Micromechanical Properties and Behavior of Residual Granite Soil: A Survey

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Abstract

This survey paper presents a comprehensive analysis of the micromechanical properties and behavior of residual granite soil, emphasizing the use of the Discrete Element Method (DEM) with PFC3D software. The study underscores the significance of particle interactions, capillary forces, and stress tensors in understanding the mechanical behavior of unsaturated granular materials. Key findings highlight the influence of particle shape, size ratios, and inter-particle friction on the mechanical stability and shear strength of residual granite soil. Advanced modeling techniques, such as the Peridynamic Discrete Element Method (PeriDEM), enhance the predictive capabilities of DEM simulations, providing a robust framework for analyzing interactions within granular media. The paper suggests future research directions, including refining theoretical models to incorporate additional forces and improving the understanding of force chains, which could lead to better predictive models for granular material behavior. The exploration of capillary stress tensors and their implications for soil stability and deformation remains a promising area for further investigation. These insights contribute to the advancement of geotechnical engineering by offering a deeper understanding of residual granite soil's micromechanical properties, informing the design and construction of resilient geotechnical structures.

1 Introduction

1.1 Importance of Micromechanical Properties in Geotechnical Engineering

Micromechanical properties of granular materials are crucial in geotechnical engineering, as they directly affect the mechanical behavior and stability of soil structures. These properties, including particle interactions at the microscale, govern macroscopic phenomena such as shear strength, compressibility, and deformation characteristics. Accurate modeling of these interactions is essential for predicting the behavior of unsaturated granular materials, where capillary forces play a significant role in determining strength and stability [1]. Additionally, understanding grain breakage in coarse granular materials is vital for the stability of civil engineering structures [2].

The segregation coefficient, S, is another critical factor influencing the behavior of granular materials in geotechnical applications [3]. The study of micromechanical properties also extends to fluid-filled granular media, which is important for predicting soil liquefaction and landslides [4]. Incorporating micromechanical properties into geotechnical analyses allows for a more accurate representation of soil behavior, particularly in scenarios where traditional methods may be inadequate. These properties provide valuable insights into the dynamic response and resilience of soil structures under various conditions [5].

The integration of micromechanical properties enhances our understanding of soil behavior by linking microscopic particle interactions to macroscopic mechanical descriptions. Advanced modeling techniques, such as the Discrete Element Method (DEM), facilitate the simulation of granular materials and their complex behaviors, including quicksand dynamics and the impact of particle

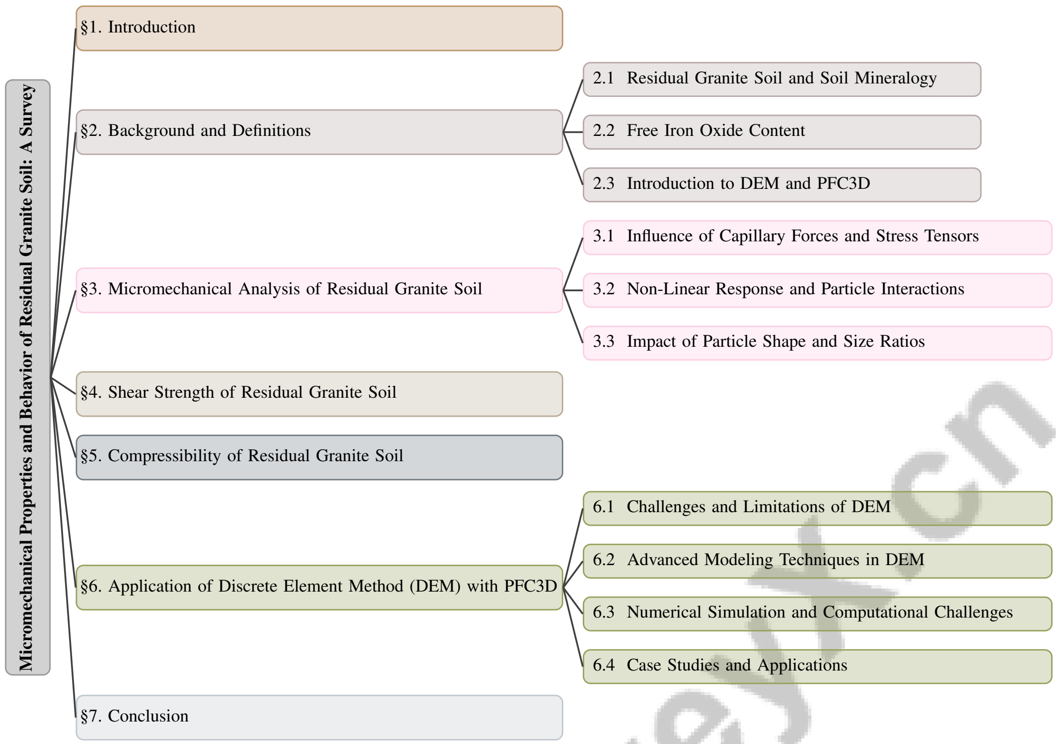

Figure 1: chapter structure

size distributions on stress-strain relationships. Data-driven methods, like artificial neural networks, can reveal hidden correlations within particle size distributions that influence mechanical behavior, leading to a more comprehensive modeling framework. Furthermore, the formulation of micro-scale boundary conditions enables a realistic representation of how macroscopic deformations affect microstructural responses, improving predictions of granular assembly behavior under various loading conditions [6, 7, 8, 9, 10].

