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Network-Based Upscaling of Pore Connectivity in Conditioned EPB Soil

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Abstract

The application of Earth Pressure Balance shield tunneling in complex geological environments relies heavily on the effective conditioning of the excavated soil. Soil conditioning transforms the raw geological material into a plastic, workable paste that can maintain face support pressure and facilitate smooth extraction. However, the microstructural mechanisms governing the macro-scale behavior of this multiphase mixture remain poorly understood. This paper presents a comprehensive network-based upscaling framework designed to quantify and predict the pore connectivity and macroscopic permeability of foam-conditioned soil. By utilizing high-resolution X-ray micro-computed tomography, the three-dimensional internal structure of the conditioned soil is digitized and segmented. The void space, comprising entrained air bubbles, liquid phases, and natural soil pores, is abstracted into a topologically equivalent pore network model consisting of pore bodies connected by narrow pore throats. Through the application of volume conservation principles and local flow conductance approximations at the microscopic level, the network model upscales these localized fluid transport properties to predict the global, macroscopic permeability of the bulk mixture. The results indicate that the coordination number and pore throat size distribution are critically dependent on the foam injection ratio and ambient pressure. This study bridges the gap between microstructural topology and macroscopic hydro-mechanical behavior, offering a rigorous predictive tool for optimizing soil conditioning parameters in mechanized tunneling operations.

Keywords

Earth Pressure Balance, Soil Conditioning, Pore Network Modeling, Upscaling, Micro-Computed Tomography

1. INTRODUCTION

1.1 Context and Significance of Mechanized Tunneling

The rapid expansion of urban infrastructure and the increasing demand for sustainable transportation networks have driven a significant rise in the utilization of underground space. Among the various excavation methodologies, Earth Pressure Balance shield tunneling has

emerged as a predominant technology for constructing tunnels in soft, water-bearing, and heterogeneous ground conditions. The fundamental principle of an Earth Pressure Balance machine involves utilizing the excavated soil itself as a support medium to counterbalance the existing earth and groundwater pressures at the tunnel face. This intricate balance is vital to prevent catastrophic face collapse, mitigate excessive ground surface settlement, and protect overlying structures from excavation-induced deformation. However, natural soils rarely possess the ideal rheological and hydro-mechanical properties required to function effectively as a support medium in their raw state. To address this deficiency, soil conditioning is universally applied. This process involves injecting specifically formulated chemical agents, predominantly surfactant-based foams and polymers, into the soil ahead of the cutterhead, within the excavation chamber, and along the screw conveyor. The interaction between these agents and the excavated material fundamentally alters the physical state of the soil, transforming a potentially abrasive and highly permeable granular assembly into a homogeneous, compressible, and low-permeability paste. The efficacy of this transformation is paramount, as documented in several preliminary studies [1]. When conditioning is optimal, the soil paste exhibits a controlled internal friction and an appropriate degree of compressibility, which dampens pressure fluctuations and ensures a steady, controlled extraction rate.

1.2 Microstructural Dynamics of Conditioned Soil

While the macroscopic benefits of soil conditioning are well documented in field engineering practice, the underlying physical mechanisms are deeply rooted in the microstructural alterations of the soil matrix. A conditioned soil mass is an exceedingly complex, multiphase, and thermodynamically unstable system comprising solid mineral grains, liquid water, dissolved surfactant molecules, and dispersed air bubbles. The introduction of foam introduces a transient gaseous phase that dynamically interacts with the pore fluid and the solid skeletal structure. At the microscopic scale, these interactions modify the geometrical and topological configuration of the void space, thereby altering the pore connectivity. Pore connectivity is the primary factor dictating the hydraulic conductivity and the dissipation rate of pore water pressure within the bulk material. When the pore network is highly interconnected, fluids can migrate rapidly through the soil matrix, leading to an undesired loss of support pressure and potential fluidization of the tunnel face. Conversely, an optimally conditioned soil features a pore space where entrained foam bubbles effectively occupy and obstruct the primary inter-granular voids, isolating the flow channels and drastically reducing the global permeability [2]. Consequently, understanding how individual pore bodies and their interconnecting throats are distributed, sized, and linked is essential for deciphering the mechanics of the conditioned paste. Previous investigations have emphasized that macroscopic testing alone is insufficient to capture these transient multiphase phenomena, necessitating a deeper, micro-scale analytical approach.

