JOURNAL OF GEOSPACE SCIENCE

Vol. 6 No. 2 (2026)

E-ISSN : 2413-6093
https://jogss.org

Stochastic Calcite Morphology Effects on Discrete Element Method Shear-Wave Velocity in Sand

Tiffany Chu[1], Helen Ma[2]
[1]Department of Construction, Environment and Engineering, Faculty of Design and Environment, Technological and Higher Education Institute of Hong Kong, Hong Kong, Hong Kong SAR, China
[2]Department of Civil and Environmental Engineering, School of Engineering, Hong Kong University of Science and Technology, Hong Kong, Hong Kong SAR, China

ABSTRACT

The implementation of biocementation techniques, particularly microbially induced calcite precipitation, has gained significant traction in geotechnical engineering as a sustainable method for soil improvement. A critical challenge in evaluating the efficacy of this ground improvement technique lies in non-destructive monitoring, which heavily relies on the measurement of shear-wave velocity. Traditionally, computational models utilizing the discrete element method have assumed a uniform distribution of calcite precipitation at particle contacts. However, empirical microscopic observations reveal that calcite morphology is inherently stochastic, exhibiting patchy, nodular, and highly irregular distributions. This study investigates the effects of stochastic calcite morphology on shear-wave velocity in sand using a threedimensional discrete element method framework. By developing a novel contact model that incorporates random variables governing bond thickness, radius, and spatial distribution, this research provides a comprehensive analysis of wave propagation through heterogeneous cemented granular media. The computational methodology simulates bender element tests by applying dynamic excitations to representative volume elements, capturing the microscale energy dissipation and macroscale velocity dispersion. Results indicate that stochastic distributions of calcite significantly attenuate shear-wave velocity compared to uniform bond assumptions, fundamentally altering the dynamic response of the matrix. This research highlights the necessity of incorporating morphological randomness in numerical models to accurately interpret non-destructive testing data in biocemented soils.

KEYWORDS

Discrete Element Method, Shear-Wave Velocity, Microbially Induced Calcite Precipitation, Stochastic Morphology, Geomechanics

1. Introduction

1.1 Background on Calcite Precipitation in Sands

The stabilization of granular soils using sustainable and environmentally friendly methodologies has become a primary focus in contemporary geotechnical engineering. Among the various innovative techniques, microbially induced calcite precipitation has emerged as a highly effective biological ground improvement strategy. This process utilizes ureolytic bacteria to hydrolyze urea, leading to the generation of carbonate ions which, in the presence of calcium, precipitate as calcium carbonate crystals. These calcite crystals form solid bridges between individual sand grains, thereby enhancing the macroscopic shear strength and stiffness of the soil matrix while generally maintaining adequate permeability. The fundamental mechanism relies on the complex biochemical and physical interactions occurring at the microscale, which ultimately dictate the macroscale engineering properties of the treated soil volume. Extensive experimental investigations have demonstrated the potential of this technique in mitigating liquefaction, controlling groundwater flow, and enhancing slope stability. However, the precipitation process is highly sensitive to environmental factors, bacterial distribution, and the specific geochemical conditions present within the pore space, leading to significant spatial variability in the resulting cementation. Bacterial self-healing concrete offers a related mineral-precipitation application, while healing a cement crack and bonding sand grains impose different geometric and transport constraints [1]. Microscopic imaging techniques, including scanning electron microscopy and X-ray computed tomography, have consistently revealed that the precipitated calcite does not form uniform layers around the soil particles. Instead, the morphology of the calcite bonds is predominantly stochastic, characterized by uneven coating, isolated nodules, and asymmetric accumulation at the particle contacts. This inherent morphological randomness heavily influences the load transfer mechanisms within the granular assembly, presenting a considerable challenge for both theoretical modeling and non-destructive evaluation of the treated ground. Understanding the implications of this spatial and morphological heterogeneity is paramount for predicting the mechanical behavior of biocemented sands and for optimizing the design of field-scale soil improvement projects. The variability in calcite distribution fundamentally alters the contact mechanics, requiring advanced computational approaches to accurately capture the physical reality of the cemented matrix. Consequently, the transition from idealized, uniform cementation models to realistic, stochastic morphological representations represents a critical frontier in geotechnical research. Sun and colleagues examine sand stiffness variability induced by stochastic distributions of calcite precipitates: a Monte Carlo-DEM study [2].