1.2 Role of Discrete Element Method (DEM) with PFC3D

The Discrete Element Method (DEM) is a key computational technique for simulating the micromechanical behavior of granular materials, providing deep insights into particle-scale dynamics. This method is particularly effective in analyzing complex systems, such as residual granite soil, where traditional continuum approaches may fall short. DEM enables detailed modeling of individual particles and their interactions, facilitating analyses of particle dynamics, including collision behavior, shear stress, and the effects of particle shape and topology on macroscopic properties. By capturing contact forces and deformations at the microscopic level, DEM bridges the gap between microscale interactions and macroscopic behavior in granular materials, deriving scalar and vector fields, as well as stress and velocity gradients [11, 12, 13, 14, 15].

PFC3D, a sophisticated implementation of DEM, provides a robust platform for simulating three-dimensional granular flows and interactions. It facilitates the simulation of complex mechanical behaviors characterized by frictional interactions at contact points and the influence of varying particle shapes and motions. The software employs a phenomenological approach to assess friction in mutual contact, enabling calculations of slide force, roll torque, and spin torque in three-dimensional setups. Furthermore, it accounts for diverse rotational dynamics in granular materials, capturing the interactions of individual and paired particles and their contributions to overall material deformation through distinct modes of contact rolling and deformation [16, 1]. Advanced algorithms in PFC3D enhance the physical accuracy and computational efficiency of simulations, addressing challenges such as micro-scale boundary condition representation and managing large datasets generated during simulations.

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The application of DEM and PFC3D in studying residual granite soil highlights their ability to simulate micromechanical properties that dictate macroscopic soil behavior, including analyses of shear strength, compressibility, and the effects of particle shape and size ratios, which are critical for predicting the stability and resilience of soil structures. The integration of novel algorithms for frictional force calculations allows for larger integration steps, ensuring convergence of numerical schemes and enhancing simulation fidelity [17].

Moreover, DEM has been employed to explore the relationship between interparticle damping and the normal modes of granular materials, improving the understanding of acoustic properties in these systems [18]. It has also been extensively utilized to model systems of anisotropic particles under gravity with friction, providing insights into transient behaviors of particle contacts during loading. Additionally, 3D DEM simulations have investigated the effects of boundary vibration amplitude and timing on frictional behavior in granular layers, further illustrating the method's versatility [19].

1.3 Structure of the Survey

This survey provides a comprehensive analysis of the micromechanical properties and behavior of residual granite soil, emphasizing the use of the Discrete Element Method (DEM) and PFC3D software. The paper begins with an **Introduction** that highlights the significance of micromechanical properties in geotechnical engineering and introduces the role of DEM with PFC3D. The **Background and Definitions** section follows, offering an overview of fundamental concepts such as residual granite soil, free iron oxide content, and principles of DEM, setting the stage for subsequent analyses.

The core of the survey is divided into three main analytical sections: **Micromechanical Analysis of Residual Granite Soil**, **Shear Strength of Residual Granite Soil**, and **Compressibility of Residual Granite Soil**. The first section focuses on how micromechanical properties, influenced by factors like soil mineralogy and free iron oxide content, dictate the behavior of residual granite soil. This is followed by an examination of the factors affecting shear strength, highlighting the application of DEM in analyzing these properties. The compressibility characteristics are then explored, emphasizing the role of micromechanical properties and DEM simulations in understanding soil compressibility.

The penultimate section, **Application of Discrete Element Method (DEM) with PFC3D**, delves into the practical aspects of using DEM and PFC3D in geotechnical research. This section discusses challenges, advanced modeling techniques, computational hurdles, and provides case studies to illustrate the application of these tools. Finally, the **Conclusion** synthesizes the key findings of the survey, reflecting on the implications for geotechnical engineering and suggesting potential areas for future research.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Residual Granite Soil and Soil Mineralogy

Residual granite soil forms through the in-situ weathering of granite bedrock, maintaining the mineralogical composition of its parent rock while exhibiting altered physical properties. Predominantly found in tropical and subtropical regions, this soil type is rich in clay minerals, primarily due to the transformation of feldspar and mica, while quartz remains stable. The mineralogical composition—comprising quartz, kaolinite, and iron oxides—plays a crucial role in defining the soil's geotechnical properties. Quartz contributes to soil strength, while clay minerals, such as kaolinite, influence plasticity, compressibility, and permeability due to their structural characteristics [20, 18, 4, 9]. Free iron oxides, from the weathering of ferromagnesian minerals like biotite, further modify mechanical properties by cementing particles, thereby affecting cohesion and color.

The mechanical behavior of residual granite soil, particularly its shear strength and compressibility, is largely governed by its mineralogy, influencing stress-strain relationships and the behavior of granular media under various loading conditions. Understanding this mineralogical composition is essential for predicting soil behavior under different loading scenarios. The elastic moduli of such granular materials are influenced by the preparation history and coordination number of particle assemblies, linked to mineral content [9]. This understanding aids in modeling soil behavior using computational methods like the Discrete Element Method (DEM), enabling the design of structures that accommodate the unique properties of residual granite soil.

2.2 Free Iron Oxide Content

Free iron oxide content significantly influences the mechanical properties of residual granite soil by affecting particle interactions and the contact network structure, crucial for determining stress-strain behavior and mechanical performance [9, 10]. Originating from the weathering of ferromagnesian minerals, these oxides act as cementing agents, enhancing cohesion by binding soil particles, thus increasing shear strength by strengthening interparticle bonds and reducing displacement likelihood under shear stress.

