
Dispersive Soils in Geotechnical Engineering: A Survey

www.surveyx.cn

Abstract

This survey paper delves into the complexities of dispersive soils, characterized by their clay-rich composition and high exchangeable sodium percentage (ESP), which pose significant challenges in geotechnical engineering. The propensity of these soils to disintegrate upon water exposure leads to structural instability and soil erosion, necessitating advanced assessment and stabilization techniques. The paper explores the significance of dispersive soils in construction and agriculture, highlighting their impact on soil health and infrastructure integrity. It evaluates traditional and innovative stabilization methods, including lignosulfonate and silica fume, emphasizing environmentally sustainable solutions. The role of advanced technologies, such as large language models (LLMs) like ChatGPT, in enhancing soil erosion modeling and predictive capabilities is also discussed. Furthermore, the survey examines the implications of high ESP on soil stability, agricultural productivity, and salinity management, underscoring the need for comprehensive soil management strategies. The integration of Microbially Induced Calcite Precipitation (MICP) and organic matter in geotechnical applications is highlighted as a promising approach to improving soil cohesion and reducing erosion risks. The paper concludes by emphasizing the importance of a multi-faceted approach, combining innovative materials, advanced modeling techniques, and sustainable practices, to effectively manage the challenges posed by dispersive soils and enhance soil stability.

1 Introduction

1.1 Significance of Dispersive Soils

Dispersive soils are critical in geotechnical engineering due to their significant swelling and shrinkage, which can lead to structural damage and instability [1]. These clay-rich soils, characterized by a high exchangeable sodium percentage, pose challenges to the integrity of construction and infrastructure. Their dynamic properties, influenced by factors such as sodium chloride, are essential for soil health and agricultural productivity [2]. Additionally, the mass physical properties of marine mud deposits, affected by hydrated organic matter, are vital in geotechnical projects, influencing soil behavior under diverse environmental conditions [3]. The integration of advanced technologies, including large language models like ChatGPT, offers opportunities to enhance efficiency and decision-making in the analysis and management of dispersive soils [4]. Furthermore, dispersive soils' role in soil organic carbon fractionation affects soil structural and chemical stability, impacting construction and infrastructure [5]. Thus, a comprehensive understanding of dispersive soils is essential for effective geotechnical engineering project planning and execution.

1.2 Challenges Posed by Dispersive Soils

Dispersive soils introduce significant challenges in engineering due to their instability and erosion susceptibility when exposed to water. This instability can lead to structural failures in hydraulic

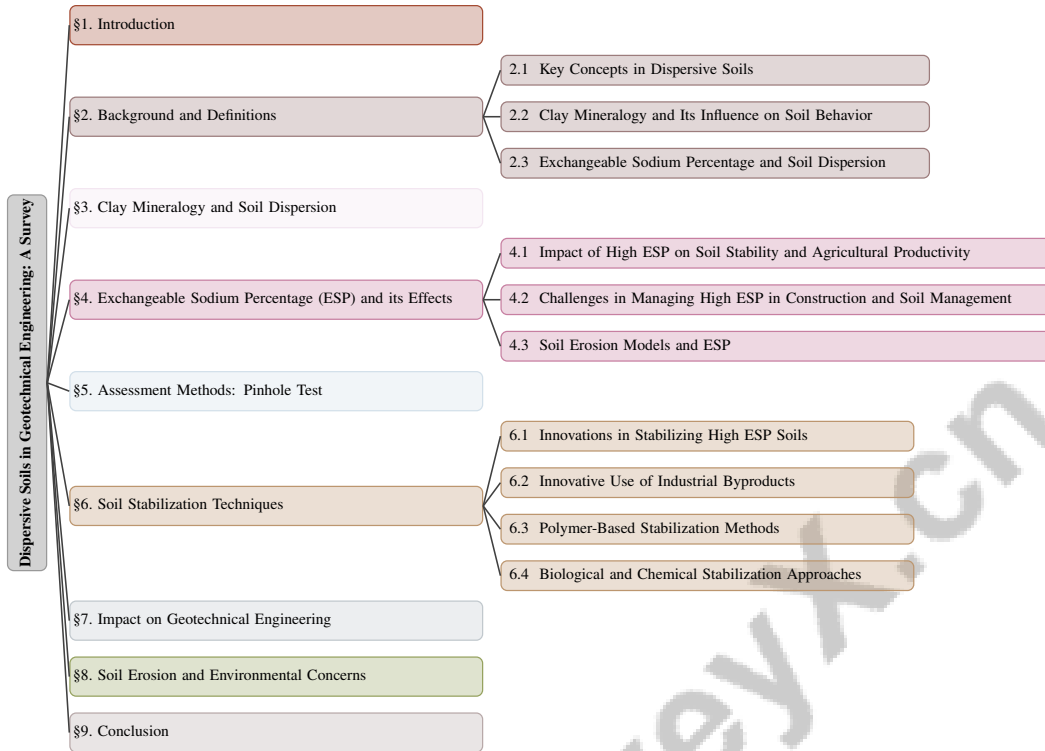


Figure 1: chapter structure

structures and earth dams, necessitating careful management and design strategies [6]. Soil erosion is not only an engineering issue but also an environmental, economic, and social challenge, particularly in agricultural contexts [7]. Current stabilization methods for expansive soils often face limitations due to environmental impacts and effectiveness, highlighting the need for innovative, non-toxic alternatives like lignosulfonate [1]. Additionally, climate change complicates the interactions between water flow and soil erosion on vegetated hillslopes, hindering predictive and management efforts [8]. The limitations of existing methods are further exacerbated by inadequate consideration of sodium chloride concentrations on soil dispersion and aggregate stability, which are crucial for maintaining soil health and productivity [2]. In coastal reclamation areas, high soil salt content and irrigation salinity complicate soil management, potentially reducing stabilization effectiveness [9]. While large language models (LLMs) like ChatGPT can advance geotechnical analysis, their potential for generating inaccurate outputs poses risks for engineering projects [4]. These multifaceted challenges necessitate comprehensive approaches to managing dispersive soils in geotechnical engineering.