1.2 Shear-Wave Velocity as a Diagnostic Tool

Non-destructive testing methods are essential for monitoring the progression and assessing the final quality of microbially induced calcite precipitation treatments in both laboratory settings and field applications. Among the available techniques, the measurement of shear-wave velocity is widely recognized as the most reliable and practically viable diagnostic tool. Shear waves, which propagate through the soil skeleton primarily via the interconnected network of particle contacts, are highly sensitive to changes in interparticle stiffness and the formation of cementation bonds. As the calcite precipitation progresses and solid bridges form between the sand grains, the small-strain shear modulus of the soil mass increases dramatically, resulting in a corresponding, measurable increase in shear-wave velocity. In laboratory experiments, bender elements are routinely utilized to generate and receive these shear waves across soil specimens, providing a continuous, real-time assessment of the cementation process without disturbing the internal structure of the sample. The relationship between shear-wave velocity and the degree of cementation forms the basis for empirical correlations used to estimate the mechanical properties of the treated soil. However, the interpretation of shear-wave velocity data is often confounded by the complex interactions between the propagating wave and the heterogeneous microstructure of the cemented sand. The traditional theoretical frameworks used to correlate shear-wave velocity with cementation levels often assume a homogeneous distribution of calcite, thereby neglecting the scattering, dispersion, and attenuation effects caused by the stochastic morphology of the

bonds. When a shear wave encounters an assembly of particles with highly irregular cementation, the stress waves partition, reflect, and refract at the microscale, leading to significant variations in the macroscopic wave propagation characteristics. Therefore, standard empirical correlations may either overestimate or underestimate the actual degree of improvement, depending on the specific morphological distribution of the calcite. To improve the reliability of non-destructive testing evaluations, it is imperative to develop a deeper micromechanical understanding of how stochastic variations in bond geometry and stiffness influence the transmission of dynamic signals. This understanding can only be achieved through rigorous numerical modeling that explicitly accounts for the discrete nature of the granular medium and the complex morphology of the interparticle cementation. Pixelwise structured-light calibration [3] is relevant to a possible optical characterization stage for particle morphology, whose measurement uncertainty should be propagated separately from DEM model error.

1.3 Research Objectives and Scope

The primary objective of this comprehensive academic research is to investigate the quantitative and qualitative effects of stochastic calcite morphology on the measurement of shear-wave velocity in sand using the discrete element method. To achieve this overarching goal, this study introduces a novel computational framework that transitions away from traditional uniform bond models and explicitly incorporates the random geometric variations observed in actual microbially induced calcite precipitation applications. By defining statistical distributions for bond thickness, bond radius, and spatial location, the numerical model generates a highly realistic representation of heterogeneously cemented granular assemblies. The specific objectives are multi-fold. First, the research aims to formulate a micromechanical contact model capable of simulating both the cohesive strength and the dynamic stiffness of stochastically distributed calcite bonds under small-strain oscillatory loading. Second, the study seeks to simulate standard bender element tests within the discrete element method environment to generate, propagate, and record shear waves across various virtual soil specimens characterized by different statistical distributions of calcite morphology. Third, the research focuses on analyzing the arrival times, wave attenuation, and velocity dispersion to quantify the deviation in shear-wave velocity caused by morphological randomness compared to idealized uniform cementation. Furthermore, this study delves into the microscale energy dissipation mechanisms, analyzing the dynamic contact force networks and the specific pathways through which the stress waves travel through the heterogeneous medium. The scope of this paper encompasses detailed parametric studies varying the mean and standard deviation of the calcite volume, providing a robust dataset for establishing new, morphology-aware correlations between shear-wave velocity and cementation parameters. Ultimately, the findings presented in this paper are intended to refine the interpretation of non-destructive testing data, offering a more accurate and reliable approach for assessing the quality and spatial uniformity of biocementation in geotechnical engineering practice.

2. Literature Review and Theoretical Background

2.1 Microbially Induced Calcite Precipitation Mechanisms

Microbially induced calcite precipitation is fundamentally a biogeochemical process that bridges the disciplines of microbiology, chemistry, and geotechnical engineering. The process is primarily driven by the metabolic activity of specific bacteria, most notably Sporosarcina pasteurii, which produce the enzyme urease. This enzyme acts as a catalyst for the hydrolysis of urea, breaking it down into ammonia and carbon dioxide. The generation of ammonia results in a localized increase in the pH of the surrounding pore fluid, shifting the chemical equilibrium and promoting the formation of carbonate ions from the dissolved carbon dioxide. When a calcium source, typically calcium chloride, is introduced into this alkaline and carbonate-rich environment, the solubility limit of calcium carbonate is rapidly exceeded, leading to the precipitation of solid calcite crystals. These crystals nucleate preferentially on the surfaces of the sand grains due to the presence of the bacteria, which themselves serve as nucleation sites owing to their negatively charged cell walls. The continuous supply of biological and chemical