Additionally, free iron oxides impact soil compressibility by limiting particle rearrangement under load, especially in unsaturated granular materials where capillary forces are significant. The interaction between capillary forces and iron oxide cementation can substantially influence stress distribution within the soil matrix [21]. They also alter hydraulic properties, such as permeability and water retention, by modifying pore structure, which influences fluid-particle interactions, shear resistance, and porosity, impacting processes like soil liquefaction and landscape evolution [7, 3, 20]. Incorporating the effects of free iron oxide into computational models, such as those using DEM, enhances predictions regarding the performance of structures built on residual granite soils.

2.3 Introduction to DEM and PFC3D

The Discrete Element Method (DEM) is a powerful computational technique for simulating granular materials by modeling the motion and interactions of individual particles, offering insights into micromechanical processes that govern soil behavior. This method is particularly effective for capturing the bulk response of granular materials under applied stresses while minimizing boundary effects [22]. DEM's capability to simulate particle dynamics is essential for analyzing complex systems like residual granite soil, where traditional continuum-based methods may be inadequate [5].

PFC3D, an advanced DEM implementation, enables precise simulations of three-dimensional granular flows and interactions, employing sophisticated computational techniques like a pseudo-energy conserving time-integration method to enhance efficiency and accuracy [23]. Its ability to integrate gravitational fields into fluid dynamics calculations improves simulation accuracy involving particle-fluid interactions [4]. Additionally, PFC3D supports general polyhedral meshes, facilitating detailed modeling of complex mechanical behaviors and customizable contact forces [12].

Innovative techniques, such as the Peridynamic Discrete Element Method (PeriDEM), enrich DEM and PFC3D applications by combining peridynamic modeling with DEM to simulate granular media with deformable particles and complex geometries [24]. GPU acceleration in DEM simulations allows for detailed modeling of hard, faceted particles under realistic conditions, improving computational speed and enabling extensive analyses [25]. In geotechnical engineering, DEM and PFC3D provide a comprehensive framework for examining intricate interactions within granular soils, facilitating exploration of soil behavior under various conditions. These tools enable simulation of complex particle dynamics, including collision, friction, and stress distribution, contributing to the development of resilient and efficient geotechnical structures [26]. Through detailed simulations, DEM and PFC3D yield critical insights into the micromechanical properties and behavior of residual granite soil, enhancing understanding and application of soil analysis in engineering practices.

3 Micromechanical Analysis of Residual Granite Soil

3.1 Influence of Capillary Forces and Stress Tensors

Capillary forces and stress tensors significantly influence the micromechanical properties of residual granite soil, especially under unsaturated conditions where water mediates interparticle dynamics. These forces, arising from liquid bridges between particles, introduce attractive interactions that alter soil behavior [27]. Accurately representing effective stress distribution within the soil matrix necessitates incorporating a capillary stress tensor, which is crucial for modeling the anisotropic effects of capillary forces on soil stability and deformation [28].

The interaction between capillary forces and stress tensors is shaped by dynamic particle contacts, including stick-slip behavior, affecting the soil's response to external loads. Inter-particle friction, dependent on normal stress and surface conditions, and the transitional inertial number, reflecting particle movement dynamics, are vital for modeling stress-strain relationships in granular media

[26, 29, 6, 9]. Integrating these interactions into DEM simulations enhances the understanding of micromechanical properties, offering insights into shear strength and compressibility.

Recent modeling advancements, such as a rheological power-law scaling, provide a unified framework for capturing the effects of concentration, dimensionless granular temperature, and inertial number on granular flows [30]. These innovations improve predictive capabilities for residual granite soil behavior under varied environmental conditions, aiding precise geotechnical analyses. Studies show that larger vibration amplitudes cause significant frictional weakening and kinetic energy release, highlighting the impact of dynamic loading on soil behavior [19]. Incorporating these forces into computational models enhances soil behavior predictions, informing geotechnical structure design and analysis.

3.2 Non-Linear Response and Particle Interactions

Understanding the non-linear response of soil particles and their microscale interactions is crucial for predicting the behavior of residual granite soil under various loading conditions. This response is determined by the interplay of particle forces, rolling deformations, and contact mechanics. Advancements in DEM simulations, particularly the GPU Accelerated Discrete Element Method, have improved the modeling of granular interactions, effectively accommodating the unique geometries of faceted particles [25].

Damping effects on normal mode trajectories in the complex frequency plane further elucidate the non-linear dynamics of soil particles, providing insights into previously unaccounted damping mechanisms [18]. Accurate modeling of these interactions is essential for simulating complex soil behaviors, particularly under dynamic loading conditions. Enhanced methods for calculating elastic and tangential forces ensure accuracy even with larger time steps, crucial for simulating slow deformation processes and capturing evolving contact geometries [16, 12].

The classification of rolling modes and their interactions provides insights into the macroscopic behavior of granular materials. Advanced rheological models incorporating both rate-dependent and rate-independent stress contributions enhance the analysis of granular materials. By integrating inter-particle friction, volumetric contributions, and inertial number, these models unify local and non-local rheological data, capturing the complexities of quasi-static and inertial flow regimes. This approach reveals critical relationships between particle size, density, and friction, offering a comprehensive understanding of granular system mechanical properties in various contexts [30, 31, 32].