1.3 Relation to Keywords

The keywords 'large language models', 'ChatGPT', 'prompt engineering', and 'hallucinations' are central to exploring advanced computational tools in geotechnical engineering, especially concerning dispersive soils [4]. LLMs like ChatGPT have been increasingly utilized to enhance analysis and decision-making in managing dispersive soils by processing extensive data and generating insights. 'Prompt engineering' is crucial for optimizing LLM performance, ensuring that outputs are relevant and accurate, which is vital given the complexities of soil behavior analysis. However, the challenge of 'hallucinations', where LLMs produce plausible yet incorrect outputs, necessitates careful verification and validation of information in geotechnical applications. This survey investigates how these computational advancements can address the challenges posed by dispersive soils while acknowledging the associated limitations and risks.

1.4 Structure of the Survey

This survey is systematically structured to provide a comprehensive exploration of dispersive soils in geotechnical engineering. It begins with an **Introduction** that highlights the significance of dispersive

soils, outlines the challenges they present, and discusses their relevance to selected keywords. The **Background and Definitions** section delves into fundamental concepts such as clay mineralogy and the role of exchangeable sodium percentage, introducing assessment methods like the pinhole test. The subsequent section, **Clay Mineralogy and Soil Dispersion**, examines the influence of mineralogical characteristics on soil behavior, utilizing spectral analysis and considering the global implications of clay-size minerals. In **Exchangeable Sodium Percentage (ESP) and its Effects**, the focus shifts to the impact of ESP on soil stability and associated challenges in construction and soil management. The **Assessment Methods: Pinhole Test** section provides a detailed examination of the pinhole test methodology and compares it with alternative assessment techniques. **Soil Stabilization Techniques** reviews various methods to mitigate soil dispersion, emphasizing innovations in stabilizing high ESP soils and the use of industrial byproducts. The **Impact on Geotechnical Engineering** section analyzes the implications of dispersive soils on engineering projects, incorporating case studies and exploring hydrological interactions. Finally, **Soil Erosion and Environmental Concerns** addresses the environmental impact of soil erosion, sustainable stabilization methods, and the agricultural implications of soil salinity. The survey concludes with a synthesis of key findings, emphasizing potential solutions and areas for future research. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Key Concepts in Dispersive Soils

Dispersive soils, characterized by their tendency to disintegrate upon water exposure, present challenges in construction due to their clay-rich mineralogy and high exchangeable sodium percentage (ESP) [6]. Understanding the mineralogical interactions, such as cation exchange and surface complexation, is crucial for analyzing dispersive soil behavior [10]. Expansive soils, a subset of dispersive soils, exacerbate engineering difficulties with their swelling and shrinkage properties [1]. The physico-chemical properties, including enzyme activities, significantly affect soil organic carbon dynamics and soil quality, especially in saline-alkali agroecosystems [11]. The complexity of dispersive soils is further highlighted by the role of hydrated organic matter in marine mud [3]. Advanced computational methods, such as the p-refined Multilevel Quasi-Monte Carlo (p-MLQMC) approach, improve the assessment of uncertainty in material parameters, refining dispersive soil analysis [12]. Hydrological models that integrate extended Saint-Venant equations with Hairsine-Rose equations enhance the understanding of water flow and erosion in vegetated landscapes [8]. Spectral analysis of clay minerals provides insights into their structural and chemical properties, crucial for comprehending dispersive soils [13]. Soil dispersion affects nutrient availability, water retention, and crop productivity [2]. A global dataset of clay-size minerals supports interdisciplinary research, aiding in understanding their roles in soil processes [14]. Mastery of these concepts is essential for developing effective stabilization techniques and enhancing engineering performance while promoting environmental sustainability [15].

2.2 Clay Mineralogy and Its Influence on Soil Behavior

Clay mineralogy significantly influences soil behavior and dispersion through molecular interactions that control metal ion retention and exchange [10]. Structural characteristics and functional groups of clay minerals, analyzed using mid-infrared (MIR) and near-infrared (NIR) spectroscopy, reveal complex interactions with environmental factors, impacting marine mud's physical properties. These interactions determine soil stability, affecting moisture, nutrient retention, structural integrity, and erosion susceptibility. Soil texture, shaped by mineral composition, affects particle size fractionation methods, crucial for understanding soil behavior and management [5]. Globally, clay-size minerals are integral to biogeochemical cycles and atmospheric processes, yet comprehensive datasets are lacking, necessitating further research [14]. Understanding mineralogical influences on soil behavior is vital for developing effective soil stabilization and management strategies, enhancing the sustainability of agricultural and construction practices.

2.3 Exchangeable Sodium Percentage and Soil Dispersion

Exchangeable sodium percentage (ESP) is a key factor in soil dispersion, affecting soil stability and agricultural productivity. High ESP levels increase dispersion, compromising structural integrity and

increasing erosion risks, challenging construction and agriculture [16]. ESP negatively impacts soil organic carbon (SOC), disrupting soil structure and reducing nutrient availability [11]. In agriculture, high ESP correlates with reduced crop yields, emphasizing its importance in soil management [17]. The complexity of clay mineral surfaces and metal ion retention processes complicates modeling ESP effects on soil dispersion, requiring sophisticated approaches for accurate predictions [10]. Innovative methods like the Sodium Chloride Dispersion Method (SCDM) evaluate soil dispersion under varying sodium chloride concentrations, providing insights into soil instability conditions [2]. Integrating geoinformation sciences and remote sensing into soil erosion risk assessments offers a comprehensive framework for evaluating ESP impacts. Models like the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE), along with artificial intelligence and machine learning, improve erosion risk prediction and management in high ESP landscapes [7]. Understanding ESP's role in soil dispersion enables targeted interventions to enhance soil stability, reduce erosion, and improve agricultural outcomes.

In examining the intricate relationships between soil composition and carbon dynamics, it is essential to consider the underlying mineralogical factors. Figure 2 illustrates the hierarchical structure of clay mineralogy and soil dispersion, effectively highlighting the mineralogical characteristics that influence carbon turnover. This figure not only emphasizes the role of spectral analysis in understanding clay minerals but also underscores the global significance of clay-size minerals. Each section of the figure delves into specific mechanisms, techniques, and implications for soil management and environmental conservation, thereby providing a comprehensive framework for understanding the complexities of soil health and its impact on carbon cycling.