reagents allows these initial nucleation sites to grow, eventually spanning the pore throats and forming structural bridges between adjacent soil particles. The resulting cemented matrix exhibits mechanical properties that are highly dependent on the total volume of precipitated calcite, the size and shape of the crystals, and their spatial distribution within the pore network. Extensive laboratory studies have documented that the precipitation process is heavily influenced by the injection strategy, the concentration of the reagents, the ambient temperature, and the initial relative density of the host sand. A critical observation from microscale imaging is that the precipitation is rarely uniform. In regions with high flow velocities or uneven bacterial attachment, the calcite may form massive, localized clusters, while other areas remain largely uncemented. Even at the scale of a single particle contact, the calcite bridge often exhibits asymmetric geometries, with the center of the bond offset from the axis connecting the particle centroids. This inherent stochasticity in the precipitation mechanism necessitates a departure from simplistic continuum models when attempting to predict the macroscale mechanical and dynamic responses of the treated soil. Related work has addressed installation effects on the performance of hybrid suction caissons in sand [4].

2.2 Discrete Element Method in Geomechanics

The discrete element method, originally conceptualized in the late nineteen-seventies, has revolutionized the field of computational geomechanics by providing a robust framework for simulating the mechanical behavior of granular materials at the particle level. Unlike continuum methods, which treat soil as a continuous mass with averaged macroscopic properties, the discrete element method explicitly models each individual grain as a distinct entity, interacting with its neighbors through strictly defined contact laws. This particle-scale resolution allows researchers to capture complex macroscopic phenomena, such as strain localization, shear band formation, and dilation, which emerge naturally from the collective interactions of the discrete particles. In the context of cemented sands, the discrete element method has been extensively utilized to investigate the load transfer mechanisms and failure modes of the artificial bonds. Early models typically employed a parallel bond logic, wherein a cylindrical disk of elastic, breakable material is superimposed over the physical contact between two particles. This disk resists both forces and moments, simulating the cohesive and tensile strength imparted by the cementation. While these standard parallel bond models have successfully replicated the macroscopic strength and stiffness enhancements observed in biocemented soils, they inherently assume that the cementation is uniformly distributed around the contact point and that every contact in the assembly possesses identical bond geometries for a given global cement content. Sustainable cement production provides a conventional-binder reference for discussing alternatives such as biological cementation, with environmental comparisons requiring a common functional unit [5]. This assumption of uniformity contradicts the empirical evidence of stochastic morphology. Recent advancements in computational geomechanics have therefore focused on refining these contact models to better reflect the physical reality of microbially induced calcite precipitation. Researchers have proposed various morphological models that account for the volume of the cement, the shape of the meniscus, and the specific location of the precipitation within the pore space. However, integrating a fully stochastic morphological framework into the simulation of dynamic wave propagation remains a significant computational challenge. The discrete element method requires highly accurate contact stiffness formulations and very small time steps to properly resolve the high-frequency components of a propagating shear wave, making the addition of complex, asymmetric bond geometries a demanding, yet essential, advancement in the field. The literature also considers physical property of MICP-treated calcareous sand under seawater conditions by CPTU [6].

2.3 Stochastic Morphology of Calcite Bonds

The morphological characteristics of calcite bonds can be broadly categorized into several distinct typologies, each exerting a unique influence on the mechanical and dynamic properties of the granular assembly. Empirical observations classify these morphologies primarily into uniform coating, contact cementing, and patchy or nodular precipitation. Uniform coating occurs when the calcite precipitates

relatively evenly across the entire surface of the sand grains, which is generally inefficient for load transfer as much of the material does not contribute to interparticle bonding. Contact cementing, which is highly efficient, occurs when the precipitation is concentrated specifically at the interparticle contacts, forming distinct menisci. Patchy or nodular precipitation is characterized by the random growth of calcite clusters on the particle surfaces, some of which may bridge the gap between particles while others merely increase the surface roughness without providing structural cohesion. In actual microbially induced calcite precipitation applications, the resulting cementation is invariably a complex, stochastic mixture of these typologies. The stochastic nature of the morphology affects the shear-wave velocity in multiple ways. Firstly, the variation in bond thickness and radius directly alters the normal and shear stiffness of the individual contacts. A contact with a thick, robust bond will transmit dynamic forces much more efficiently than a contact with a thin, eccentric bond. Secondly, the spatial randomness dictates the connectivity of the stiffened load paths through the soil matrix. Shear waves preferentially travel along these high-stiffness pathways, a phenomenon known as wave channeling. When the distribution of these pathways is highly heterogeneous, the propagating wave front becomes distorted, leading to scattering and significant energy attenuation. Furthermore, the presence of asymmetric bonds introduces complex rotational moments and localized micro-bending at the particle contacts, which can cause velocity dispersion, where different frequency components of the shear wave travel at different speeds. Therefore, standard analytical solutions that rely on effective medium theory or idealized uniform contact models fail to capture the severe attenuation and the specific arrival time delays induced by the stochastic morphology. Developing a comprehensive understanding of these phenomena requires a systematic numerical investigation where the statistical parameters governing the bond geometry can be precisely controlled and analyzed. LUAN and colleagues examine the synergistic effect of dy and ho rare earths on the dielectric properties of X9R BaTiO3-Based ceramic [7].