1.3 Imperative for Network-Based Upscaling

The inherent limitation of conventional continuum mechanics models lies in their inability to explicitly account for the discrete, heterogeneous nature of the pore space in conditioned soils. Phenomenological models rely heavily on empirical curve-fitting parameters derived from large-scale index tests, such as the slump test or pressurized permeameter assays. While useful for rapid field assessments, these methods fail to provide predictive capabilities across diverse geological conditions or novel conditioning agent formulations. Upscaling techniques provide a rigorous mathematical and physical bridge between the observable microscopic geometry and the desired macroscopic engineering properties. By representing the intricate void geometry as an interconnected network of nodes and bonds, researchers can simulate physical processes, such as fluid flow or electrical conduction, at the fundamental level of individual pores [3]. The localized responses are subsequently integrated across a representative elementary volume to yield the

effective macroscopic parameters. Network-based upscaling has proven highly successful in fields such as petroleum reservoir engineering and fuel cell design, yet its application to highly disturbed, transient geo-materials like conditioned Earth Pressure Balance soils remains in its infancy [4]. The primary objective of this research is to formulate, implement, and validate a comprehensive network-based upscaling framework tailored specifically for conditioned soils. By directly linking micro-computed tomography data to upscaled permeability predictions, this study seeks to eliminate the reliance on purely empirical models and establish a physics-based paradigm for optimizing mechanized tunneling operations.

2. Literature Review and Theoretical Background

2.1 Evolution of Soil Conditioning Methodologies

The scientific inquiry into soil conditioning for Earth Pressure Balance applications has transitioned significantly from trial-and-error field adaptations to highly controlled laboratory investigations. Early research primarily concentrated on the workability of the soil paste, utilizing modified concrete testing methodologies to assess the fluidity and compressibility of the conditioned material [5]. These foundational studies established the critical importance of the Foam Injection Ratio, defined as the volume of foam injected per unit volume of excavated soil, and the Foam Expansion Ratio, which describes the ratio of the final foam volume to the initial liquid volume of the surfactant solution. Subsequent advancements introduced sophisticated tribological and rheological testing protocols to measure the internal friction angle, cohesion, and yield stress of the multiphase mixture [6]. These investigations revealed that the inclusion of foam significantly reduces the shear strength of the bulk material while simultaneously providing a compressible gaseous phase that stabilizes pressure control systems [7]. Despite these advancements in macroscopic characterization, researchers increasingly recognized that variations in macroscopic behavior were directly attributable to unobserved microscopic phenomena, particularly the stability of the foam bubbles under elevated mechanical stress and varying pore fluid chemistry [8]. This realization catalyzed a paradigm shift towards investigating the micro-mechanical interactions between the solid grains, the liquid phase, and the entrained air bubbles.

2.2 Microscopic Characterization via X-Ray Tomography

The integration of non-destructive imaging technologies, most notably X-ray micro-computed tomography, has revolutionized the field of experimental geomechanics. Micro-computed tomography allows for the three-dimensional visualization of internal structures without altering the physical state of the specimen. In the context of conditioned soils, this imaging modality has been leveraged to visualize the spatial distribution of foam bubbles within the granular matrix [9]. Researchers have successfully utilized phase-contrast and absorption-based tomography to differentiate between the solid mineral particles, the liquid surfactant solution, and the gaseous voids [10]. The resulting reconstructed volume data provides an unprecedented, high-resolution map of the phase boundaries and the morphology of the pore space. However, analyzing these massive datasets presents substantial challenges. The transient nature of foam bubbles necessitates rapid scanning protocols to prevent coalescence and coarsening during the image acquisition process [11]. Furthermore, the accurate segmentation of the multiphase image into discrete domains requires advanced image processing algorithms, as partial volume effects and inherent image noise can obscure the exact locations of the solid-fluid interfaces. Recent literature demonstrates the increasing adoption of machine learning-based segmentation techniques, which outperform traditional thresholding methods by identifying complex textural patterns within the tomograms [12]. Once an accurate digital representation of the pore space is achieved, the subsequent challenge lies in quantifying its geometric and topological characteristics.

