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Digital twin construction for lifecycle analysis of tunnels

PhD. Lucas Bellini Machado, Polytechnic School of the University of São Paulo.

Caprock integrity in geologic carbon storage: Effects of heterogeneity and coupled processes

PhD. Hyunbin Kim, Postdoctoral Fellow, University of California San Diego.

Influence of the Scale Effect on the Dilatancy and Strength Behavior of Rock Masses: An Experimental Laboratory-Scale Approach

Meng. Edison Martinez Bautista, Ph.D. student, Universidad Católica del Norte, Antofagasta, Chile.

Engineering behavior of soft rock masses in Costa Rica: Recent research and practical applications

Meng. Isaac Núñez Morales, Instituto Costarricense de Electricidad (ICE)

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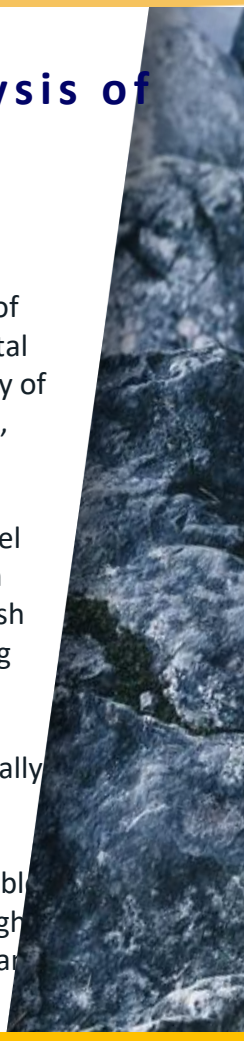
Digital Twin Construction for Lifecycle Analysis of Tunnels



Abstract

This research applies Industry 4.0 methodologies to connect physical and digital assets through classification, prediction, information modeling, assessment, and management of tunnel degradation, enabling optimized decision-making, intervention planning, and digital inspection environments. Novel frameworks were proposed to evaluate the serviceability of unlined rock tunnels by integrating advanced modeling techniques, field data acquisition, geological mapping and digitization, simulation of data acquisition processes, and the identification of susceptible zones using Discrete Fracture Network (DFN) modeling for water inflow assessment. The developed methodologies enabled the correlation of tunnel performance degradation with inspection data, supporting predictive modeling based on virtual representations. A procedural modeling script was implemented to automate mesh generation and enhance the Level of Development (LoD), using Terrestrial Laser Scanning (TLS) as a primary data source, thereby improving efficiency and accuracy. UAV-based autonomous data acquisition and LiDAR-based point cloud processing (PCD) were integrated for automated tunnel geometry reconstruction, with performance systematically evaluated through simulation. DFN modeling, coupled with permeability tensor analysis, characterized the hydraulic behavior of fractured rock masses, introducing novel connectivity optimization strategies and enabling high-resolution assessment of susceptibl zones and potential water inflow paths. The proposed frameworks were validated through real-world case studies in Brazilian tunnels, including accelerated degradation scenarios a complex fractured rock environments.

Speaker

Lucas Bellini Machado is a Brazilian Civil Engineer and Ph.D. in Geotechnical Engineering from the Polytechnic School of the University of São Paulo (USP), under the supervision of Prof. Marcos Massao Futai. His research focuses on the application of Industry 4.0 concepts to underground infrastructure, particularly the development of Digital Twins for tunnel inspection, degradation assessment, predictive performance modeling, rock mass characterization, and Discrete Fracture Network (DFN) modeling for permeability analysis in complex rock tunnels. He completed international research internships at the National Laboratory for Civil Engineering (LNEC), Portugal, within the Urban and Transportation Geotechnics Unit under the supervision of Joana Maria Carreto, and at Polytechnique Montréal, Canada, in the Department of Civil, Geological and Mining Engineering under the supervision of Prof. Pedro Pazzoto Cacciari. He has authored multiple peer-reviewed articles in leading journals such as Tunnelling and Underground Space Technology and Journal of Infrastructure Systems, as well as papers presented at international conferences.

