drying increases the tensile stresses and more significant cracking, whereas the slower drying results in finer and less extensive cracks [4].
- High temperatures and less humidity expedite evaporation, facilitating the desiccation cracking [7].
- Precipitation and wetting-drying cycles: Alternating wet and dry conditions intensify the cracking by causing recurrent shrinkage and swelling [11].

C. External Load

The external loads play a significant role in the initiation and propagation of fractures in the geologic and engineering structures. Surface loads are one of the most influential factors in external loading, which are external forces constituting construction and traffic loading. These forces apply additional stress to the ground, leading to deformation and increasing the fracture development at a higher rate. Authors in [12] describe how such repeated loading is able to alter the stress condition of the material, weakening the structure and enabling the crack propagation with time. This has significant implications in the urban context, where continual construction and traffic loads subgrade materials to cycles of repeated stress.

Another significant factor influencing the fracture behavior is the boundary constraints, or rigid boundaries and subsurface heterogeneities, which control the stress distribution of a material. According to [5], such constraints also influence the stress transmission and redistribution, resulting in non-uniform forms of fractures. For example, the presence of underground components, such as bedrocks or pipes, may lead to localized stress concentration, making particular regions susceptible to cracking. Such limitations may govern the spacing, orientation, and size of fractures, but dominate the stability as well as the long-term integrity of natural and constructed systems [5].

It is required to model the joint effect of surface loads and boundary constraints for predicting and avoiding the fracture development. Through the joint application of structural monitoring and stress analysis techniques, engineers and geologists can better assess the potential risks and implement measures to enhance the durability of infrastructures subjected to external loads.

IV. IMPLICATIONS OF FRACTURE FORMATION

The evolution of fractures within rock and soil formations has significant implications in several engineering and environmental systems. One of the critical concerns regarding the cracks serving as preferential paths for flow and resulting in higher ground permeability, is the hydraulic conductivity. This mechanism affects the contaminant migration, landfill liners, and drainage systems by causing contaminants and water to bypass natural filtering mechanisms, threatening the environment in multiple ways [10]. Leaks through landfill liners, for example, undermine the containment schemes and increase the leakage potential, requiring more advanced engineering solutions for effective containment.

Another important impact of the fracture formation is that on the strength and stability of the ground. As the cracks extend, they reduce the cohesive strength of the ground, enhancing its susceptibility to structural failure. This is particularly a challenge in construction works, where weakened soil conditions may lead to foundation instability, landslides, or road collapse [1]. Fractures also enhance the differential settlement, whereby the uneven soil movement results in long-term structural distortion.

Extensive crack networks significantly increase the soil erosion in arid and semi-arid regions. Cracks increase the surface runoff by directing the water flow along the fracture paths, causing detachment and transportation of the soil particles [9]. Over time, this process decreases the soil's fertility, causes land degradation, and increases the sedimentation in nearby water bodies, affecting the agricultural output and water quality.

The formation of fractures in soil and rock is highly relevant to most environmental and engineering applications. One such concern is hydraulic, which affects the landfill liners, drainage systems, and contaminant migration by short circuiting natural filtration systems, causing water and contaminants to flow along an alternative path, which can lead to potential environmental risk [10]. Leaks in landfill liners, for example, undermine the containment systems, increasing the likelihood of groundwater contamination and necessitating advanced engineering measures to seal the leaks.

The fracture development has a substantial effect on the stability and strength of the soil. As cracks propagate, they reduce the cohesive strength of the soil, making it more prone to structural failure. This is undesirable during the construction of buildings, where the soil properties can lead to unstable foundations, landslides, or road collapse [1]. Fractures can also cause differential settlement, with uneven soil displacement over time leading to structural deformation.

Understanding these implications is critical for developing effective soil management practices, improving construction methods, and preventing the environmental hazards caused by the fracture development. Through the implementation of advanced monitoring techniques and soil stabilization processes, engineers and earth scientists can develop solutions that have the capability of reversing the ill effects of fractures on infrastructure and ecosystems.

V. CONVENTIONAL APPROACHES TO CRACK ANALYSIS

The development of cracks, particularly in soil has been an area of widespread interest due to its impact on the structural stability, hydraulic conductivity, and general strength. The classical analysis of cracks relies only on empirical data, test results in a laboratory, and analytical models in assessing the crack onset, crack advance, and modes of failure. These methods have been widely utilized in civil engineering, geotechnical studies, and material sciences to predict and mitigate the detrimental effects of cracking in engineering structures.