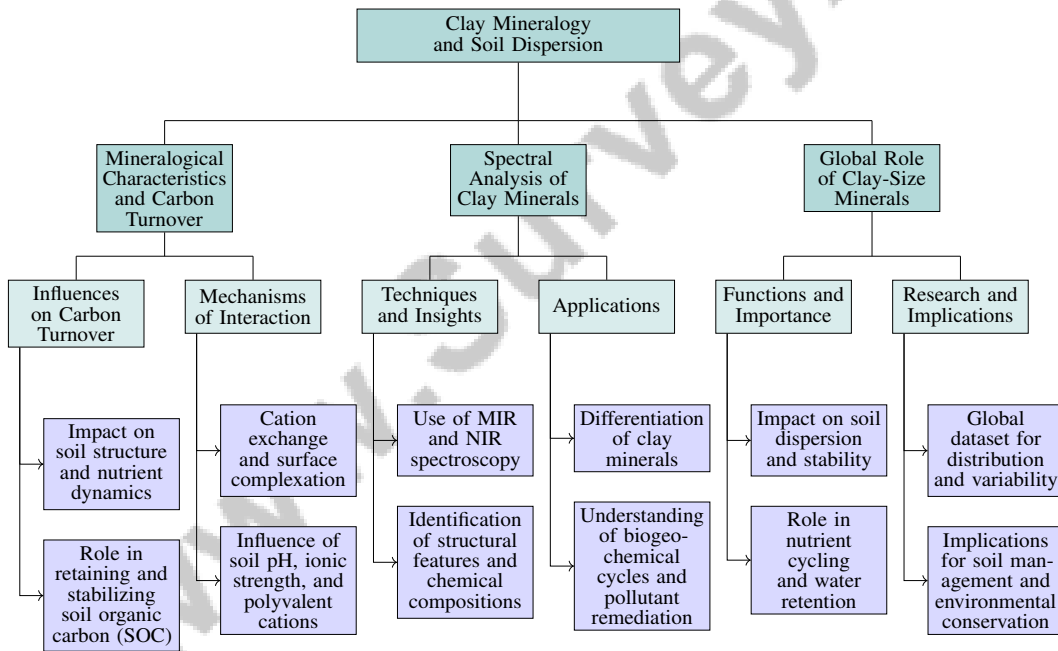


Figure 2: This figure illustrates the hierarchical structure of clay mineralogy and soil dispersion, highlighting the mineralogical characteristics influencing carbon turnover, the role of spectral analysis in understanding clay minerals, and the global significance of clay-size minerals. Each section delves into specific mechanisms, techniques, and implications for soil management and environmental conservation.

3 Clay Mineralogy and Soil Dispersion

3.1 Mineralogical Characteristics and Carbon Turnover

The mineralogical attributes of clay minerals are pivotal in influencing carbon turnover in soils, impacting both soil structure and nutrient dynamics. Spectral techniques such as mid-infrared (MIR) and near-infrared (NIR) spectroscopy elucidate clay minerals' structural properties and interactions

with organic matter, which are crucial for retaining and stabilizing soil organic carbon (SOC), thereby enhancing soil fertility and aiding climate change mitigation [13]. Clay minerals, with their extensive surface areas and reactive sites, facilitate the adsorption and protection of organic carbon, modulating carbon turnover rates. Structural features like layer charge and interlayer spacing are critical in binding organic matter, shielding it from microbial decomposition, and thus contributing to SOC's long-term stabilization, which supports soil health and agricultural productivity [11, 5]. Furthermore, clay mineralogy affects physical properties such as porosity and water retention, influencing microbial activity and organic matter decomposition. Complex interactions between clay minerals and organic matter are governed by soil pH, ionic strength, and polyvalent cations, which can alter clay minerals' binding affinity, affecting carbon turnover rates. Mechanisms such as cation exchange, surface complexation, and the physicochemical properties of clay are essential for understanding organic compounds' retention and release, impacting soil health and carbon cycling dynamics [13, 1, 5, 10]. Understanding the interplay between clay mineralogy and carbon turnover is crucial for developing soil management strategies that enhance carbon sequestration and improve soil resilience to environmental changes. Insights into clay interactions' molecular mechanisms and global clay mineral distribution can inform practices optimizing soil health and productivity amidst climate variability [14, 11, 10, 5]. Advanced analytical techniques characterizing clay mineral structures and their interactions with organic matter offer valuable insights into soil carbon dynamics.

3.2 Spectral Analysis of Clay Minerals

Spectral analysis is essential for identifying and understanding clay minerals' properties, revealing insights into their structural characteristics and chemical compositions. Distinct spectral patterns of different clay minerals correlate with their structural features and compositional elements [13]. Techniques such as MIR and NIR spectroscopy enable detailed examinations of clay mineral structures and their interactions with environmental factors. Comparative spectral data analysis differentiates clay minerals based on vibrational modes indicative of specific functional groups and bonding environments, enhancing understanding of clay minerals' influence on terrestrial biogeochemical cycles, metal ion retention, and pollutant remediation processes, vital for environmental management and resource recovery strategies [10, 14]. Spectral analysis aids in identifying clay minerals and supports investigations into their interactions with organic matter and other soil constituents, essential for predicting soil behavior and stability. A comprehensive global dataset encompassing both topsoil and subsoil clay-size mineral compositions at various spatial resolutions enhances spectral analysis utility in soil studies [14]. This dataset mitigates previous limitations focused primarily on dust emission, providing a nuanced understanding of clay mineral distributions and their implications for soil dispersion and stability. Leveraging spectral analysis deepens understanding of clay minerals' mineralogical properties, informing soil management practices and contributing to agricultural and environmental systems' sustainability.