These advancements in DEM simulations and modeling techniques significantly enhance the understanding of non-linear responses and microscale interactions of soil particles. Improved precision and efficiency in particle interaction simulations provide deeper insights into the micromechanical properties of residual granite soil, crucial for informing geotechnical structure design and analysis under diverse loading conditions.

3.3 Impact of Particle Shape and Size Ratios

The properties and behavior of residual granite soil are profoundly influenced by the shape and size ratios of its particles. Variations in particle morphology, such as angularity and sphericity, affect packing density, shear strength, and mechanical stability. DEM simulations indicate that angular particles typically exhibit higher shear strength due to increased interlocking and frictional resistance [12].

Particle size distribution is also critical, as broader distributions enhance packing arrangements, increasing load-bearing capacity and reducing compressibility. In contrast, narrow distributions may create void spaces, potentially increasing compressibility and decreasing shear strength. The coordination number, representing average contacts per particle, further influences soil stiffness and deformation characteristics [9].

The interaction between particle shape and size ratios is complicated by free iron oxides, which can cement particles and alter mechanical behavior. This cementation effect is significant in soils with diverse particle sizes, as smaller particles fill voids between larger ones, enhancing cohesion and stability. Research utilizing DEM has shown that the effective stress principle, relating contact forces to soil mechanics, is vital for understanding how varying particle sizes enhance resistance to deformation under load [33, 9, 10]. DEM simulations provide valuable insights into the interplay between particle morphology and soil behavior, enabling accurate predictions of soil performance under various loading conditions.

Advancements in DEM modeling techniques, including polyhedral meshes and GPU acceleration, enhance the simulation of particle shape and size effects on soil behavior [25]. These innovations facilitate detailed analyses of particle interactions, contributing to a deeper understanding of the micromechanical properties of residual granite soil. Incorporating these factors into geotechnical analyses allows engineers to design more resilient structures that consider the unique characteristics of soils with varying particle shapes and size distributions.

In examining the factors influencing the shear strength of residual granite soil, it is essential to consider the hierarchical structure that underpins these interactions. As illustrated in Figure 3, this figure elucidates the complex interplay of various factors, particularly emphasizing the implications of the Discrete Element Method (DEM). The depiction highlights how particle shape and size ratios impact the properties of residual granite soil, focusing on the effects of angularity and sphericity on interlocking and friction, the role of size distribution in packing and shear strength, and the contributions of DEM innovations like polyhedral meshes and GPU acceleration to understanding soil behavior. By integrating these elements, we gain a comprehensive understanding of how these factors collectively affect shear strength, thereby enhancing our approach to soil mechanics and geotechnical engineering.

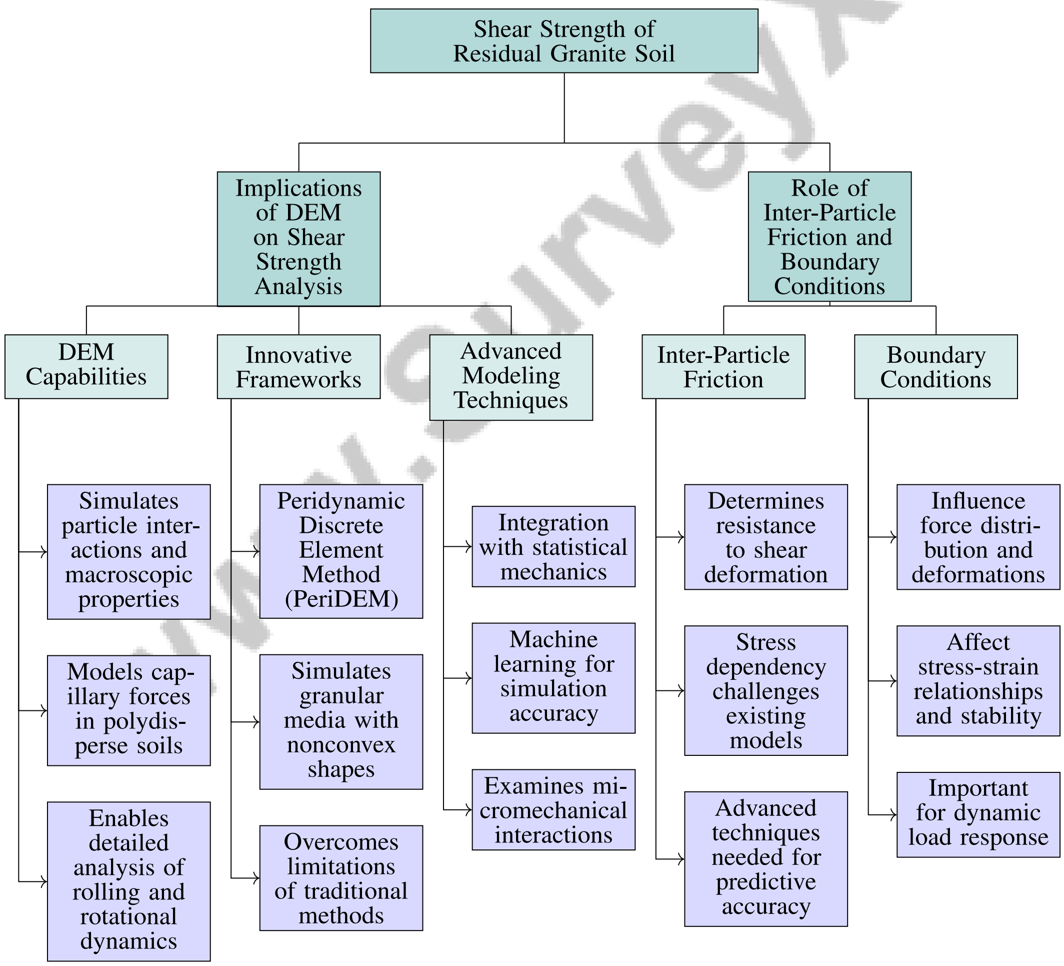

Figure 2: This figure illustrates the hierarchical structure of factors affecting the shear strength of residual granite soil, focusing on the implications of the Discrete Element Method (DEM) and the role of inter-particle friction and boundary conditions. It highlights key capabilities and innovations in DEM, the importance of frictional interactions, and the influence of boundary conditions on soil behavior.