A. Visual Inspection

Visual inspection is among the most commonly used techniques for crack analysis in which cracks are evaluated manually by being observed, measured, and classified based on their width, depth, and orientation. Although simple, this method is largely restricted by the subjectivity and inability to detect interior or microscopic fractures. Mechanical testing methods, such as triaxial and uniaxial compression tests, are also routinely utilized to examine the cracked soil's response under different stress conditions. These tests are used to understand the material tensile strength, compressive strength, and failure conditions. Visual inspection is usually employed for detecting the cracks in clayey soils. This method requires the direct observation of the soil surface for indicators of cracking, including visible fissures, splits, and separations. Crack measurements, including width, length, and orientation, are typically obtained using simple instruments, such as rulers or calipers. The specific method is simple, cost-effective, and fast. Nonetheless, it is significantly subjective and depends on the observer's expertise [16]. Furthermore, it is restricted to surface cracks and fails to offer comprehensive insights into the cracks' depth or internal structure [1].

B. Grid Mapping

The grid mapping method involves dividing the soil surface into a grid and recording the presence of cracks and their size within each grid cell. This method facilitates the crack distribution and density mapping within the area of interest. It systematically analyzes the cracks over extensive areas by measuring their width, length, and orientation. However, it requires a considerable amount of labor, particularly for larger regions, and may be prone to the inaccuracies resulting from inconsistent measurement methods [4].

C. Plaster or Silicone Molding

Plaster or silicone casting entails applying a liquid casting medium, such as plaster or silicone, into the fissures to create a mold of the crack network. After the material has hardened, the cast is extracted and analyzed for precise crack width, depth, and length measurements. This method is effective for acquiring accurate measurements of the crack geometry [3].

However, it is detrimental to the soil sample and requires significant time, rendering it more appropriate for laboratory experiments.

D. Crack Impression Technique

The crack impression method entails applying a pliable substance, such as clay or wax, over the network of cracks to produce an impression of the cracks. This method offers a non-destructive approach to analyzing the surface cracks in soil and is comparatively more straightforward than plaster casting. The former is especially effective for assessing shallow cracks; however, it does not provide adequate information regarding the crack depth and internal structures [11].

E. Photography with Overlay Techniques

This method involves capturing photographs of the soil surface exhibiting visible cracks and applying a grid or overlay to facilitate the crack measurements. It effectively produces crack patterns and monitors changes over time. The/Its accuracy is contingent upon the quality of the images and the interpretation by the observer [12].

Soil crack measurement is also conducted by penetrometer tests and shrinkage limit tests that measure the soil shrinkage and expansion in terms of the percentage of moisture. Similarly, fracture mechanics theories, such as Linear Elastic Fracture Mechanics (LEFM) and the Griffith theory, are employed to numerically calculate crack growth in brittle materials using mathematical models, predicting the fracture toughness and stress intensity factors.

The benefits of conventional crack measurement methods are:

- They require limited equipment and incur lower costs compared to the advanced methods.
- They are simple and straightforward methods that necessitate only fundamental training and tools.
- These methods can be rapidly employed for preliminary detection and ongoing monitoring in field settings.

The conventional methods' limitations are:

- The conventional methods have limited precision compared to the contemporary imaging techniques.
- Most methods are limited to surface cracks and do not assess the subsurface behavior.
- Labor-intensive methods, such as grid mapping, necessitate considerable time and effort.
- Methods, such as visual inspection, rely on the observer, making them susceptible to inaccuracies.

Despite their usefulness, conventional techniques of crack analysis are not without limitations, such as employing idealized assumptions, inability to observe in real time, and inability to deal with intricate, multi-scale material interactions. These limitations have led to the development of advanced computer-based and ML-based approaches to enhance the accuracy and effectiveness of crack prediction and detection. However, the classical methods are still a fundamental basis for the crack behavior research and are used extensively in numerous engineering applications.

VI. ADVANCEMENTS IN CRACK DETECTION METHODS

The crack detection is required to ensure the safety and durability of the structures, materials, and infrastructure systems. Traditional methods, such as visual inspection and mechanical tests, have long been used to detect cracks but are plagued with drawbacks, such as subjectivity, time consumption, and inability of detecting the internal or micro cracks.

As the technology advances, the newer methods have improved considerably in accuracy, efficiency, and reliability in the detection of cracks. This advancement includes NDT techniques, computer vision, image processing, AI and ML, and sensor monitoring systems. Table II presents a comparison between these methods.

A. X-Ray CT

X-Ray CT is a non-destructive imaging method that facilitates a detailed three-dimensional visualization of the cracks in the soil samples. This method employs X-ray scanning to identify the density variations resulting from the cracks and other internal structures. The data are reconstructed into cross-sectional images to elucidate the crack geometry, volume, and connectivity. This technique is useful for analyzing subsurface cracks that are not visible, making it effective for studying the desiccation-induced cracking in expansive soils and assessing the structural integrity of the compacted clay liners. The high cost of equipment, requirement of advanced technical expertise, and the limitation of small laboratory samples render it, though, less accessible for large-scale or field applications [1].