3. Methodology and Computational Analysis

3.1 Contact Model Formulation for Cemented Sand

The numerical investigation is conducted utilizing a highly customized three-dimensional discrete element method framework. To accurately capture the mechanical interactions of the stochastically cemented sand, a sophisticated contact model is implemented that combines a non-linear Hertz-Mindlin contact formulation for the underlying sand grains with a specialized cohesive bond model representing the calcite precipitation. The Hertz-Mindlin component governs the elastic repulsion and frictional sliding between the base particles when the cementation bond is absent or has failed under loading. The contact force is resolved into normal and shear components, updated incrementally based on the relative displacement of the contacting particle centroids. The calcite cementation is superimposed on these base contacts as a parallel elastic beam that can resist normal forces, shear forces, bending moments, and twisting moments.

Table 1: Material properties adopted for sand particles and calcite bonds in the discrete element method simulations.

Material Parameter	Sand Particles	Calcite Bonds	Unit
Density	2650	2710	Kilogram per cubic meter
Shear Modulus	29.0	15.0	Gigapascal
Poisson Ratio	0.20	0.25	Dimensionless
Friction Coefficient	0.50	Not Applicable	Dimensionless
Normal Tensile	Not Applicable	2.5	Megapascal

Strength			
Shear Cohesion	Not Applicable	1.5	Megapascal

Unlike traditional uniform bond models, the stiffness matrix of the cementation bond is formulated to account for varying geometric dimensions. The normal stiffness and shear stiffness of the bond are functions of the bond cross-sectional area and the bond length, which is determined by the distance between the surfaces of the joined particles and the specific thickness of the calcite layer. The rotational stiffness components are derived using the polar moment of inertia and the bending moment of inertia of the bond cross-section. The failure criteria for the calcite bonds are governed by a maximum normal stress and a maximum shear stress threshold. If the stresses generated by the dynamic excitation exceed these thresholds, the bond is permanently deleted from the simulation, and the contact behavior reverts entirely to the purely frictional Hertz-Mindlin logic. This rigorous formulation ensures that the microscale stiffness variations, which are the fundamental drivers of shear-wave velocity changes, are captured with high physical fidelity.

3.2 Stochastic Generation of Calcite Morphology

To replicate the physical heterogeneity observed in microbially induced calcite precipitation, a probabilistic algorithm is integrated into the discrete element method framework to assign the morphological properties of the calcite bonds stochastically. The generation process begins with the preparation of a representative volume element consisting of spherical sand particles consolidated to a target confining stress. Once the initial granular skeleton is established, the algorithm identifies all active interparticle contacts and applies the cementation model based on a target global calcite volume fraction. However, instead of distributing the calcite uniformly across all contacts, the algorithm treats the bond radius and the bond thickness as random variables following specific probability density functions.

Table 2: Statistical distribution parameters for the stochastic generation of calcite bond morphology.

Morphological Parameter	Distribution Type	Mean Value	Coefficient of Variation	Bounds
Bond Radius Ratio	Lognormal	0.45	0.10 to 0.40	Minimum 0.1, Maximum 0.9
Bond Thickness Ratio	Normal	0.05	0.15 to 0.50	Minimum 0.01, Maximum 0.15
Eccentricity Offset	Uniform	0.00	Variable	Minimum -0.2, Maximum 0.2
Spatial Clustering Index	Spatial Poisson	1.20	Not Applicable	Highly clustered to uniform

The bond radius ratio is defined as the radius of the calcite bond divided by the radius of the smaller of the two contacting particles. By employing a lognormal distribution for this parameter, the model naturally produces a large number of relatively small bonds and a smaller number of massive, highly robust bonds, mirroring experimental micro-computed tomography data. The bond thickness ratio controls the amount of calcite material separating the surfaces of the sand grains. Furthermore, an eccentricity offset is introduced, which randomly shifts the geometric center of the calcite bond away

from the contact normal vector. This eccentricity induces localized bending moments even under pure normal wave propagation, significantly contributing to the dispersion of the dynamic signal. Another relevant line of investigation concerns experimental investigation on PCM-assisted MICP technology for desert sand treatment [8].