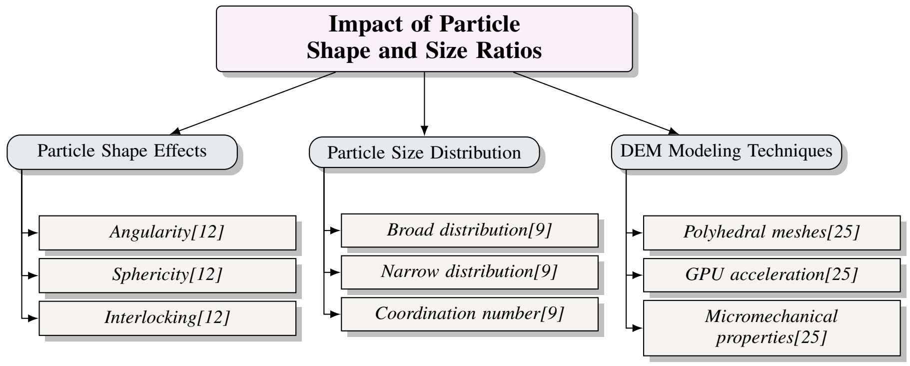

Figure 3: This figure illustrates the impact of particle shape and size ratios on the properties of residual granite soil, focusing on particle shape effects, size distribution, and advancements in DEM modeling techniques. It highlights how angularity and sphericity influence interlocking and friction, the role of size distribution in packing and shear strength, and the contributions of DEM innovations like polyhedral meshes and GPU acceleration to understanding soil behavior.

4 Shear Strength of Residual Granite Soil

4.1 Implications of DEM on Shear Strength Analysis

Benchmark	Size	Domain	Task Format	Metric

Table 1: Overview of representative benchmarks used in the analysis of shear strength in residual granite soil, detailing the benchmark name, size, domain, task format, and evaluation metric. This table provides a concise summary of the critical parameters and metrics employed in the benchmarking process for assessing the effectiveness of the Discrete Element Method (DEM) in geotechnical applications.

The Discrete Element Method (DEM) offers profound insights into the shear strength of residual granite soil by enabling detailed analysis of particle interactions and macroscopic mechanical properties. Its capability to simulate complex dynamics, such as rolling and rotational interactions, is crucial for predicting soil behavior under load [22]. DEM effectively models capillary forces in polydisperse soils, essential for accurate shear strength assessments [1].

Figure 4 illustrates the key implications of the Discrete Element Method (DEM) on shear strength analysis, highlighting its capabilities in modeling particle interactions and capillary forces, innovative frameworks like PeriDEM for nonconvex shapes, and integration with statistical mechanics for understanding stress distributions and frictional weakening. Table 1 presents a comprehensive summary of the representative benchmarks utilized in evaluating the Discrete Element Method (DEM) for shear strength analysis, highlighting key parameters and metrics. Innovative frameworks like the Peridynamic Discrete Element Method (PeriDEM) enhance the modeling of inter-particle and intra-particle interactions, overcoming limitations of traditional methods and improving understanding of shear strength in granular materials [24]. PeriDEM is particularly effective for simulating granular media with nonconvex shapes, providing deeper insights into particle interactions under diverse conditions [12].

Integrating DEM with statistical mechanics provides insights into stress distributions within granular media, enhancing the understanding of shear strength [22]. Its ability to model the non-smooth and transient nature of grain movements is crucial for understanding granular material mechanics [26]. Moreover, DEM elucidates grain-scale mechanisms of frictional weakening, pertinent to seismic triggering in granular materials [19].

DEM's application in analyzing the shear strength of residual granite soil establishes a robust framework for investigating micromechanical interactions affecting soil behavior. It allows for a comprehensive examination of contact forces and deformations at the microscopic level while deriving macroscopic quantities such as stress and fabric. Recent advancements, including multiple contact interactions and machine learning integration, enhance simulation accuracy and reveal

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complex correlations between particle size distributions and mechanical properties [11, 14, 10]. These advanced modeling techniques provide valuable insights into the shear strength characteristics of granular materials, informing geotechnical structure design and analysis.