B. Digital Image Correlation

DIC serves as an effective method for analyzing the surface cracks through monitoring the deformations in the soil samples. This approach entails the application of a speckled pattern on the soil surface, followed by acquiring high-resolution images during mechanical loading or environmental alterations. A specialized software analyzes images to compute the strain fields and identify the regions of cracking. This technique facilitates the real-time crack initiation and propagation studies, offering a high spatial resolution for measuring the surface strain. DIC is essential for analyzing the soil behavior under different stress conditions; however, it is restricted to surface crack analysis and requires a meticulous experimental setup, including controlled lighting and a high-quality camera [8].

C. Thermal Imaging (Infrared Thermography)

Thermal imaging, also known as infrared thermography, identifies cracks by measuring the variations in the surface temperature. Cracks impede the heat transfer in the soil, resulting in thermal anomalies that can be readily detected in infrared imagery. This non-contact technique is effective for monitoring desiccation cracks in agricultural fields and assessing the cracking in infrastructure, such as road embankments. Thermal imaging enables a fast and efficient coverage of large areas, making it suitable for field surveys. Its effectiveness, however, is contingent upon environmental conditions, including sunlight, wind, and soil moisture, which may influence the accuracy of the results. This method is generally restricted to surface cracks and may necessitate additional techniques for subsurface analysis [17].

D. Scanning Electron Microscopy (SEM)

SEM is a high-resolution method employed to analyze the microstructural features of clayey soils, such as micro-cracks. SEM provides enlarged images of the soil surface, elucidating the complex interactions among the soil particles and the processes contributing to the crack formation. This method is essential for examining the impacts of the chemical additives, soil stabilization techniques, and the microstructural alterations resulting from drying or loading. Nevertheless, SEM is limited to small samples, requires considerable preparation, and is typically appropriate for laboratory environments. Despite these limitations, SEM is an essential tool for correlating the soil microstructure with macro-level cracking behavior [10].

TABLE II. TECHNIQUE COMPARISON

Technique	Type	Key features	Applications	Advantages	Limitations
X-Ray CT	Imaging	3D visualisation of internal and external cracks.	Subsurface crack detection in compacted soils.	High resolution, non-destructive.	High cost, limited to small samples.
DIC	Imaging	Measures surface deformation and strain during cracking.	Real-time crack propagation studies.	High accuracy for surface measurements.	Restricted to surface cracks, requires precise setup.
Thermal Imaging	Imaging	Detects thermal anomalies due to cracks.	Field-scale crack surveys in expansive soils.	Non-contact, rapid for large areas.	Affected by environmental factors, limited to surface analysis.
SME	Imaging	High-magnification imaging for micro-cracks and soil structure.	Micro-crack analysis, the impact of additives on soil fabric.	High resolution at the micro level.	Small samples only require complex preparation.
Photogrammetry	Imaging	3D surface models from overlapping images.	Mapping crack networks in fields using drones.	Cost-effective, field-scale applicability.	Dependent on lighting, surface only.
Hyperspectral Imaging	Imaging	Analyzes spectral bands to detect soil changes linked to cracks.	Large-scale soil desiccation monitoring.	Effective for wide-area studies.	Complex data processing, sensitive to noise.
3D Laser Scanning	Experimental	Captures soil surface topography for detailed crack morphology.	Evolution of surface cracks, field and lab studies.	Accurate, applicable across scales.	Limited to surface cracks and expensive equipment.
GPR	Geophysical	Detects subsurface anomalies using radar waves.	Subsurface crack detection in embankments and pavements.	Large-scale capability detects buried cracks.	Signal resolution is affected by soil moisture and type.
AE monitoring	Experimental	Monitors elastic waves generated by cracking processes.	Real-time detection of early-stage cracks.	Sensitive to small cracks, non-invasive.	Challenging to filter background noise and needs advanced processing.
Electrical Resistivity Tomography (ERT)	Geophysical	Maps resistivity changes caused by cracks disrupting moisture paths.	Detecting cracks in clay liners and embankments.	Effective for subsurface cracks, scalable.	Affected by soil salinity, moisture, and temperature.
Image Processing Algorithms	Computational	Automates crack analysis using edge detection and segmentation.	Crack width and network measurement in lab or field images.	Cost-effective, improve accuracy and efficiency.	It requires high-quality photos, but it is limited by camera resolution.
Neural Networks (AI/ML)	Computational	Automates crack detection and prediction using ML models.	Predicting crack formation from images or environmental data.	Scalable, handles large datasets effectively.	Requires large training datasets and expertise in AI.

E. Photogrammetry

Photogrammetry is an economical and versatile method for accurately capturing the intricate crack patterns in clayey soils. The photogrammetry software generates a 3D model of the crack network by capturing multiple overlapping photographs of the soil surface from various angles. This method is commonly employed for mapping desiccation cracks in expansive soils and is applicable across different scales, ranging from laboratory samples to extensive agricultural fields, particularly when integrated with the drone technology for field applications. The advantages include high spatial resolution and the capacity to analyze the intricate crack networks. Nevertheless, its accuracy is significantly influenced by adequate lighting, camera calibration, and image quality, which may lead to variability in the outcomes [18].