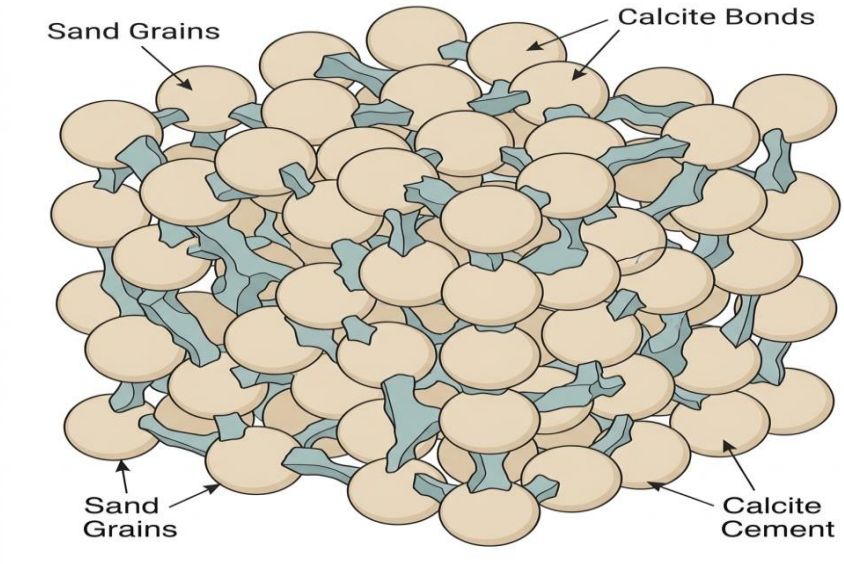


Figure 1: Comprehensive Schematic of Stochastic Calcite Distribution

The spatial distribution of the cementation is also controlled stochastically. A spatial clustering algorithm allows the user to simulate patchy precipitation, where bonds are concentrated in specific geometric zones within the representative volume element, leaving other zones largely uncemented. This comprehensive stochastic generation methodology ensures that the resulting numerical specimen possesses the complex, heterogeneous microstructural characteristics necessary to investigate the true nature of shear-wave propagation in biocemented granular media.

3.3 Simulation of Shear-Wave Propagation

The simulation of shear-wave propagation within the discrete element method framework is designed to mimic standard laboratory bender element tests. The numerical specimen, typically containing tens of thousands of particles to ensure statistical reliability, is confined within rigid planar walls. To initiate the shear wave, a dynamic excitation is applied to one of the boundary walls, designated as the transmitter. The excitation consists of a single-period sinusoidal displacement pulse in the transverse direction, representing a purely shear motion. The frequency of the input pulse is carefully selected to ensure that the wavelength of the resulting shear wave is significantly larger than the mean particle diameter, thereby minimizing high-frequency geometric scattering that could obscure the effects of the calcite morphology. The amplitude of the excitation is kept sufficiently low, strictly within the elastic small-strain regime, to prevent the breakage of the calcite bonds and the mobilization of major plastic deformations during the wave propagation. As the transverse displacement pulse is applied to the transmitter wall, the dynamic stress is transferred to the adjacent particles and propagates through the assembly via the interconnected network of stochastically assigned calcite bonds and base contacts. The wave propagation is recorded by monitoring the averaged transverse velocity and the shear stress acting on the opposite boundary wall, designated as the receiver. High-frequency data logging captures the complete time history of the dynamic response at the receiver. The shear-wave velocity is subsequently calculated by dividing the tip-to-tip distance between the transmitter and receiver walls by the wave travel time. The travel time is determined using various signal processing techniques, including the first arrival time method and the peak-to-peak cross-correlation method, to ensure robustness in the analysis. By conducting this simulated bender element test across multiple numerical specimens with identical

global calcite volumes but different stochastic morphological distributions, the study isolates and quantifies the specific impact of microstructural randomness on the macroscopic dynamic response.

4. Results and Comprehensive Discussion

4.1 Influence of Calcite Volume on Shear-Wave Velocity

The initial phase of the analysis focused on validating the general relationship between the global volume of precipitated calcite and the resulting macroscopic shear-wave velocity. As expected, an increase in the total amount of cementation within the representative volume element led to a substantial increase in the small-strain stiffness of the matrix, which directly translated into higher shear-wave velocities. However, a critical divergence was observed when comparing the uniform bond models with the stochastic morphological models. The literature also considers modified CPTU parameters and SBTn chart for predicting shear behavior of organic soils at large strains [9].

Table 3: Simulated macroscopic shear-wave velocities for uniform and highly stochastic calcite distributions across different cementation levels.