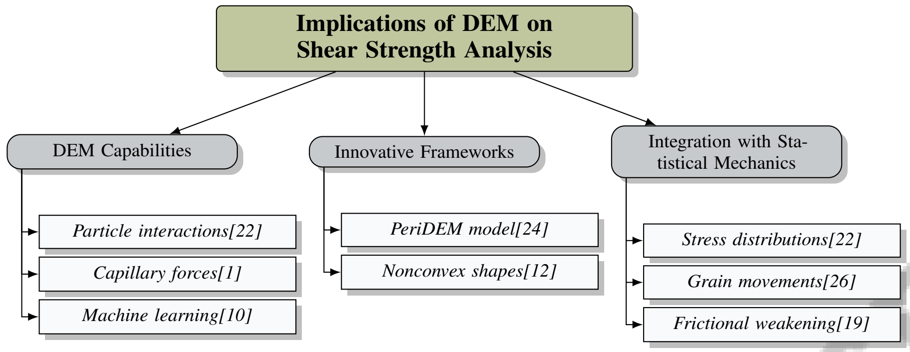

Figure 4: This figure illustrates the key implications of the Discrete Element Method (DEM) on shear strength analysis, highlighting its capabilities in modeling particle interactions and capillary forces, innovative frameworks like PeriDEM for nonconvex shapes, and integration with statistical mechanics for understanding stress distributions and frictional weakening.

4.2 Role of Inter-Particle Friction and Boundary Conditions

Inter-particle friction and boundary conditions are crucial in determining the shear strength of residual granite soil. Frictional interactions among particles dictate resistance to shear deformation, directly influencing mechanical stability. The stress dependency of inter-particle friction, particularly in non-spherical particles, presents challenges for existing models, which often fail to accurately capture this aspect, leading to discrepancies between simulation results and experimental observations [29]. This limitation highlights the need for advanced modeling techniques that account for stress-dependent friction to enhance DEM's predictive accuracy.

Boundary conditions significantly influence the macroscopic behavior of granular materials by affecting force distribution and deformations within the soil matrix. Properly applied boundary conditions are essential for accurately simulating the mechanical response of residual granite soil under various loading scenarios. These conditions critically influence stress-strain relationships and overall stability, as they are fundamental to understanding particle interactions at contact points. Factors such as damping and density, which affect the elastic and dissipative properties of granular materials, are vital for predicting soil structure response under different loading conditions. These aspects must be meticulously considered in geotechnical assessments to ensure the reliability and safety of soil-related engineering projects [18, 9].

Advancements in DEM have facilitated the exploration of complex boundary interactions, including the effects of boundary vibration amplitude and timing on frictional behavior in granular layers. Such studies underscore the importance of boundary conditions in modulating soil response to dynamic loads, providing valuable insights into frictional weakening mechanisms and energy dissipation [19]. Incorporating these factors into computational models allows for a more comprehensive understanding of shear strength in granular materials, thereby informing the design and analysis of resilient geotechnical structures.

5 Compressibility of Residual Granite Soil

5.1 Rheological Behavior and Mechanical Response

The compressibility of residual granite soil is governed by intricate grain-scale interactions effectively captured through advanced discrete element modeling techniques. The Generalized Shear Thickening Rheology (GST-R) framework provides a nuanced understanding of these interactions by linking macroscopic friction with inertial number, softness, small pressure effects, and Bond number [34]. This framework emphasizes the roles of frictional and cohesive forces in influencing compressibility under various stress conditions.

Discrete element simulations, particularly those modeling tubular particle breakage, reveal critical insights into particle morphology and contact mechanics, especially under high-pressure scenarios where particle rearrangement occurs [35]. These simulations underscore the importance of local damping and friction in accurately depicting the deformation and damage processes in nonconvex particles [12]. Capturing these dynamic processes is essential for understanding the evolution of contact networks and stress redistribution within the soil matrix.

The averaging formalism in discrete element simulations bridges micromechanical interactions with macroscopic behavior, translating complex particle-scale phenomena into continuum-level descriptions [11]. This enhances model predictive accuracy in geotechnical engineering by providing insights into critical packing fractions, shear rate and pressure effects on flow behavior, and transitions between shear thinning and thickening [30, 6]. By integrating grain-scale interactions with robust computational frameworks, these methods offer valuable insights into the compressibility characteristics of residual granite soil, guiding the design and analysis of geotechnical structures.

5.2 Rheological and Elasto-hysteretic Models

Rheological and elasto-hysteretic models are pivotal in understanding the compressibility behavior of residual granite soil under varying stress conditions. The GST-R framework is instrumental in modeling complex grain-scale interactions, relating macroscopic friction to parameters like inertial number and Bond number [34]. These models elucidate deformation characteristics and energy dissipation mechanisms during loading and unloading cycles.

Elasto-hysteretic models enhance this understanding by capturing the time-dependent and path-dependent nature of deformation, accounting for hysteresis during cyclic loading. This provides a more accurate representation of energy dissipation and recoverable strain in soil systems. The integration of these models with insights from the Discrete Element Method (DEM) and artificial neural networks enables the prediction of mechanical responses under complex loading scenarios, improving the design and analysis of geotechnical structures [9, 10].

Future research should focus on refining these models to incorporate higher-order Bond number effects and explore applications in diverse granular flow scenarios [34]. Advancements in this area will enhance the predictive capabilities of these models, offering a comprehensive understanding of the micromechanical properties and behavior of residual granite soil under compressibility tests.

6 Application of Discrete Element Method (DEM) with PFC3D

6.1 Challenges and Limitations of DEM

The Discrete Element Method (DEM) is a crucial computational tool for simulating granular materials, but it faces challenges that affect its efficacy in soil analysis. A significant issue is the high computational cost of simulating large particle numbers, which limits scalability, especially in complex geometries or large systems [12]. Accurately modeling non-convex or irregular particle geometries further complicates simulations [5]. Additionally, the assumption of proportionality between damping and stiffness matrices may not hold across all granular systems, affecting accuracy when mechanical properties vary [18]. The rounding of particle shapes can cause unphysical interdigitation effects, though these are generally manageable [25].