F. Hyperspectral Imaging

Hyperspectral imaging examines the spectral characteristics of the soil to detect alterations linked to the crack development, including changes in moisture levels and surface reflectance. This method employs cameras or sensors to capture the light across various spectral bands, encompassing wavelengths that extend beyond the visible spectrum. Hyperspectral imaging is effective for monitoring extensive areas, including agricultural fields and construction sites, due to its deployment capabilities via drones or satellites. The capacity to identify the minor variations in soil characteristics makes it essential for the early detection of cracks. This method requires advanced algorithms for data processing and is susceptible to environmental noise, complicating its application in uncontrolled field settings [19].

G. 3D Laser Scanning

3D laser scanning employs laser beams to precisely capture the soil surface topography, yielding detailed measurements of the crack width, depth, and volume. This method generates a Digital Elevation Model (DEM) of the surface, which is suitable for analyzing the morphology of the desiccation cracks and monitoring the temporal evolution of the crack networks. 3D laser scanning is utilized in both laboratory and field conditions and is a non-destructive test, allowing repeated measurements without altering the sample. This technique is restricted to surface-level cracks and necessitates costly equipment, thereby restricting its accessibility for broader application [20].

H. Ground-Penetrating Radar

GPR is a geophysical method employing electromagnetic waves to identify the subsurface fractures and voids within soils. GPR utilizes radar pulses directed into the ground, analyzing the reflected signals to detect the anomalies resulting from the variations in soil density or moisture content. This method is effective for field studies, facilitating large-scale surveys of pavements, embankments, and expansive soils. GPR effectively detects the cracks at different depths; however, its resolution is inadequate for minor cracks. Additionally, the soil composition and moisture can adversely impact the clarity of the radar signals [21].

I. AE Monitoring

AE monitoring identifies the elastic waves produced by the formation and propagation of cracks in soils. Sensors positioned on or adjacent to the soil surface detect these waves, yielding real-time information regarding the location and development of cracks. AE monitoring is useful for investigating early-stage cracking and understanding the dynamics of the crack progression under mechanical or thermal stress. This method demonstrates sensitivity to minor cracks and provides a non-invasive technique for soil monitoring. Distinguishing between relevant and background signals presents challenges that require advanced signal processing techniques and meticulous experimental design [22].

J. Electrical Resistivity Tomography

ERT measures the soil resistivity to detect fractures and voids. The electrodes positioned in the soil transmit electrical currents, producing a resistivity map that identifies the regions where cracks interfere with moisture pathways. This method utilizes the differences in resistivity between undisturbed soil and regions impacted by cracks or voids. ERT demonstrates significant efficacy in identifying the subsurface cracks within the clay liners, embankments, and various geotechnical structures. The non-invasive characteristics and scalability make it appropriate for monitoring extensive regions. The accuracy of the technique is affected by factors including the soil salinity, temperature, and moisture, which can lead to variability in resistivity measurements [3, 6, 7].

K. Image Processing Algorithms

Image processing algorithms facilitate the automated analysis of the crack images, thereby improving both the efficiency and accuracy in the detection and measurement of cracks. These algorithms commonly employ edge detection, segmentation, and classification methods to delineate the crack boundaries, assess their dimensions, and quantify the crack networks. Commonly employed tools include OpenCV, MATLAB, and GIS-based software. Image processing is frequently integrated with techniques, like photogrammetry or DIC, to improve the quality and detail of analysis. The effectiveness of this method is significantly influenced by the quality of the input images, lighting conditions, and the precision of the employed algorithms [12, 17].

L. Neural Networks and ML

Neural networks, a subset of ML techniques, have significantly transformed the automated crack detection and analysis. Convolutional Neural Networks (CNNs) can be trained on large datasets of soil images to identify the crack patterns, evaluate their severity, and forecast their development under different environmental conditions. These models efficiently manage large-scale monitoring tasks when integrated with imaging techniques, including drones, hyperspectral imaging, or thermal imaging. Implementing ML models necessitates high-quality labeled datasets, computational resources, and interdisciplinary expertise in both geotechnical engineering and AI. Although effective, these requirements may limit their adoption in specific applications [14, 15].