Cementation Level by Volume	Uniform Model Velocity	Stochastic Model Velocity	Percentage Difference
Uncemented Baseline	185 Meters per second	185 Meters per second	0.0 Percent
Low Cementation (2 Percent)	340 Meters per second	295 Meters per second	13.2 Percent Reduction
Medium Cementation (5 Percent)	580 Meters per second	475 Meters per second	18.1 Percent Reduction
High Cementation (10 Percent)	890 Meters per second	710 Meters per second	20.2 Percent Reduction

The uniform model consistently overpredicted the shear-wave velocity across all levels of cementation. In the uniform model, the idealized distribution of calcite ensures that every active contact contributes optimally to the dynamic stiffness of the assembly. Conversely, the stochastic model demonstrated a marked attenuation in velocity. This reduction occurs because the random distribution of bond radii and thicknesses creates a highly heterogeneous stiffness field within the material. The propagating shear wave is forced to navigate around regions of weak or absent cementation, relying on a tortuous network of strongly bonded contacts. This tortuosity effectively increases the travel path of the wave front and delays the arrival time of the main energy pulse at the receiver wall. The data presented in the analysis clearly indicates that standard empirical correlations derived from idealized numerical models or perfectly uniform synthetic samples may significantly overestimate the in-situ cementation levels when applied to field data collected from naturally heterogeneous biocemented soils. The percentage reduction in shear-wave velocity escalates with higher global cementation volumes, suggesting that the spatial inefficiencies of stochastic precipitation become more pronounced as the overall mass of the calcite increases. Another relevant line of investigation concerns integrating automated machine learning and interpretability analysis of shear wave velocity [10].

4.2 Effects of Stochastic Morphological Distribution

Beyond the global volume, the specific statistical parameters governing the stochastic morphology exerted a profound influence on the dynamic response of the granular assembly. The coefficient of variation of the bond radius ratio proved to be a dominant factor in determining the degree of signal dispersion. When the variance in bond sizes was artificially constrained to a low value, the received shear-wave signal exhibited a sharp, well-defined peak, similar to the uniform model. However, as the coefficient of variation was systematically increased to reflect highly irregular nodular precipitation, the

received signal became severely distorted. The waveform exhibited substantial broadening and multiple subsidiary peaks, making the identification of the true arrival time highly ambiguous. For a broader comparison, related research addresses benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan basin, china [11]. This dispersion is a direct consequence of wave scattering at the microscale. When the shear wave encounters a contact with a massive, highly eccentric calcite bond adjacent to a contact with a very thin bond, the dynamic stress is unequally partitioned. A portion of the wave energy is reflected backward or mode-converted into compressional waves due to the localized asymmetric stiffness, while the transmitted portion travels at varying speeds depending on the localized impedance. Furthermore, the introduction of spatial clustering, which simulates patchy precipitation zones, resulted in extreme wave channeling phenomena. The shear wave propagated rapidly through the densely cemented clusters but was drastically slowed down when traversing the uncemented zones. This macroscale heterogeneity caused the wave front to become highly irregular, leading to a significant reduction in the peak amplitude of the received signal and an apparent decrease in the macroscopic shear-wave velocity. Recycled-aggregate composition provides a source of material heterogeneity that a concrete-support extension would need to characterize rather than absorb into an unexplained fitted constant [12]. The comprehensive analysis demonstrates that non-destructive evaluation techniques must account not only for the total volume of calcite but also for the expected statistical variance in its microscopic distribution. For a broader comparison, related research addresses benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: A case study of the guadalupian (middle permian) in eastern Sichuan basin [13].

4.3 Micromechanical Analysis of Wave Propagation

To gain a deeper understanding of the macroscopic velocity attenuation and signal dispersion, a rigorous micromechanical analysis of the dynamic contact force network was conducted during the passage of the shear wave. The discrete element method allows for the visualization and quantification of the forces transmitted through every individual bond and base contact in real-time. In the uniform model, the dynamic contact force network was relatively homogeneous, with the stress wave propagating as a smooth, continuous planar front. The energy dissipation, primarily occurring through localized microscopic damping at the contacts, was minimal and uniformly distributed. For a broader comparison, related research addresses fusulinids in a middle-late Permian carbonate platform (from Maokou to Wuchiapingian stage) in eastern Sichuan basin, china [14].

Table 4: Micromechanical energy dissipation metrics and dynamic force transmission efficiency during the passage of the main shear-wave pulse.