DEM also struggles with predicting bulk mechanical behaviors from micro-scale analyses, particularly under large strains. Simulating frictional behavior is challenging due to difficulties in capturing environmental factors like temperature, normal stress, and surface conditions. Most simulations are confined to specific parameter ranges, limiting their ability to model complex interactions, especially where particle shape and size ratios significantly affect frictional characteristics [3, 1, 4, 29, 36]. These constraints hinder DEM's applicability in scenarios where natural soils exhibit diverse behaviors under varying conditions.

Despite these challenges, advancements such as GPU acceleration and sophisticated modeling techniques are enhancing DEM's applicability and usability [25]. Addressing these limitations is essential for optimizing DEM's effectiveness in soil analysis, ensuring accurate and efficient simulations across diverse geotechnical applications.

6.2 Advanced Modeling Techniques in DEM

Method Name	Simulation Accuracy	Mechanical Behavior Representation	Predictive Capabilities
VDEM-CE[37]	Rotational Degrees Freedom	Stress-dependent Friction Models	Forecast Soil Behavior
VIDEM[38]	Rotational Degrees Freedom	Dynamic Interactions Modeling	Forecast Soil Behavior
EBP[39]	Rotational Degrees Freedom	Stress-dependent Friction Models	Machine Learning Enhance
SDIFM[29]	Pressure-dependent Friction	Stress Dependent Friction	Not Explicitly Mentioned
DEM[40]	Complex Geometries	Rheological Scaling Relations	Phase Diagrams
MMGF[41]	Discrete-element-method Simulations	Friction Coefficients Involved	Predict Phase Diagram
DEM[32]	Strain Degrees Freedom	Interparticle Friction Effects	Granular Flow Behavior

Table 2: Comparison of advanced modeling techniques in discrete element method (DEM) simulations, highlighting their simulation accuracy, mechanical behavior representation, and predictive capabilities. The table provides a comprehensive overview of various methods, including VDEM-CE, VIDEM, EBP, SDIFM, DEM, MMGF, and DEM, showcasing their unique features and contributions to the field of geotechnical engineering.

Table 2 presents a comparative analysis of advanced modeling techniques in discrete element method (DEM) simulations, illustrating their impact on improving simulation accuracy and predictive capabilities in geotechnical engineering. Advanced modeling techniques in DEM have significantly improved its application in geotechnical engineering by enhancing simulation accuracy and efficiency. The incorporation of rotational degrees of freedom into the DEM framework simplifies the integration of rotations during dynamic evolutions, improving the simulation of particle interactions and complex geometries [37]. This innovation allows for precise representation of granular materials' mechanical behavior, particularly in scenarios involving non-convex shapes and intricate contact dynamics.

The variational integrator approach enhances energy conservation and stability in simulations, effectively addressing both static and dynamic scenarios [38]. This method is valuable for capturing transient behaviors of granular materials under varying loading conditions, providing a robust framework for soil mechanics analysis. The Enhanced Descend Algorithm reformulates contact problems into solvable equations via Newton's method, allowing for efficient and accurate solutions to complex contact problems [39]. Stress-dependent interparticle friction models in DEM simulations better capture bulk friction behavior under varying normal stresses, addressing a critical challenge in predicting soil behavior [29].

Modeling granular rheology through scaling relations facilitates the integration of rheological parameters into computational fluid dynamics (CFD) simulations, enhancing DEM's predictive capabilities in simulating granular flows [40]. This approach offers valuable insights into the flow behavior of residual granite soil, particularly regarding its shear and compressibility characteristics. Predicting phase diagrams that include erosion, sedimentation, and stationary-flow regimes aligns quantitatively with experimental results and DEM simulations, providing a comprehensive framework for analyzing soil behavior under various conditions [41]. By avoiding the assumption of coaxiality between stress and strain rate tensors, the model captures granular flow behavior more accurately, enhancing the understanding of micromechanical properties of soils [32].

These advanced modeling techniques contribute to a detailed analysis of the micromechanical properties and behavior of residual granite soil, informing the design and analysis of geotechnical structures. By leveraging advancements such as machine learning to identify correlations between particle size distributions and mechanical behavior, and novel simulation models that account for multiple contact interactions in dense granular materials, researchers gain a deeper understanding of soil mechanics. This enhanced insight significantly improves DEM's application in geotechnical engineering, enabling more accurate predictions and analyses of granular material behavior under various conditions [16, 14, 10].

6.3 Numerical Simulation and Computational Challenges

Numerical simulations in DEM face computational challenges, particularly in balancing accuracy and efficiency. A significant advancement is the development of methods that allow for larger integration steps while maintaining convergence, enhancing computational efficiency [42]. This improvement is crucial for simulating large-scale systems where computational resources are limited. However, these methods are often restricted to quasi-static regimes, limiting their applicability in dynamic conditions or high deformation rates [7]. This poses challenges for accurately capturing granular material behavior under rapidly changing conditions, such as during seismic events or other dynamic loading scenarios.

To address these challenges, ongoing research focuses on developing robust algorithms that accommodate a broader range of deformation rates and dynamic conditions. These advancements aim to extend DEM's applicability beyond quasi-static regimes, providing comprehensive insights into soils' micromechanical behavior under various conditions. Enhancing computational efficiency and accuracy—particularly through GPU acceleration and coupled computational fluid dynamics—enables a nuanced understanding of soil behavior. This improved understanding facilitates the design and analysis of geotechnical structures by enabling detailed simulations of complex material interactions, sedimentation processes, and the effective stress principle, ultimately informing engineering practices across various applications [33, 13].