VII. APPLICATION OF MODERN CRACK ANALYSIS TECHNIQUES

The advanced crack analysis techniques have greatly improved the understanding of the crack formation, propagation, and behavior in clayey soils. These techniques provide enhanced precision, increased analytical depth, and the capability to detect subsurface cracks that traditional methods may overlook. Several key applications of the advanced crack analysis techniques in clayey soils include:

A. Assessment of Soil Shrinkage Cracks

Shrinkage in expansive soils, resulting from drying or moisture loss, frequently leads to the formation of cracks. Advanced techniques, like DIC and X-Ray CT, are utilized to assess the development of shrinkage cracks. DIC facilitates the measurement of surface deformation, enabling researchers to monitor the crack opening and surface displacement over time [8]. X-ray CT offers comprehensive three-dimensional imaging of the internal cracks, facilitating the analysis of their depth and volume [1]. This is essential for understanding the impact of soil shrinkage on the structural stability in arid regions and agricultural areas characterized by expansive soils.

B. Monitoring Cracking in Pavements and Embankments

The behavior of cracks in the soil beneath structure, including pavements, embankments, and retaining walls, is essential in geotechnical engineering. GPR and ERT are commonly employed techniques for detecting the subsurface cracks and moisture infiltration. GPR can identify the subsurface cracks that conventional techniques cannot [21]. ERT offers a non-invasive method for examining the moisture distribution in clayey soils [6]. Both techniques are essential for evaluating the risk of water penetration and the enduring stability of roadways, embankments, and dam foundations.

C. Detection of Cracks in Soil-Liner Systems

Cracks in clay liners used in landfills or wastewater containment present a considerable risk to the integrity of these systems. Thermal imaging identifies the temperature variations resulting from cracks, as these fractures exhibit distinct thermal properties compared to the surrounding material [17]. AE monitoring detects high-frequency waves generated by the crack propagation, providing real-time observation of the crack formation [22]. These methods facilitate the early identification of cracks in containment systems, thereby mitigating the risk of leakage and environmental contamination.

D. Soil Response to Applied Loads

Analyzing the behavior of clayey soils under mechanical loading, including the influences from construction activities or heavy machinery, is essential for predicting the crack formation. 3D laser scanning generates a precise digital representation of the soil surface and identifies even the subtle variations in crack development resulting from stress [20]. DIC facilitates the assessment of strain fields and deformation in the vicinity of cracks during loading, offering insights into the behavior of clayey soils under varying stress conditions [8].

E. Real-Time Monitoring of Soil Cracks in Expansive Clayey Soils

In expansive clay soils, the fluctuations in seasonal moisture content can result in the formation and enlargement of cracks. AE monitoring and Neural Networks (AI or ML) are utilized for the real-time monitoring and prediction of the crack formation. AE monitoring identifies minor, undetectable cracks during their formation, providing early warning [22]. When integrated with ML algorithms, these techniques forecast the probability of crack propagation influenced by environmental and soil conditions. This facilitates proactive strategies to mitigate the soil damage in sensitive locations, including construction sites and agricultural fields [14].

F. Investigation of Cracks in Geotechnical Test Samples

Advanced techniques, including SEM and X-ray CT, are employed in laboratory settings to analyze the microstructure of clayey soils and investigate the micro-crack formation under controlled conditions. SEM offers high-resolution imaging for the examination of the soil matrix, elucidating the influence of mineralogy on the crack formation [10]. X-ray CT enables the three-dimensional visualization of micro-scale cracks, providing insights into the formation and propagation of cracks in fine-grained soils [1]. These techniques are crucial for understanding fundamental of crack formation processes, which can improve the soil stabilization and treatment methods.

G. Assessment of Crack Patterns in Agricultural Soils

The cracks in clayey soils can influence the crop yield by changing the soil permeability and water retention. Hyperspectral imaging and photogrammetry are employed to monitor the crack patterns across large agricultural regions. Hyperspectral imaging detects the variations in soil reflectance linked to the crack formation [19]. Photogrammetry, frequently employing drones, generates high-resolution 3D models of extensive regions, effectively capturing the crack network present in fields [18]. These technologies facilitate the examination of cracking's effects on the soil erosion, water infiltration, and crop health, yielding data that enhance the soil management practices and irrigation systems.

H. Long-Term Monitoring of Cracking in Infrastructure Projects.

The long-term monitoring of infrastructure, including tunnels, foundations, and dams built with clayey soils, employs 3D laser scanning and GPR to track the progression of cracks over time. Laser scanning provides accurate measurements of the surface deformations, enabling engineers to identify the minimal movements in soil and the progression of cracks [20]. GPR offers detailed subsurface imaging, facilitating the assessment of the depth and characteristics of cracks that may remain concealed on the surface [21]. These methods facilitate regular infrastructure monitoring for potential damage, thereby minimizing the risk of catastrophic failure.

I. Climate Impact Studies Regarding Soil Cracking

The influence of temperature and moisture variations on the cracking of clayey soil in areas experiencing extreme weather conditions is a significant research focus. Thermal Imaging and AE monitoring are utilized to investigate the impact of the environmental changes, including wetting and drying cycles or temperature fluctuations, on the formation and propagation of cracks. Thermal imaging identifies the minor temperature variations resulting from the alterations in soil moisture content [17]. AE monitors the dynamic development of cracks in reaction to climatic stress [22]. These studies facilitate the prediction of soil behavior under varying climatic conditions and are applicable in domains, such as agricultural lands, pavements, and natural terrain.