3.3 Global Role of Clay-Size Minerals

Clay-size minerals are integral to global soil processes, significantly affecting soil dispersion and stability due to their fine size and high surface area. These minerals play a crucial role in soil functions such as nutrient cycling, water retention, and soil structure formation. The global dataset of clay-size minerals offers a comprehensive overview of their distribution and variability across different soil orders, essential for understanding their role in continental-scale soil processes [14]. This dataset supports studies in biogeochemistry, climatology, and agronomy by establishing a benchmark for assessing clay minerals' influence on soil behavior. Spectral characteristics of clay minerals, analyzed through MIR and NIR spectroscopy, provide insights into their structural features and environmental interactions [13]. However, gaps remain regarding less-studied clay mineral varieties' spectral behavior and structural variations' implications. Addressing these gaps is vital for understanding clay minerals' functions and their impact on soil dispersion. The variability in clay-size mineral compositions underscores the importance of considering mineralogical diversity in soil management practices, influencing critical soil processes such as aggregation, erosion, and nutrient availability, essential for maintaining soil health and productivity. Investigating global clay-size mineral distribution and composition enables precise strategies to enhance soil stability and mitigate soil dispersion's adverse effects. This research deepens understanding of terrestrial biogeochemical cycles and atmospheric interactions, promoting sustainable soil management practices and advancing environmental conservation efforts [2, 5, 14].

4 Exchangeable Sodium Percentage (ESP) and its Effects

4.1 Impact of High ESP on Soil Stability and Agricultural Productivity

High exchangeable sodium percentage (ESP) significantly impacts soil stability and agricultural productivity by disrupting soil structure and nutrient dynamics. Elevated ESP levels lead to soil dispersion, which weakens soil structure, increases erosion risk, and reduces the soil's ability to support plant growth [10]. Integrating molecular insights into macroscopic models enhances predictions of metal ion behavior in clay-rich environments, improving understanding of soil stability under high ESP conditions.

In agriculture, high ESP is linked to increased soil salinity, complicating management and adversely affecting crop productivity. The interplay of salinity and sodicity disrupts soil's biological, physical, and chemical properties, leading to land degradation and reduced sustainability, especially in arid and semi-arid regions relying on irrigation with unsuitable soils or poor-quality water. This interaction affects nutrient balance and plant health, reducing infiltration and hydraulic conductivity due to sodium-induced dispersion [18, 16]. Salt accumulation, exacerbated by droughts and limited water resources, challenges agricultural productivity, impacting crop yields like corn, and necessitates effective soil management strategies to mitigate high ESP and salinity effects.

The role of hydrated organic matter is crucial for soil stability and productivity. Ignoring this component can lead to misunderstandings of soil behavior, especially in marine sediments under varying conditions [3]. Techniques ensuring high recovery rates of soil organic carbon are vital for sustaining soil health, enhancing structural stability, and improving nutrient availability [5].

The transition from dispersion to flocculation in sandy clay loam soils indicates that higher ionic strengths can mitigate the dispersive effects of high ESP, offering insights into potential soil stabilization strategies [2]. Evaluating high ESP's effects on soil stability and agricultural productivity enables the formulation of targeted interventions to enhance soil management practices, improve crop yields, and ensure sustainable agricultural production.

4.2 Challenges in Managing High ESP in Construction and Soil Management

Managing high exchangeable sodium percentage (ESP) soils in construction and soil management presents significant challenges due to their instability and dispersion characteristics. Traditional stabilization methods often rely on costly chemical additives, necessitating exploration of sustainable alternatives [6]. Recent research has improved understanding of metal ion-clay interactions, enhancing predictive models for retention behavior, yet applying these models in practice remains challenging [10].

In construction, challenges include limited evaluation standards for polymer stabilization, life-cycle cost considerations, and the moisture susceptibility of stabilized soils, all requiring comprehensive testing protocols for reliability and effectiveness [15]. Additionally, managing saline-sodic soils is complicated by methods that often overlook the dynamic interplay between soil salinity and evaporation, leading to suboptimal outcomes [9].

In agriculture, while regions like the Bule Hora District have soils suitable for irrigation, detailed management practices are essential to address salinity issues and enhance productivity [19]. However, many studies are conducted under idealized conditions that may not be replicable in practice, often resulting in harmful byproducts [20].

Moreover, overlapping spectral features of various minerals complicate current studies, hindering the interpretation of soil characteristics and the development of effective management strategies [13]. These multifaceted challenges highlight the need for innovative approaches and comprehensive research to effectively manage high ESP soils in both construction and agricultural settings.

4.3 Soil Erosion Models and ESP

Soil erosion models are essential for predicting dispersion and erosion in high exchangeable sodium percentage (ESP) soils. Traditional models, such as the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE), estimate soil erosion risks by incorporating factors

like rainfall, soil type, topography, crop management, and conservation practices. However, their ability to account for the specific impacts of high ESP on soil dispersion is limited [7].

Advancements in artificial intelligence (AI) and machine learning have introduced methodologies that enhance accuracy and adaptability in predicting soil erosion. These AI-based models can integrate a broader range of variables, including soil chemical properties like ESP, improving predictions of soil erosion across diverse environmental conditions. Their adaptability allows for dynamic assessment of erosion risks, accommodating changes in soil management practices and environmental factors influencing soil stability [7].

Challenges in managing high ESP soils, such as inadequate drainage and inappropriate irrigation practices, exacerbate soil erosion and salinization, leading to reduced agricultural yields [16]. Addressing these challenges necessitates integrating ESP-specific data into erosion models to enhance predictive capabilities. By incorporating ESP into soil erosion models, researchers can develop effective soil management strategies that mitigate adverse effects of soil dispersion, enhance soil stability, and improve agricultural productivity, which is vital for sustainable land management and preventing soil degradation in high ESP-affected areas.

5 Assessment Methods: Pinhole Test

Category	Feature	Method
Introduction to Pinhole Test	Soil Stability Evaluation	ESVMV[8]
Methodology of Pinhole Test	Soil Stability Evaluation	SQAM[11]
Comparison with Other Assessment Methods	Soil Stability Evaluation	SFSM[6], SCDM[2]

Table 1: This table summarizes the methods used for assessing soil dispersibility through the pinhole test, highlighting the specific features and methodologies employed. It includes references to the Enhanced Support Vector Machine Validation (ESVMV), Soil Quality Assessment Model (SQAM), and comparative methods such as the Soil Feature Stability Model (SFSM) and the Soil Chemical Dispersion Model (SCDM). These methods provide insights into soil stability and erosion risk evaluation under various environmental conditions.