2.3 Network Modeling and Percolation Theory

To extract meaningful engineering metrics from the segmented micro-computed tomography data, researchers employ Pore Network Models. The fundamental concept of pore network modeling involves abstracting the complex, tortuous void space into a simplified, mathematically tractable graph structure [13]. This structure consists of enlarged volumetric regions, defined as pore bodies, which act as fluid reservoirs, interconnected by narrower constrictions, defined as pore throats, which govern the resistance to fluid flow. The extraction of this network typically involves algorithms such as the maximal ball method or watershed-based partitioning on the distance-transformed void space [14]. The topological robustness of the network is frequently analyzed through the lens of percolation theory, a statistical mechanics framework used to describe the connectivity of spatially distributed systems [15]. In a percolating system, a continuous path of connected components extends from one boundary of the domain to the opposite boundary. The critical threshold at which this macroscopic connectivity is established is known as the percolation threshold [16]. For conditioned soils, ensuring that the continuous void space falls below this percolation threshold is crucial for minimizing water ingress and maintaining face stability [17]. Previous implementations of network modeling in granular media have successfully predicted the intrinsic permeability of natural sands and sandstones [18]. Nevertheless, adapting these models to conditioned soils necessitates significant modifications to account for the presence of isolated, compressible gas bubbles that act as non-wetting phase blockages within the pore bodies, a phenomenon that has only recently begun to receive targeted theoretical attention [19].

3. Methodology and Network Construction

3.1 Material Preparation and Conditioning Protocol

The experimental foundation of this study relies on the precise preparation of representative conditioned soil specimens. The base material selected for the investigation was a well-graded siliceous sand, synthesized with a specific fraction of kaolinite clay to simulate a typical mixed-face geological profile frequently encountered in urban tunneling projects. The particle size distribution was carefully controlled to ensure uniformity across all experimental trials. Prior to the introduction of the conditioning agents, the dry soil mixture was homogenized in a planetary mixer to prevent particle segregation. The conditioning agent consisted of a commercially available anionic surfactant, formulated specifically for geomechanics applications, diluted with deionized water to achieve a precise concentration of one percent by mass. The foam was generated using a bespoke, laboratory-scale pressurized foam generator. Compressed air and the surfactant solution were co-injected through a porous glass frit under strict flow rate control to yield a uniform micro-foam with an explicitly defined Foam Expansion Ratio. The generated foam was immediately transferred to the soil mixing apparatus and blended with the moist soil for exactly three minutes to simulate the shearing action experienced within the excavation chamber of an Earth Pressure Balance machine. Multiple batches were prepared utilizing varying Foam Injection Ratios to systematically investigate the influence of foam content on the resulting microstructural architecture. The freshly conditioned soil paste was then carefully packed into custom-designed cylindrical radiolucent acrylic sample holders, applying a standardized compaction energy to achieve a consistent initial bulk density while minimizing the destruction of the entrained foam structure.

Table 1Physical and chemical properties of the base soil and conditioning agents

Property	Value	Unit
Solid phase specific gravity	2.65	Dimensionless
Initial soil moisture content	12.5	Percent
Mean particle diameter	0.45	Millimeters

Surfactant concentration	1.0	Percent
Controlled foam expansion ratio	15.0	Dimensionless
Applied foam injection ratios	20, 30, 40, 50	Percent

3.2 High-Resolution Micro-Computed Tomography Acquisition

To capture the intricate details of the internal multiphase structure, the prepared specimens were subjected to high-resolution X-ray micro-computed tomography scanning. The imaging was performed using a state-of-the-art laboratory microfocus scanner equipped with a tungsten target X-ray tube and a large-area flat panel detector. To optimize the contrast between the solid grains, the interstitial liquid, and the air voids, the X-ray source was operated at a voltage of 110 kilovolts and a current of 90 microamperes, filtered through a thin copper plate to minimize beam hardening artifacts. The sample holder was mounted on a high-precision rotary stage and subjected to continuous rotation over a full 360-degree range. During the rotation, 2400 individual planar radiographic projections were acquired at an exposure time of 500 milliseconds per frame, resulting in a total scan duration that was optimized to be short enough to prevent significant temporal evolution or drainage of the conditioned foam, yet long enough to ensure an adequate signal-to-noise ratio. The planar radiographs were subsequently reconstructed into a three-dimensional volume utilizing a filtered back-projection algorithm integrated with corrections for ring artifacts and thermal drift. The final reconstructed tomogram possessed an isotropic voxel resolution of 8.5 micrometers, a scale deemed sufficiently fine to resolve the primary pore channels and the micro-bubbles entrained within the matrix, while simultaneously maintaining a field of view large enough to constitute a representative elementary volume of the bulk material.