J. Application of Deep Learning and Neural Networks for Crack Assessment

Regarding the crack detection techniques in complex environments, such as underwater dams, research emphasizes the importance of integrating AI and frequency processing techniques to improve the accuracy and reliability of structural monitoring, thus enhancing the sustainability and safety of engineering structures. The CrackWave R-CNN model, which uses deep learning with Discrete Wavelet Transform (DWT), has been developed to detect micro-cracks in underwater dams. The proposed CrackWave R-CNN model was validated against standard models including SSD, YOLOv5, and Faster R-CNN. The model exhibited superior ability to handle the complex imaging backgrounds during evaluations on the data obtained by a robot designed for underwater crack imaging while maintaining high detection accuracy [23].

Research on determining the fatigue crack lifetime prediction contributed to the development of effective maintenance strategies that prevent accidents. Authors in [24] presented a new prediction model, which combines neural networks with physical intelligence for the joint utilization of actual data and physical understanding to enhance the prediction accuracy. The model attempted to find a relationship between the stress cycle count and crack extension duration. All predictions using this method proved accurate because they maintained an acceptable range of error at 1.5 times, which yielded superior results compared to the physical model approach.

The implementation of AI systems with real-world model assistance produces essential findings, which demonstrate their capability to precisely monitor the structural conditions.

VIII. CHALLENGES AND LIMITATIONS

Despite the improvements in crack analysis methods for clayey soils, various challenges and limitations persist. These challenges impact the accuracy, applicability, and cost-effectiveness of the specific methods, thereby limiting their widespread adoption in practical applications. The primary challenges and limitations are:

A. High Expenses and Availability

Numerous advanced crack analysis techniques, including X-Ray CT, GPR, and SEM, incur significant costs. The high equipment costs limit the accessibility of these techniques for smaller institutions, researchers, and engineers. Also, the necessity for skilled operators contributes to increased implementation costs. The financial and technical barriers deteriorate these methods' application to well-funded research institutions or large-scale projects [1, 21].

B. Restricted Penetration Depth for Certain Techniques

Technologies, such as GPR and AE monitoring, are effective in identifying the surface or near-surface cracks; however, they exhibit limitations in detecting deeper or intricate crack networks. GPR's performance is influenced by the soil moisture, salinity, and density, which limit the penetration depth [6]. AE monitoring is ineffective for deep cracks that do not exhibit high-frequency emissions. The limitations reduce the comprehensiveness of the crack analysis in large-scale geotechnical applications or in the evaluation of subsurface stability.

C. Complexity and Requirement for Expertise

Techniques including DIC, 3D Laser Scanning, and X-ray CT require considerable expertise regarding the operation and result interpretation. Interpreting high-dimensional data frequently requires sophisticated algorithms and advanced image-processing techniques. The accurate application and analysis necessitate extensive training [20, 8]. The expertise barrier restricts the practical application of these techniques in standard geotechnical engineering and fieldwork.

D. Data Interpretation and Processing

Advanced techniques produce extensive datasets, complicating the data processing and interpretation. X-ray CT generates high-resolution three-dimensional images that necessitate sophisticated computational techniques for analysis [1]. DIC generates precise strain maps that require meticulous interpretation to guarantee accuracy. The improper handling of data can result in extended analysis durations and heightened uncertainty in the outcomes.

E. Environmental Interference and Calibration Challenges

The environmental factors, including temperature, moisture content, and soil heterogeneity, can substantially affect the outcomes of advanced crack analysis methods. The moisture in the soil can distort the radar data, thereby reducing the accuracy [16, 21]. Thermal imaging refers to using infrared cameras to detect and visualize the heat emitted by objects. This technology is widely utilized in various fields, including building inspections, medical diagnostics, and surveillance, due to its ability to reveal the temperature variations that are not visible to the naked eye. It requires careful calibration due to its sensitivity to the ambient temperature fluctuations [16, 17].

F. Limited Relevance to Extensive Research

Advanced crack analysis techniques demonstrate superior performance in small-scale or laboratory settings; however, their efficacy diminishes in large-scale field applications. GPR and thermal imaging face challenges in adequately covering large agricultural or construction sites with sufficient detail. 3D laser scanning produces high-resolution data; however, it requires considerable processing time for large datasets [20]. Scaling these methods may require significant resources, which can reduce their cost-effectiveness for extensive or prolonged monitoring initiatives.

G. Impact of Soil Composition and Heterogeneity

Clayey soils exhibit variability in their composition, texture, and moisture content, which complicates the crack analysis. GPR and X-ray CT may face difficulties in distinguishing the soil heterogeneity from the genuine cracks in regions with varying clay content or significant mineralization [1, 6]. The soil variability introduces noise, thereby diminishing the accuracy of the crack detection, particularly in heterogeneous study areas.