In geotechnical engineering, evaluating soil dispersibility, particularly in soils with high clay content and elevated exchangeable sodium percentage (ESP), is crucial for assessing erosion risks and infrastructure stability. Table 1 provides a comprehensive overview of the methodologies employed in the pinhole test for soil stability evaluation, detailing the features and comparative assessment methods used in geotechnical engineering. Additionally, Table 3 offers a comprehensive comparison of various soil assessment methods, emphasizing their unique features and applications in evaluating soil stability and dispersibility. Methods like the pinhole test assess soil permeability and drainage characteristics, informing soil health assessments and agricultural suitability [18, 4, 5]. This test simulates natural hydraulic conditions, providing direct insights into soil behavior under water flow.

5.1 Introduction to Pinhole Test

Benchmark	Size	Domain	Task Format	Metric
GDCM[14]	168	Soil Science	Mineral Composition Analysis	Mineral Composition Percentage, Data Uncertainty

Table 2: This table presents a benchmark dataset, GDCM, used in the domain of soil science for analyzing mineral composition. It details the dataset size, the specific task format employed, and the metrics used for evaluation, including mineral composition percentage and data uncertainty. Such benchmarks are crucial for advancing research in soil dispersibility and stability assessments.

The pinhole test is a key method for assessing soil dispersibility in high clay content and elevated ESP soils. It replicates hydraulic conditions that lead to soil dispersion, offering insights into structural integrity and stability under water flow. This test is vital for identifying soils prone to erosion and structural failure, critical for developing effective soil management strategies and ensuring engineering project stability [18, 20, 5]. The test's relevance is enhanced by its ability to mimic natural conditions, providing a practical approach to understanding soil behavior. Similar to artificial

neural networks (ANN) in analyzing soil properties and their agricultural impacts [17], the pinhole test directly assesses soil dispersibility, essential for predicting erosion risks and formulating management strategies. It complements other evaluation methods, such as clay dispersion ratios and water-stable aggregate stability [2], by focusing on dispersive characteristics. This method is particularly relevant in scenarios where soil dispersion threatens infrastructure stability, such as dam failures and flash floods [8]. Incorporating the pinhole test into assessment protocols allows for better anticipation and mitigation of challenges associated with dispersive soils in diverse environmental contexts. Table 2 provides an overview of a representative benchmark dataset utilized in soil science, highlighting its relevance to the study of soil dispersibility and stability.

5.2 Methodology of Pinhole Test

The pinhole test evaluates soil dispersibility, particularly in high clay content and elevated ESP soils, by simulating hydraulic conditions that replicate natural soil-water interactions. Water is directed through a small aperture in a compacted soil sample, analyzing hydrological responses and identifying signs of soil dispersion or erosion. This methodology is crucial for understanding soil organic carbon cycling dynamics and assessing the impacts of various dispersion techniques on soil stability and health within sustainable management practices [18, 5]. Preparing soil samples is critical, requiring careful consideration of soil composition and compaction to reflect field scenarios accurately. Similar to long-term wetting-drying experiments that monitor evaporation rates and salt distribution in soil columns with varying sodicity levels [9], the pinhole test necessitates precise sample preparation for consistent testing conditions. During the test, water is introduced at a controlled rate, and effluent turbidity and sediment content are monitored as indicators of soil dispersion. Standardizing test duration and water flow rate ensures consistent conditions for evaluating the effects of soil salinity and sodicity on these processes [19, 18, 9, 16, 5]. Results yield insights into the soil's dispersive potential, guiding the development of management and stabilization strategies. Integrating the pinhole test with methodologies like the Soil Quality Assessment Model (SQAM), which evaluates relationships between soil organic carbon (SOC), properties, and enzyme activities [11], enhances understanding of soil behavior under varying environmental conditions, enabling researchers to identify key soil quality indicators and develop targeted interventions to mitigate risks associated with dispersive soils.

5.3 Comparison with Other Assessment Methods

The pinhole test, while prominent for evaluating soil dispersibility, is one of several techniques for assessing soil susceptibility to dispersion. Alternative methods, such as the crumb test and the double hydrometer test, offer different approaches to understanding soil behavior under varying conditions. The crumb test qualitatively measures soil stability and dispersion potential by observing the disintegration of soil aggregates in water, making it useful for quick field assessments [6]. In contrast, the double hydrometer test quantifies soil particle dispersibility by measuring sedimentation rates with and without a dispersing agent, offering a detailed analysis of particle behavior and often used alongside other methods for a comprehensive understanding of soil dispersibility [2]. This method effectively distinguishes between mechanical and chemical dispersion caused by high ESP. The pinhole test's advantage lies in simulating natural hydraulic conditions; however, it is limited by its focus on small-scale samples and may not fully capture complex interactions present in larger field scenarios. Integrating spectral analysis techniques, such as mid-infrared (MIR) and near-infrared (NIR) spectroscopy, into soil assessment can enhance understanding of clay mineral structures and their impact on soil dispersion [13], providing valuable mineralogical insights that complement findings from physical dispersion tests. Each assessment method presents distinct advantages and disadvantages, necessitating careful selection based on project objectives and the unique physical and chemical properties of the soil. Techniques such as conventional field assessments, advanced geostatistical methods, and remote sensing technologies can be employed depending on factors like soil salinity, sodicity, and desired accuracy, as highlighted in recent studies on soil diagnostics and erosion risk assessment. Understanding these nuances is crucial for effective soil management and tailored intervention strategies [18, 4, 7, 5]. By employing a combination of methods, researchers and engineers can gain a holistic view of soil dispersibility, facilitating informed decision-making in soil management and stabilization efforts.