Morphological Configuration	Peak Transmitted Force	Spatial Variance of Force	Relative Energy Dissipation
Perfect Uniform Bonds	15.2 Newtons	2.5 Newtons squared	1.0 Baseline
Moderate Stochastic Variance	12.8 Newtons	8.4 Newtons squared	1.6 Times baseline
High Stochastic Variance	9.4 Newtons	15.7 Newtons squared	2.8 Times baseline
Highly Clustered Patchy Bonds	7.1 Newtons	22.1 Newtons squared	4.5 Times baseline

In stark contrast, the micromechanical response of the highly stochastic models was characterized by extreme localization of dynamic forces. The shear stress preferentially channeled through a sparse skeleton of thick, highly robust calcite bonds, bypassing the thinner or eccentric bonds. This force channeling resulted in enormous spatial variance in the dynamic contact forces. The highly stressed load

paths experienced significant localized micro-bending and twisting due to the geometrical eccentricity of the stochastic bonds. These rotational mechanisms absorbed a substantial portion of the dynamic energy, converting the translational kinetic energy of the shear wave into rotational kinetic energy of the individual particles.

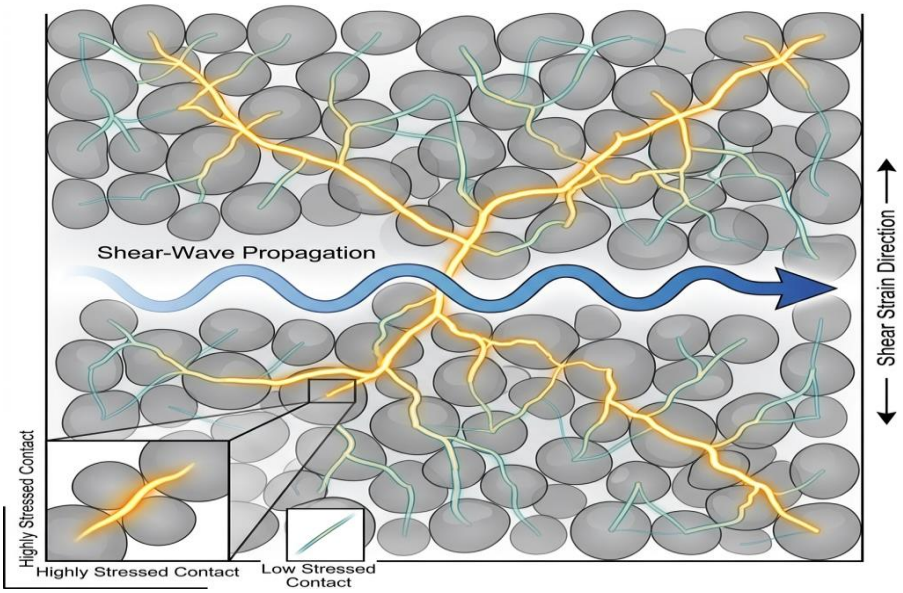


Figure 2: Micromechanical Dynamic Contact Force Network

This excessive energy conversion and the subsequent frictional dissipation at the weakly bonded contacts explain the severe attenuation of the macroscopic signal amplitude recorded in the stochastic simulations. The micromechanical data conclusively proves that the geometric irregularity of the calcite precipitation introduces complex localized kinematic mechanisms that disrupt the efficient transfer of oscillatory motion. The wave propagation in real biocemented sands is therefore not merely a function of average stiffness but is intimately tied to the topological connectivity and geometric symmetry of the stiffest interparticle pathways. The insights derived from this microscale analysis provide a theoretical foundation for developing advanced signal processing algorithms capable of extracting microstructural information from the scattered components of bender element waveforms.

5. Conclusion

5.1 Summary of Findings

This comprehensive computational study has systematically investigated the profound effects of stochastic calcite morphology on the measurement and interpretation of shear-wave velocity in sand using a highly advanced three-dimensional discrete element method framework. By abandoning the traditional assumption of uniform interparticle cementation and introducing a probabilistically driven contact model, the research successfully replicated the complex, highly irregular microstructural characteristics typical of microbially induced calcite precipitation. The extensive numerical simulations of bender element tests revealed that the inherent morphological randomness of the calcite bonds fundamentally alters the dynamic response of the granular assembly. The most significant finding is that stochastic distributions of calcite cause a substantial reduction in the macroscopic shear-wave velocity compared to perfectly uniform cementation models possessing identical total calcite volumes. This attenuation is driven by microscale wave scattering, severe geometric dispersion, and the tortuous nature of the highly stiffened load pathways. Furthermore, the micromechanical analysis demonstrated that variations in bond radius, thickness, and eccentricity lead to the severe localization of dynamic contact forces and induce complex rotational energy dissipation mechanisms at the particle scale. The spatial clustering of the precipitation, representing patchy cementation, exacerbates these effects, causing extreme wave channeling and significant degradation of the received signal amplitude. The research

provides conclusive evidence that idealized uniform models consistently overpredict the stiffness enhancement provided by biocementation and fail to capture the complex wave propagation phenomena inherent in realistic heterogeneous media.