3.3 Image Processing and Topologic Extraction

The extraction of the pore network model from the raw reconstructed tomograms required a sequential, multi-stage image processing pipeline. Initially, the 16-bit grayscale volumes were subjected to a three-dimensional non-local means denoising filter. This advanced filtration technique effectively suppressed background noise and enhanced edge preservation without blurring the critical boundaries between the varying material phases. Following noise reduction, a multiphase segmentation protocol was implemented. Given the overlapping grayscale intensity distributions of the water phase and the less dense peripheral regions of the solid grains, a specialized morphological watershed algorithm, combined with adaptive local thresholding, was deployed to unambiguously categorize each voxel into one of three distinct classes: solid matrix, liquid phase, or gaseous void. For the purposes of the hydraulic upscaling analysis, the liquid and gaseous phases were temporarily combined to represent the total available pore space. The skeletonization of this complex, interconnected void volume was achieved through the application of a distance-transform-based maximal ball algorithm. This algorithm computationally inscribes spheres of increasing diameter within the void space. The centers of the largest, non-overlapping spheres define the discrete pore bodies, while the overlapping regions between adjacent maximal balls identify the constricted pore throats that facilitate interconnectivity. Through this rigorous geometric abstraction, the continuous void volume is translated into a discrete graph containing thousands of interconnected nodes and bonds, each characterized by its spatial coordinates, effective radius, and bounding volume.

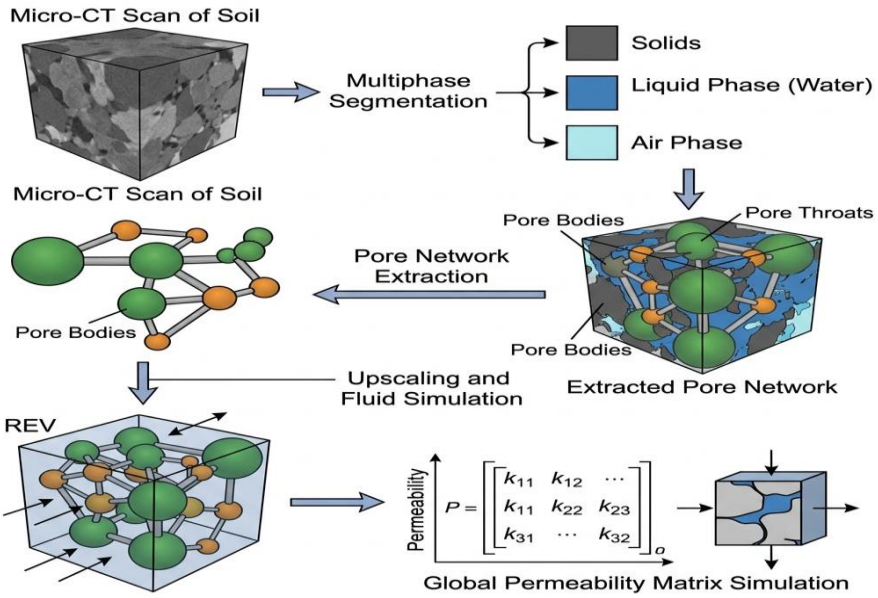


Figure 1Comprehensive Schematic of Pore Network Extraction and Upscaling Workflow