Feature	Pinhole Test	Crumb Test	Double Hydrometer Test
Evaluation Focus	Hydraulic Conditions	Soil Aggregate Stability	Particle Dispersibility
Testing Scale	Small-scale Samples	Field Assessments	Laboratory Analysis
Data Output	Turbidity, Sediment Content	Qualitative Observations	Sedimentation Rates

Table 3: This table provides a detailed comparison of the pinhole test, crumb test, and double hydrometer test, highlighting their respective evaluation focuses, testing scales, and data outputs. It underscores the distinct methodologies employed in each test to assess soil stability and dispersibility under varying conditions. Such comparisons are essential for selecting appropriate techniques in geotechnical engineering applications.

6 Soil Stabilization Techniques

6.1 Innovations in Stabilizing High ESP Soils

Innovative stabilization techniques for high exchangeable sodium percentage (ESP) soils focus on sustainability and effectiveness. Lignosulfonate, a non-toxic byproduct, enhances soil stability while reducing environmental impacts, serving as an eco-friendly alternative to conventional stabilizers by decreasing soil plasticity and improving structural integrity [1]. Silica fume, a waste material, is increasingly used in stabilization, reflecting a trend towards utilizing industrial byproducts in geotechnical applications [6]. This aligns with sustainability goals by promoting resource efficiency. Polymer-based stabilization techniques are also gaining attention, emphasizing the synergy of polymers with traditional stabilizers to enhance soil resilience [15]. Microbially Induced Calcite Precipitation (MICP) leverages biological processes to improve soil strength and mitigate erosion [20]. Integrating these advanced methods with existing practices establishes a comprehensive framework for effective soil management, while understanding sodium chloride's impact on soil structure offers insights for refining irrigation and management strategies [5, 2].

6.2 Innovative Use of Industrial Byproducts

The use of industrial byproducts in soil stabilization enhances soil properties and promotes environmental sustainability. Materials such as fly ash, silica fume, and slag improve soil stability and reduce the environmental impact of traditional stabilizers like cement and lime. The integration of polymers and waste materials, like silica fume, offers a cost-effective means to enhance soil mechanical properties and sustainability through electrostatic interactions and aluminosilicate gel formation [6, 15]. Silica fume, with its fine particle size and high pozzolanic activity, enhances soil strength and durability by reducing plasticity and improving load-bearing capacity [1, 15]. Fly ash improves soil compaction and reduces shrink-swell potential, providing a sustainable solution to disposal issues by repurposing waste materials [6]. Polymers offer environmentally friendly alternatives to traditional stabilizers, improving soil cohesion and water resistance [15]. By leveraging industrial byproducts like lignosulfonate and silica fume, advanced stabilization techniques enhance expansive and dispersive soils while supporting sustainable development goals.

6.3 Polymer-Based Stabilization Methods

Polymer-based stabilization methods effectively enhance the stability of dispersive soils. Polymers present a promising alternative to traditional stabilizers, improving soil cohesion and water resistance, thus reducing susceptibility to dispersion and erosion [15]. The incorporation of polymers alters soil's molecular structure, strengthening adhesive forces and mitigating dispersion risks. Various polymer types, including geopolymers, biopolymers, and synthetic organic polymers, influence stabilization mechanisms such as electrostatic interactions and structural changes. For instance, lignosulfonate creates a waterproofing effect, while silica fume enhances dynamic properties [1, 6, 15]. Advancements in material science have led to new polymer formulations, expanding applications across diverse environmental conditions [6]. The environmental benefits include reducing the carbon footprint and ecological impact of stabilization activities. By utilizing diverse polymer properties, targeted interventions can stabilize dispersive soils, enhancing stability through electrostatic interactions, structural modifications, and binding gel formations [1, 6, 15, 2, 5].

6.4 Biological and Chemical Stabilization Approaches

Biological and chemical stabilization approaches enhance dispersive soil stability, offering sustainable solutions to combat soil dispersion and erosion. Biological methods, like Microbially Induced Calcite Precipitation (MICP), use microbial processes to enhance soil cohesion by inducing calcite formation, improving engineering properties and mitigating erosion risks [15, 11, 20, 5]. Chemical stabilization involves agents such as lime, cement, and polymers to improve soil properties by altering its chemical composition. Understanding soil chemistry, particularly interactions between metal ions and clay minerals, is crucial for effective chemical stabilization [10]. Integrating artificial intelligence and machine learning into soil erosion models can enhance predictive capabilities, allowing for more robust stabilization strategies [7]. By improving model integration and examining climate change impacts, researchers can devise adaptive stabilization strategies.

7 Impact on Geotechnical Engineering

7.1 Geotechnical Applications of MICP and Organic Matter

Microbially Induced Calcite Precipitation (MICP) and organic matter are crucial for enhancing soil stability and mitigating dispersion in geotechnical applications. MICP employs microorganisms to precipitate calcite within soil matrices, thereby improving cohesion and reducing erosion risks, offering a sustainable alternative to traditional chemical stabilizers [20]. This biotechnological approach is particularly valuable in environments where conventional methods are inadequate for addressing dispersive soil issues.

Incorporating organic matter into soil stabilization strategies further enhances structural integrity by improving soil aggregation, water retention, and nutrient availability, essential for maintaining stability and preventing dispersion. A framework categorizing soil and water quality based on physicochemical properties underscores the influence of land use practices on soil characteristics, highlighting organic matter's pivotal role in soil management [19].

Exploring the synergistic effects of MICP and organic matter can lead to targeted interventions for dispersive soil challenges. This approach leverages microbial processes to enhance soil properties through calcite production, potentially improving construction materials and addressing liquefaction and erosion issues, while mitigating environmental concerns associated with traditional ground improvement methods [20, 5]. These innovations not only bolster soil stability but also promote sustainable land management and environmental conservation, emphasizing the necessity for ongoing research into MICP and organic matter applications in geotechnical engineering.

7.2 Hydrological Interactions and Erosion Control

Hydrological interactions are vital in controlling soil erosion and dispersion, particularly in geotechnical projects where soil stability is crucial. These interactions involve complex relationships among water flow, soil structure, and vegetation, influencing erosion processes and soil dispersion potential. Advanced hydrological models, integrating the extended Saint-Venant equations with the Hairsine-Rose equations, offer comprehensive insights into these interactions by accurately modeling water flow and sediment transport in vegetated landscapes [8]. Such models aid in predicting erosion patterns and identifying vulnerable areas in geotechnical projects, guiding effective erosion control measures.