6.4 Case Studies and Applications

Method Name	Methodological Approaches	Application Scenarios	Future Directions
CFDEM[43]	Resolved Cfd-DEM	Particle-fluid Interactions	Optimizing Larger Systems
VDEM[23]	Variational Discrete Element	Dynamic Elasto-plastic Behavior	Dynamic Cracking Fragmentation
AF[11]	Averaging Formalism	Soil Stability Analysis	Complex Particle Interaction
DEM[44]	Dem Simulations	Cratering Dynamics	Complex Impact Scenarios
Mka3D[17]	Mka3d	Lamb's Problem	Complex Material Models

Table 3: Overview of various discrete element methods (DEM) and their applications in geotechnical engineering. The table delineates the methodological approaches, specific application scenarios, and potential future directions for each method, highlighting their contributions to understanding complex soil behaviors and interactions.

The application of DEM with PFC3D in geotechnical engineering is exemplified through various case studies, demonstrating its effectiveness in simulating complex soil behaviors. One notable application involves modeling particle-fluid interactions, where DEM has been utilized to incorporate body forces, enhancing the accuracy of predicting settling velocities in fluid-particle systems [43]. This methodology improves understanding of granular material behavior in fluid environments, providing insights into phenomena such as sedimentation and erosion.

Table 3 provides a comprehensive overview of discrete element methods (DEM) employed in geotechnical engineering, detailing their methodological approaches, application scenarios, and future research directions. The Variational Discrete Element Method (VDEM) has effectively simulated elasto-plastic behavior in materials, showcasing robustness and accuracy across various test cases [23]. The VDEM framework captures the mechanical response of granular materials, making it invaluable for analyzing soil stability and deformation under different loading conditions. Successful application of averaging procedures in DEM simulations has provided insights into shear bands and anisotropic behavior of granular materials, highlighting its potential for capturing essential features of soil mechanics [11]. This approach enables a deeper understanding of micromechanical interactions within soil structures, informing the design and analysis of geotechnical systems.

Future research directions include exploring the effects of various granular materials and more complex impact scenarios, such as differing projectile shapes and sizes [44]. These studies aim to enhance DEM's predictive capabilities, providing a comprehensive framework for analyzing soil behavior under diverse conditions. Advancements in DEM modeling techniques, such as integrating more complex material models and asynchronous symplectic integrators, are expected to facilitate larger time steps and improved simulation fidelity [17]. These innovations will further extend DEM's applicability in geotechnical engineering, enabling more accurate and efficient simulations of large-scale systems.

The diverse applications of DEM with PFC3D in geotechnical engineering illustrate its capacity to simulate intricate soil behaviors, offering valuable insights for the design and analysis of resilient geotechnical structures. Ongoing advancements and refinement of DEM methodologies are set to significantly enhance soil mechanics by providing deeper insights into complex interactions and behaviors of granular materials. Recent studies have revealed diverse rotational behaviors of particles within granular assemblies and their influence on material deformation, illustrating intricate patterns akin to rolling gears. Furthermore, integrating machine learning techniques with DEM simulations has uncovered hidden correlations between particle size distributions and mechanical behavior of granular materials, facilitating improved predictions of macroscopic properties such as stress and strain responses. These developments collectively contribute to a more comprehensive understanding of granular material analysis, bridging the gap between microscopic interactions and macroscopic continuum theories [11, 16, 10].

7 Conclusion

The exploration of micromechanical properties in residual granite soil is pivotal for advancing geotechnical engineering practices. Employing the Discrete Element Method (DEM) via PFC3D offers a comprehensive platform for analyzing particle interactions, capillary effects, and stress distributions, crucial for understanding the behavior of unsaturated granular materials. This study underscores the influence of particle morphology, size distributions, and inter-particle friction on the mechanical stability and shear strength of residual granite soil, providing essential insights for geotechnical design and evaluation.

Innovative modeling approaches, such as the Peridynamic Discrete Element Method (PeriDEM) and the Phase-Field Discrete Element Method (PFDEM), enhance the predictive accuracy of DEM simulations, effectively capturing intricate granular behaviors across varied conditions, thereby propelling the field of soil mechanics forward. Future research should aim to refine DEM theoretical frameworks to tackle complex geotechnical challenges, integrating additional forces like van der Waals and electrostatic interactions to improve simulation fidelity in cohesive particle systems. Incorporating a fluctuational energy balance law could further extend model applicability in dense regimes, fostering a more profound comprehension of soil dynamics. Additionally, examining strong contacts and force chains may yield more accurate predictive models for granular material behavior.

Investigating the role of the capillary stress tensor in unsaturated granular materials and its impact on soil stability and deformation offers a promising research direction. Enhanced studies on the mean stress tensor within granular assemblies could improve fluid-solid interaction modeling, enriching the understanding of granular materials in diverse applications. Furthermore, examining a broader range of vibration amplitudes and confining pressures, alongside the long-term effects of boundary vibrations on granular systems, warrants further exploration.

The insights derived from this review significantly contribute to geotechnical engineering by elucidating the micromechanical properties and behavior of residual granite soil. Ongoing development and refinement of DEM methodologies are anticipated to enhance predictive capabilities in soil analysis, thereby informing the design and construction of more resilient geotechnical structures.

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