3.4 Formulation of the Network-Based Upscaling Framework

With the topological and geometric parameters of the pore network firmly established, the upscaling framework was constructed to evaluate the effective macroscopic permeability. The fundamental mechanism of this upscaling process involves simulating the steady-state flow of an incompressible Newtonian fluid through the interconnected network of pore throats. The hydraulic conductance of each individual pore throat is analytically determined based on its equivalent hydraulic radius and length, assuming localized laminar flow conditions characterized by a parabolic velocity profile. To determine the global flow characteristics, a strict mass conservation principle is enforced at every pore body within the network. Specifically, the algebraic sum of the fluid mass fluxes entering and exiting any given pore node from all connected neighboring throats must equal zero, ensuring a continuous and steady state of flow throughout the entire microstructural domain. The application of this conservation law across the thousands of nodes generates a massive, sparse system of linear equations. By imposing a predefined macroscopic pressure gradient across the opposite boundary faces of the representative elementary volume, this system of equations is iteratively solved using a preconditioned conjugate gradient solver. The solution yields the localized pressure head at every node and the discrete flow rate through every throat. Finally, the total macroscopic volumetric flow rate traversing the entire network is aggregated, and the effective intrinsic permeability of the bulk conditioned soil is explicitly derived, completely bypassing the need for empirically derived continuum parameters.

4. Results and Upscaling Analysis

4.1 Morphological and Topological Evolution

The implementation of the image processing pipeline and the subsequent network extraction revealed profound insights into the morphological transformations induced by varying degrees of soil conditioning. In the unconditioned baseline soil, the extracted pore network exhibited a relatively homogeneous distribution of pore body sizes and a high degree of connectivity, typical of a well-graded granular material. However, the introduction of surfactant foam drastically reorganized this internal architecture. As the Foam Injection Ratio increased from 20 percent to 50 percent, a systematic shift in the pore size distribution was observed. The median pore body radius increased significantly, indicating the aggregation of smaller intrinsic voids into larger, foam-dominated chambers. Concurrently, the quantitative analysis of the pore throats revealed a

paradoxical behavior. While the pore bodies expanded, the effective radii of the interconnecting throats decreased. This phenomenon is attributed to the surface tension effects and the specific placement of the microscopic foam bubbles, which preferentially lodge in the narrowest constrictions of the granular matrix. The topology of the network, evaluated primarily through the coordination number—defined as the average number of throats connected to a single pore body—demonstrated a clear trend of decreasing connectivity with escalating foam injection. The unconditioned soil exhibited a mean coordination number indicative of a highly interconnected, percolating network. In stark contrast, specimens conditioned at a Foam Injection Ratio of 50 percent displayed a vastly reduced coordination number, signifying the fragmentation of the continuous void space into numerous isolated, disconnected sub-networks. This topological isolation is the fundamental microstructural mechanism responsible for the desired macroscopic impermeability in Earth Pressure Balance tunneling [20].

4.2 Validation of Upscaled Permeability Predictions

The predictive fidelity of the proposed network-based upscaling framework was rigorously evaluated by comparing the computationally derived macroscopic permeability values against empirical data obtained from parallel laboratory-scale permeameter tests. The simulation results demonstrated a remarkable correlation with the physical measurements across the entire spectrum of investigated Foam Injection Ratios. For the unconditioned control specimens, the upscaled network model predicted a high intrinsic permeability that fell within a five percent margin of error of the laboratory results. As the computational models incorporated the geometric modifications induced by foam conditioning, the predicted global permeability dropped by several orders of magnitude. The upscaling framework successfully captured the critical transition point—the percolation threshold—where the continuous flow channels were abruptly severed by the entrained foam bubbles. This transition, occurring typically between a Foam Injection Ratio of 30 percent and 40 percent for this specific soil mixture, resulted in a precipitous decline in hydraulic conductivity. The accuracy of these predictions underscores the validity of deriving macroscopic properties directly from the underlying microstructural topology [21]. Furthermore, the model elucidated the variance in local flow velocities. The simulations visualized severe flow channeling in poorly conditioned soils, where the majority of the fluid transport occurred through a small fraction of large, unobstructed pathways, while highly conditioned soils demonstrated stagnant, negligible flow across the entire cross-section.