Vegetation significantly influences hydrological interactions, as plant roots enhance soil cohesion and reduce surface runoff velocity, thus lowering erosion risks. Vegetation also affects soil hydraulic conductivity, impacting water infiltration and retention—key factors in maintaining soil stability. Research highlights vegetation's role in altering water dynamics and the distribution of eroded soil particles, emphasizing its critical role in mitigating erosion [18, 8, 7, 5, 16].

Effective management of hydrological interactions in geotechnical projects involves strategic vegetation placement, drainage system design, and soil stabilization techniques that enhance soil structure and reduce dispersion potential. Innovative materials, such as polymers and industrial byproducts, can complement these strategies by improving soil cohesion and water resistance. Techniques like MICP and lignosulfonate admixtures enhance soil resilience against hydrological stresses, mitigating erosion and dispersion risks. MICP strengthens soil structure through calcite production, while lignosulfonate

provides waterproofing, reducing swelling in expansive soils. Together, these innovations foster robust infrastructure and effective environmental remediation strategies [18, 1, 4, 7, 20].

Analyzing hydrological interactions and their impact on soil erosion and dispersion is essential for developing sustainable geotechnical solutions that safeguard infrastructure and uphold environmental integrity. By integrating sophisticated modeling techniques with practical erosion control strategies, researchers and practitioners can effectively navigate the complexities of hydrological interactions in geotechnical projects. This comprehensive approach enhances understanding of water-soil-plant dynamics and contributes to the development of resilient infrastructure systems, ultimately improving soil conservation and management practices in the face of climate change and escalating erosion risks [18, 4, 7, 8].

8 Soil Erosion and Environmental Concerns

8.1 Environmental Impact of Soil Erosion

Soil erosion in dispersive soils presents significant environmental challenges, including topsoil loss and long-term degradation of soil health, agricultural productivity, and ecosystem stability. These soils, high in sodium and low in structural integrity, exacerbate salinity and sodicity, degrading essential soil properties and threatening sustainable agriculture [18, 7, 5, 16]. This degradation contributes to increased sedimentation in water bodies, impairing aquatic ecosystems by affecting light penetration and oxygen levels, and mobilizing nutrients and contaminants that can lead to eutrophication and pollution downstream.

Erosion impacts terrestrial ecosystems by degrading soil structure and fertility, primarily through the loss of organic matter and nutrients vital for soil health and plant growth. Salinization further impairs plant growth and nutrient uptake, reducing agricultural productivity and leading to biodiversity loss [16]. Socio-economically, erosion from dispersive soils threatens food security by reducing arable land and crop yields, increasing soil salinity and sodicity, and imposing financial burdens through higher water treatment costs and infrastructure maintenance [19, 18, 17, 7, 16].

Mitigating soil erosion's environmental impacts requires comprehensive soil management practices addressing physical and chemical properties. Techniques such as organic amendments and vegetation cover can enhance soil structure and reduce erosion risks, while optimized irrigation and salt-tolerant crops are crucial in salinity-prone regions [18, 16]. These strategies promote ecosystem and community resilience by minimizing adverse environmental effects.

8.2 Sustainable Soil Stabilization Methods

Sustainable soil stabilization methods are essential for preventing erosion and degradation in dispersive soils. These approaches enhance soil structural integrity while minimizing environmental impact. A multidisciplinary strategy involving biological and chemical techniques, such as Microbially Induced Calcite Precipitation (MICP), is effective in improving soil cohesion and reducing erosion [20].

Chemical stabilization using lime and cement remains prevalent; however, environmental concerns have led to alternatives like industrial byproducts (e.g., fly ash, silica fume) that improve soil properties and reduce waste [6, 1, 20, 5]. These materials promote pozzolanic reactions, increasing soil density and reducing plasticity. Organic amendments like compost and biochar enhance soil structure, microbial activity, and water retention, contributing to resilience and fertility [6, 1, 15, 5]. Vegetation cover, through root reinforcement, also mitigates erosion.

Integrating these sustainable methods allows for comprehensive soil management strategies that address dispersive soil challenges, supporting environmental conservation and sustainable land use in line with global goals like the UN's Sustainable Development Goals [18, 1, 6, 7, 5]. Continued exploration of innovative stabilization techniques is vital for advancing soil management and ensuring ecosystem resilience.

8.3 Soil Salinity and Agricultural Implications

Soil salinity significantly impacts agricultural productivity, especially in dispersive soils, leading to land degradation and affecting soil properties. High salinity disrupts soil-water relations and plant growth, particularly in arid regions where irrigation exacerbates salinization [19, 18, 16, 2]. High soluble salt concentrations cause osmotic stress, reducing water and nutrient absorption, thus decreasing crop yields. In dispersive soils, high sodium levels further degrade soil structure and increase salinity, complicating management practices.

The Bule Hora District's soil and irrigation water characterization highlights knowledge gaps in salinity's impact on irrigation suitability [19]. Understanding electrical conductivity and total soluble salts is crucial for salinity management and agricultural productivity [18]. Localized relationships between these parameters aid in developing targeted interventions for salinity challenges.

The interaction between salinity and dispersion is significant as dispersive soils are prone to erosion and instability, worsening salinity issues. Sodium ion dispersion disrupts soil aggregates, increasing salt mobility and accumulation, impairing plant growth by affecting soil properties. This is evident in sandy clay loam soils, where sodium chloride reduces aggregate stability, lowers infiltration rates, and increases crusting, negatively impacting nutrient availability and uptake [2, 16]. Effective salinity management requires salt-tolerant crops, improved irrigation, and soil amendments to enhance structure and reduce dispersion.

Addressing salinity and its correlation with dispersion involves sustainable agricultural practices that improve productivity and soil health. This includes understanding salinization's socio-economic and environmental impacts, employing diverse assessment techniques, and mitigating land degradation, particularly in arid regions [18, 16]. Advanced soil characterization and localized management strategies are essential for improving agricultural outcomes in salinity-affected regions.