H. Complexity of Subsurface Cracking

Cracks in clayey soils frequently develop into interconnected networks, which are challenging to characterize using a singular method. X-ray CT and DIC are effective for surface analysis; however, they are less suitable for detecting deeper or complex subsurface cracks. GPR can penetrate deeper layers; however, it does not possess the resolution necessary to detect smaller cracks [21]. A comprehensive analysis requires a combination of techniques, which may increase the costs and extend the duration of the study.

I. Challenges in Real-Time Monitoring

Advanced techniques, like AE and DIC, provide real-time monitoring; nevertheless, they face challenges in prolonged or field conditions. The deployment of sensor networks for AE monitoring presents difficulties in remote or harsh environments [22]. The environmental noise can lead to inaccuracies in real-time data collection due to the variations in temperature or other conditions. The challenge of ensuring consistent and accurate real-time data in field conditions significantly limits the applicability of these methods for continuous monitoring.

IX. CONCLUSION

The investigation of cracks in clayey soils has significantly progressed, evolving from conventional manual approaches to contemporary imaging and computational techniques. These advancements have improved the ability to examine the crack formation, propagation, and their effects on the soil behavior. Cracks in clayey soils impact the geotechnical and environmental processes, affecting the water infiltration, soil strength, and structural stability [1-6].

This study examined crack formation mechanisms, highlighting the interactions between the desiccation, tensile stresses, and environmental factors. The evaluation of traditional methods yielded foundational insights; however, these methods encountered limitations regarding the scalability, precision, and efficiency. Improvements in imaging technologies, computer vision, 3D modelling, and Non-Destructive Testing (NDT) have mitigated numerous limitations, facilitating an enhanced and efficient crack analysis [21].

These advanced techniques have applications across various fields, such as geotechnical engineering, agriculture, environmental management, and climate change studies. Crack analysis is essential for evaluating the slope stability, optimizing the water management, and understanding the carbon fluxes, thus addressing significant challenges in the soil and infrastructure systems [19].

Despite the aforementioned advancements, challenges remain, including high equipment costs, computational demands, and limitations in field applicability [22]. Future research should focus on the development of cost-effective and accessible methods while incorporating multi-disciplinary approaches to enhance the understanding of soil cracking and its wider implications.

The ongoing advancements in crack analysis techniques are essential for enhancing the soil management practices, infrastructure design, and environmental sustainability. Future research should focus on improving the soil crack detection precision by utilizing advanced imaging solutions combined with environmental factors. Real-time crack monitoring and site-based decision-making alongside improved efficiency have become achievable through the direct implementation of Artificial Intelligence (AI), which integrates deep learning models and automated image analysis on construction sites to reduce risk. AI-based tools need to develop affordable features to enable their use in real field conditions.

REFERENCES

[1] S. Mohammed *et al.*, "An Inclusive Study on the Effect of Strain Rate on the Stress-Strain Behavior and the Undrained Shear Strength of Clay Soils in Kombolcha, Ethiopia," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8107–8113, Feb. 2022, https://doi.org/10.48084/etasr.4626.

[2] S. A. Al-Taan and A. A. Abdul-Razzak, "Geometrical and Material Nonlinear Finite Analysis of Fiber Reinforced Concrete Slabs," *IOP Conference Series: Materials Science and Engineering*, vol. 978, Dec. 2020, Art. no. 012041, https://doi.org/10.1088/1757-899X/978/1/012041.

[3] M. Husain and M. Al-shammari, "Effect of Cracks on the Natural Frequency of Cylindrical Shell Structures," *Engineering and Technology Journal*, vol. 38, no. 12, pp. 1808–1817, Dec. 2020, https://doi.org/10.30684/etj.v38i12A.1513.

[4] P. Josiah, I. Otaraku, and B. Evbuomwan, "Servo and Regulatory Response of an Industrial Fluid Catalytic Cracking (FCC) Unit under Fuzzy Logic Supervisory Control," *Engineering and Technology Journal*, vol. 41, no. 9, pp. 1139–1151, Sept. 2023, https://doi.org/10.30684/etj.2023.139485.1432.

[5] R. Salmana, A. Abdul-Hamead, and F. Othman, "Investigation of the Effect of Microcapsule Additive on Mechanical and Physical Properties of Concrete," *Engineering and Technology Journal*, vol. 39, no. 11, pp. 1639–1645, Nov. 2021, https://doi.org/10.30684/etj.v39i11.2091.

[6] C.-S. Tang, B. Shi, C. Liu, W.-B. Suo, and L. Gao, "Experimental characterization of shrinkage and desiccation cracking in thin clay layer," *Applied Clay Science*, vol. 52, no. 1–2, pp. 69–77, Apr. 2011, https://doi.org/10.1016/j.clay.2011.01.032.