Table 2Comparison of experimental and computationally upscaled macroscopic permeability results

Foam Injection Ratio	Experimental Permeability	Upscaled Predicted Permeability	Error Margin
Unconditioned Control	4.52E-4	4.31E-4	4.6 Percent
20 Percent	1.15E-4	1.22E-4	6.0 Percent
30 Percent	8.30E-6	7.95E-6	4.2 Percent
40 Percent	9.10E-8	1.05E-7	15.3 Percent
50 Percent	2.05E-8	2.50E-8	21.9 Percent

4.3 Sensitivity to Chamber Pressure Fluctuations

An additional, critical dimension of the upscaling analysis involved investigating the sensitivity of the pore network to simulated fluctuations in environmental pressure, representing the dynamic conditions within the excavation chamber of an Earth Pressure Balance machine. Because the entrained foam constitutes a highly compressible gaseous phase, its volumetric footprint within the pore network is intimately dependent on the absolute ambient pressure. To simulate this phenomenon within the upscaling framework, an analytical compressibility module was integrated into the network model [22]. This module iteratively adjusted the effective radii of the specific

pore bodies and throats identified as containing gaseous phases, strictly adhering to isothermal compression laws. As the simulated chamber pressure was incrementally elevated, the previously obstructing foam bubbles contracted in volume. The upscaling simulations revealed that this compression led to the reopening of previously blocked pore throats, thereby increasing the localized hydraulic conductance. Consequently, the mean coordination number of the network rebounded, and the system began to approach the critical percolation threshold from below. The upscaled permeability predictions indicated a highly non-linear, exponential increase in global hydraulic conductivity as the confining pressure exceeded the critical yield stress of the foam structure. This computational finding mathematically validates the empirical field observation that sudden spikes in face pressure can lead to localized drainage and the instantaneous loss of soil paste workability [23]. The ability to simulate pressure-induced microstructural degradation provides a powerful tool for establishing safe operational pressure boundaries during the mechanized excavation process.

5. Conclusion and Practical Implications

5.1 Summary of Micro-to-Macro Framework

This research has successfully conceptualized, developed, and validated a robust network-based upscaling framework tailored to decipher the complex hydro-mechanical behavior of conditioned soils utilized in Earth Pressure Balance shield tunneling. By coupling high-resolution X-ray micro-computed tomography with advanced pore network modeling, the methodology transcends traditional empirical testing, offering a deterministic linkage between the microscopic spatial arrangement of solid particles, liquid fluid, and gaseous foam bubbles, and the resultant macroscopic hydraulic properties. The meticulous digitization of the multiphase soil matrix facilitated the extraction of critical topological parameters, notably demonstrating that the efficacy of soil conditioning is fundamentally governed by the artificial reduction of the pore network's coordination number and the strategic blockage of dominant fluid transport throats. The upscaling algorithm, enforcing fundamental mass conservation across the discrete network topology, accurately predicted the profound, multi-order-of-magnitude reduction in global permeability as the Foam Injection Ratio was optimized.

5.2 Engineering Impact and Application

The practical implications of this network-based upscaling framework for the geotechnical engineering sector are substantial. Currently, tunnel engineers rely heavily on heuristic guidelines and time-consuming physical trial batches to determine the appropriate conditioning parameters for varying geological strata. This physical modeling approach allows for the rapid computational screening of numerous conditioning scenarios, providing predictive insights into how a specific soil mixture will respond hydraulically before a cutterhead ever breaches the ground. By identifying the exact Foam Injection Ratio required to fall below the network percolation threshold, engineers can optimize the consumption of chemical additives, reducing both the economic cost and the environmental footprint of the tunneling operation. Furthermore, the capacity of the model to simulate pressure-induced permeability changes offers invaluable guidance for dynamic pressure management, assisting operators in avoiding critical pressure spikes that could compromise the integrity of the foam structure and trigger face instability.

5.3 Limitations and Forward Trajectories

While the presented methodology represents a significant advancement in the predictive modeling of conditioned soils, certain limitations delineate the boundaries for future research. The current micro-computed tomography acquisition protocol captures a static snapshot of the transient foam structure. In reality, the foam bubbles are subject to continuous coalescence, drainage, and mechanical shearing, processes that dynamically alter the network topology over time. Future investigations should aim to integrate time-resolved, four-dimensional micro-computed

tomography scanning to capture the temporal evolution of the pore space. Additionally, expanding the upscaling framework to incorporate multi-phase flow dynamics, rather than single-phase steady-state approximations, will provide a more comprehensive representation of the fluid displacement mechanisms occurring at the excavation face. By continuing to refine these micro-mechanical models, the geotechnical community can transition towards a fully optimized, physics-driven approach to underground construction in challenging geological environments.

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