9 Conclusion

Dispersive soils pose intricate challenges in geotechnical engineering, primarily due to their inherent instability and high erosion potential. The application of advanced technologies, such as large language models (LLMs) like ChatGPT, is crucial in enhancing predictive models for soil erosion and overcoming the limitations of existing methodologies. The utilization of innovative materials, such as silica fume, demonstrates significant potential in stabilizing these soils by improving their plasticity and dynamic characteristics. Additionally, the exploration of lignosulfonate as a stabilizing agent across various soil types and conditions presents promising avenues for further research.

In the context of agriculture, sustainable irrigation practices and the development of alternative water sources are vital for maintaining soil health and managing salinity. Investigating crop genetic tolerance to salinity and devising innovative management strategies are essential to mitigate the socio-economic ramifications of soil salinization. Furthermore, the refinement of artificial neural network (ANN) models and the optimization of crop requirement tables can significantly enhance soil management practices in agricultural settings.

The integration of vegetation in controlling water flow and mitigating soil erosion is well-established, underscoring its critical role in hydrological processes and erosion control strategies. Future research should focus on the effects of various organic materials on the physical properties of marine mud, which is pivotal for effective management of dispersive soils. Moreover, the potential of Microbially Induced Calcite Precipitation (MICP) as an alternative to conventional soil stabilization methods highlights the promising role of biotechnological solutions in addressing the challenges posed by dispersive soils.

References

- [1] Dennis Pere Alazigha, Buddhima Indraratna, Jayan S Vinod, and Ana Heitor. Mechanisms of stabilization of expansive soil with lignosulfonate admixture. *Transportation Geotechnics*, 14:81–92, 2018.
- [2] Chinyere Blessing Okebalama, Chioma Mary Udeani, and Chukwuebuka Edwin Awaogu. Aggregate stability and the influence of sodium chloride on dispersion of sandy clay loam soils in southeastern nigeria. *Global Journal of Agricultural Sciences*, 23(1):49–60, 2024.
- [3] Richard H. Bennett, Matthew H. Hulbert, and Roger W. Meredith. Hydrated organic matter: Functional relationships with the mass physical static and dynamic properties of marine mud, 2022.
- [4] Krishna Kumar. Geotechnical parrot tales (gpt): Harnessing large language models in geotechnical engineering, 2023.
- [5] Christopher Just, Christopher Poeplau, Axel Don, Bas van Wesemael, Ingrid Kögel-Knabner, and Martin Wiesmeier. A simple approach to isolate slow and fast cycling organic carbon fractions in central european soils—importance of dispersion method. *Frontiers in Soil Science*, 1:692583, 2021.
- [6] Murat Türköz, Seyfettin Umut Umu, and Ogan Öztürk. Effect of silica fume as a waste material for sustainable environment on the stabilization and dynamic behavior of dispersive soil. *Sustainability*, 13(8):4321, 2021.
- [7] Lachezar Filchev and Vasil Kolev. Assessing of soil erosion risk through geoinformation sciences and remote sensing – a review, 2023.
- [8] Stelian Ion, Dorin Marinescu, and Stefan-Gicu Cruceanu. Water flow model on vegetated hillslopes with erosion, 2024.
- [9] Dongdong Liu, Dongli She, and Xingmin Mu. Water flow and salt transport in bare saline-sodic soils subjected to evaporation and intermittent irrigation with saline/distilled water. *Land Degradation & Development*, 30(10):1204–1218, 2019.
- [10] Xiandong Liu, Christophe Tournassat, Sylvain Grangeon, Andrey G Kalinichev, Yoshio Takahashi, and Maria Marques Fernandes. Molecular-level understanding of metal ion retention in clay-rich materials. *Nature Reviews Earth & Environment*, 3(7):461–476, 2022.
- [11] Qing Zhao, Jie Tang, Zhaoyang Li, Wei Yang, and Yucong Duan. The influence of soil physico-chemical properties and enzyme activities on soil quality of saline-alkali agroecosystems in western jilin province, china. *Sustainability*, 10(5):1529, 2018.
- [12] Philippe Blondeel, Pieterjan Robbe, Stijn François, Geert Lombaert, and Stefan Vandewalle. On the selection of random field evaluation points in the p-mlqmc method, 2021.
- [13] Jana Madejová, Will P Gates, and Sabine Petit. Ir spectra of clay minerals. In *Developments in clay science*, volume 8, pages 107–149. Elsevier, 2017.
- [14] Akihiko Ito and Rota Wagai. Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. *Scientific data*, 4(1):1–11, 2017.
- [15] Jianxin Huang, Reginald B Kogbara, Narain Hariharan, Eyad A Masad, and Dallas N Little. A state-of-the-art review of polymers used in soil stabilization. *Construction and Building Materials*, 305:124685, 2021.
- [16] Birhane Hailu and Hagos Mehari. Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas: A review. *J. Nat. Sci. Res*, 12(3):1–10, 2021.
- [17] Modeling of yield and rating of.
- [18] Mohammad Zaman, Shabbir A Shahid, Lee Heng, Shabbir A Shahid, Mohammad Zaman, and Lee Heng. Introduction to soil salinity, sodicity and diagnostics techniques. *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques*, pages 1–42, 2018.

-
- [19] Abdissa Debela. Characterization and classification of salt affected soils and irrigation water at bule hora district, west guji zone. *J. Environ. Earth Sci*, 7(12):1–8, 2017.
- [20] KJ Osinubi, AO Eberemu, TS Ijimdiya, SE Yakubu, EW Gadzama, JE Sani, and P Yohanna. Review of the use of microorganisms in geotechnical engineering applications. *SN Applied Sciences*, 2:1–19, 2020.

www.SurveyX.cn

Disclaimer:

SurveyX is an AI-powered system designed to automate the generation of surveys. While it aims to produce high-quality, coherent, and comprehensive surveys with accurate citations, the final output is derived from the AI's synthesis of pre-processed materials, which may contain limitations or inaccuracies. As such, the generated content should not be used for academic publication or formal submissions and must be independently reviewed and verified. The developers of SurveyX do not assume responsibility for any errors or consequences arising from the use of the generated surveys.

www.SurveyX.cn