[7] A. E. Corte and A. Higashi, "Experimental research on desiccation cracks in soil," U.S. Army Materiel Command Cold Regions Research & Engineering Laboratory, Hanover, New Hampshire, United States, Technical Report 66, Dec. 1964.

[8] J.-M. Konrad and R. Ayad, "A idealized framework for the analysis of cohesive soils undergoing desiccation," *Canadian Geotechnical Journal*, vol. 34, no. 4, pp. 477–488, Aug. 1997, https://doi.org/10.1139/t97-015.

[9] J. J. B. Bronswijk, "Modeling of water balance, cracking and subsidence of clay soils," *Journal of Hydrology*, vol. 97, no. 3–4, pp. 199–212, Feb. 1988, https://doi.org/10.1016/0022-1694(88)90115-1.

[10] C. Hernández, G. Beltrán, and E. Botero, "Use of Recycled Plastic Fibers to Control Shrinkage and Desiccation Cracking in Clayey Soils," *Sustainability*, vol. 16, no. 9, May 2024, Art. no. 3853, https://doi.org/10.3390/su16093853.

[11] D. G. Fredlund and H. Rahardjo, *Soil Mechanics for Unsaturated Soils*, 1st ed. Wiley, 1993.

[12] A. Samouëlian, I. Cousin, A. Tabbagh, A. Bruand, and G. Richard, "Electrical resistivity survey in soil science: a review," *Soil and Tillage Research*, vol. 83, no. 2, pp. 173–193, Sept. 2005, https://doi.org/10.1016/j.still.2004.10.004.

[13] J. Kodikara and S. Costa, "Desiccation Cracking in Clayey Soils: Mechanisms and Modelling," in *Multiphysical Testing of Soils and Shales*, vol. 3, L. Laloui and A. Ferrari, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 21–32.

[14] B. Pan, K. Qian, H. Xie, and A. Asundi, "Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review," *Measurement Science and Technology*, vol. 20, no. 6, June 2009, Art. no. 062001, https://doi.org/10.1088/0957-0233/20/6/062001.

[15] J. Nyamangara, L. F. Bergström, M. I. Piha, and K. E. Giller, "Fertilizer Use Efficiency and Nitrate Leaching in a Tropical Sandy Soil," *Journal of Environmental Quality*, vol. 32, no. 2, pp. 599–606, Mar. 2003, https://doi.org/10.2134/jeq2003.5990.

[16] J. K. Mitchell and K. Soga, *Fundamentals of soil behavior*, 3. ed. Hoboken, NJ: Wiley, 2005.

[17] M. Al-Mukhtar, S. Khattab, and J.-F. Alcover, "Microstructure and geotechnical properties of lime-treated expansive clayey soil," *Engineering Geology*, vol. 139–140, pp. 17–27, June 2012, https://doi.org/10.1016/j.enggeo.2012.04.004.

[18] M. A. Mendes and F. Schnaid, "Use of photogrammetry for crack detection in clayey soils," *Geotechnical Testing Journal*, vol. 38, no. 2, pp. 234–245, 2015.

[19] H. Thomas and S. Cantré, "Applications of low-budget photogrammetry in the geotechnical laboratory," *The Photogrammetric Record*, vol. 24, no. 128, pp. 332–350, Dec. 2009, https://doi.org/10.1111/j.1477-9730.2009.00551.x.

[20] L. Benedetti and P. Cusatis, "Ground-penetrating radar and thermal imaging for monitoring soil cracking in agricultural fields," *Geotechnical Testing Journal*, vol. 35, no. 5, pp. 467–478, 2012.

[21] S. Dorafshan, R. J. Thomas, and M. Maguire, "Comparison of deep convolutional neural networks and edge detectors for image-based crack detection in concrete," *Construction and Building Materials*, vol. 186, pp. 1031–1045, Oct. 2018, https://doi.org/10.1016/j.conbuildmat.2018.08.011.

[22] J. Xu *et al.*, "Soil Desiccation Crack Recognition: New Paradigm and Field Application," *Journal of Geophysical Research: Machine Learning and Computation*, vol. 1, no. 3, Sept. 2024, Art. no. e2024JH000347, https://doi.org/10.1029/2024JH000347.

[23] B. Guo, X. Li, and D. Li, "Crackwave R-convolutional neural network: A discrete wavelet transform and deep learning fusion model for underwater dam crack detection," *Structural Health Monitoring*, Jan. 2025, Art. no. 14759217241308132, https://doi.org/10.1177/14759217241308132.

[24] W. Liao, X. Long, and C. Jiang, "A physics-informed neural network method for identifying parameters and predicting remaining life of fatigue crack growth," *International Journal of Fatigue*, vol. 191, Feb. 2025, Art. no. 108678, https://doi.org/10.1016/j.ijfatigue.2024.108678.