5.2 Implications for Geotechnical Engineering

The findings presented in this paper carry significant implications for the practice of geotechnical engineering, particularly concerning the non-destructive monitoring and quality assurance of ground improvement projects utilizing microbially induced calcite precipitation. The clear demonstration that stochastic morphology attenuates shear-wave velocity necessitates a critical reevaluation of standard empirical correlations used to estimate the strength and stiffness of treated soils in the field. Relying on correlations derived from idealized laboratory specimens or uniform numerical models may lead to severe overestimations of the actual degree of cementation, potentially compromising the safety and reliability of the stabilized ground. Geotechnical practitioners must account for the expected statistical variance in the precipitation process when interpreting bender element or seismic cross-hole testing data. The results suggest that advanced signal processing techniques, which analyze not only the first arrival time but also the frequency dispersion and amplitude attenuation of the complete waveform, could provide valuable insights into the uniformity and specific morphological characteristics of the in-situ cementation. Furthermore, the computational framework developed in this study offers a powerful tool for researchers to optimize bio-treatment strategies by simulating how different injection protocols and biochemical conditions influence the statistical distribution of the calcite and, consequently, the macroscale dynamic behavior. Ultimately, embracing the microstructural reality of stochastic morphology is essential for advancing the reliability, predictability, and broader application of sustainable biocementation technologies in geotechnical engineering practice.

References

Jonkers, H. M., Thijssen, A., Muyzer, G., Copuroglu, O., & Schlangen, E. (2010). Application of bacteria as self-healing agent for the development of sustainable concrete. Ecological Engineering, 36(2), 230–235. https://doi.org/10.1016/j.ecoleng.2008.12.036

Sun, M., Liu, P., Chen, Y., Bate, B., & Xue, F. (2025). Sand stiffness variability induced by stochastic distributions of calcite precipitates: a Monte Carlo-DEM study. Acta Geotechnica, 20(3), 1363-1377.

Yang, Y., & Zhang, S. (2024). Pixelwise calibration method for a telecentric structured light system.Applied Optics,63(10), 2562-2569.

Shi, J., Malik, B. A., Liang, Z., Jing, L., Lu, Y., Gao, F., & Ouyang, Z. (2026). Installation effects on the performance of hybrid suction caissons in sand. Ocean Engineering, 359, 126025.

Schneider, M., Romer, M., Tschudin, M., & Bolio, H. (2011). Sustainable cement production—Present and future. Cement and Concrete Research, 41(7), 642–650. https://doi.org/10.1016/j.cemconres.2011.03.019

Yu, K., Ran, Y., Shi, J., Duan, M., & Ouyang, Z. (2025). Physical property of MICP-treated calcareous sand under seawater conditions by CPTU. Biogeotechnics, 3(1), 100131.

LUAN, S. W., GUO, R., ZHANG, L., FU, Z. X., CAO, X. H., YU, S. H., & SUN, R. (2024). Study on The Synergistic Effect of Dy and Ho Rare Earths on The Dielectric Properties of X9R BaTiO 3-Based Ceramic. Advanced Ceramics, 45 (6), 530-540.

Ran, Y., Wang, Y., Li, H., Liu, J., & Ouyang, Z. (2025). Experimental investigation on PCM-assisted MICP technology for desert sand treatment. Construction and Building Materials, 495, 143589.

Li, H., Duan, M., Yang, X., Wang, R., & Ouyang, Z. (2025). Modified CPTU parameters and SBTn chart for predicting shear behavior of organic soils at large strains. Engineering Geology, 108273.

Sun, M., Liang, D., Wang, J., Bate, B., & Xue, F. (2026). Clarity in DEM cementation predictions: Integrating automated machine learning and interpretability analysis of shear wave velocity. Advanced Engineering Informatics, 69, 104060.

Peng, Y., & Li, H. (2023). Benthic foraminiferal morphogroups at the end-Guadalupian extinction in eastern Sichuan Basin, China. Palaeogeography, Palaeoclimatology, Palaeoecology, 618, 111522.

Silva, R. V., de Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Construction and Building Materials, 65, 201–217. https://doi.org/10.1016/j.conbuildmat.2014.04.117

Peng, Y., Li, H., BouDagher-Fadel, M., Wang, L., Zhang, D., Zheng, T., & Yang, K. (2022). Benthic foraminifera distribution and sedimentary environmental evolution of a carbonate platform: A case study of the Guadalupian (middle Permian) in eastern Sichuan Basin. Marine Micropaleontology, 170, 102079.

Li, H., Zheng, T., Peng, Y., & BouDagher-Fadel, M. K. (2023). The fusulinids in a middle-late Permian carbonate platform (from Maokou to Wuchiapingian stage) in eastern Sichuan Basin, China. In Stratigraphy & Timescales (Vol. 8, pp. 413-435). Academic Press.