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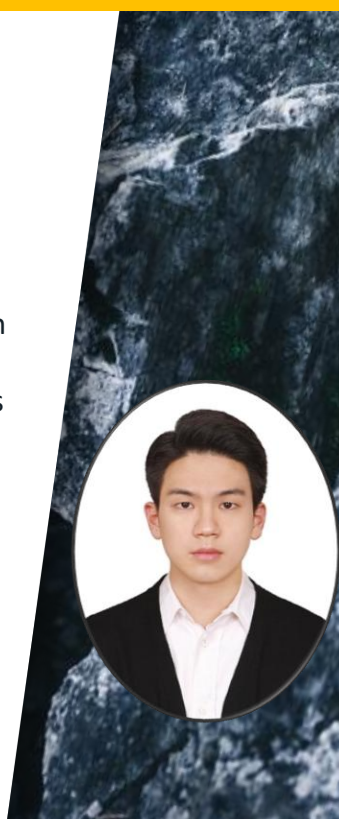
Caprock Integrity in Geologic Carbon Storage: Effects of Heterogeneity and Coupled Processes

Abstract

The long-term security of geologic carbon storage depends on the ability of low permeability caprocks to prevent upward migration of CO2. In practice, caprocks are heterogeneous and may contain facies transitions or fractures that influence fluid transport and sealing performance. This presentation summarizes laboratory investigations of the sealing potential of heterogeneous caprocks using integrated pore-scale characterization, flow-through experiments, and poromechanical analysis. Results from representative formations reveal that clay-rich facies generally maintain nanodarcy-scale permeability and high CO2 breakthrough pressures, whereas sandy inclusions and fractures can significantly reduce sealing efficiency. The role of coupled hydro-mechanical-chemical processes during CO2 injection and their implications for long-term caprock integrity will also be discussed. By combining direct measurements of sealing properties with constitutive frameworks based on poroelasticity and chemo-poroviscoelasticity, this work contributes to improved risk assessment and design of geologic carbon storage projects, while offering broader insights into barrier performance in other subsurface geoenergy applications.

Speaker



Dr. Hyunbin Kim is a Postdoctoral Scholar in Structural Engineering at the University of California San Diego. He received his Ph.D. in Civil and Environmental Engineering from the University of Illinois Urbana-Champaign in 2025. His research focuses on coupled hydro-mechanical-chemical processes in geomaterials, including capillary phenomena, multiphase flow, poromechanics, and petrophysical characterization of low permeability rocks for applications such as carbon sequestration, hydrogen storage, and nuclear waste disposal. He has authored multiple journal articles on caprock integrity and fluid–rock interactions and has received several awards, including Mavis Future Faculty Fellowship at UIUC and Best Oral Presentation Award at CouFrac 2024. At UC San Diego, he is currently developing experimental and constitutive frameworks to characterize the thermo-hydro-mechanical behavior of compacted bentonite for nuclear waste disposal applications.

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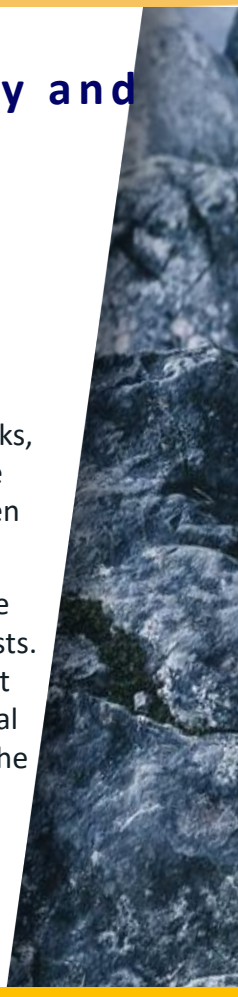
Influence of the Scale Effect on the Dilatancy and Strength Behavior of Rock Masses: An Experimental Laboratory-Scale Approach



Abstract

Dilatancy and scale effect are fundamental phenomena for understanding the deformational and strength behavior of rocks and, consequently, rock masses in mining engineering contexts. Dilatancy, which is associated with irreversible deformations in rocks, plays a key role in post-peak behavior and degradation processes of rocks. In parallel, the scale effect shows that the strength measured in laboratory tests depend on the specimen size, which directly influences the estimation of strength and mechanical parameters.

The aim of this research is to evaluate, in an integrated manner, the influence of the scale effect on the mechanical behavior of rock through the analysis of triaxial compression tests. For this purpose, complete stress-strain curves obtained from rock specimens of different sizes were analyzed under several confinement levels, considering intact rock and artificial jointed specimens. This approach allows quantifying the influence of specimen size and the presence of joints on dilatancy in Blanco Mera granite, with the aim of developing a dilatancy angle model that explicitly integrates the scale effect, in contrast to existing models reported in the literature. Furthermore, rock strength is evaluated to better understand its behavior under the influence of the scale effect.

Speaker

Edison Martinez Bautista is a Mining Engineer (2020) and M.Sc. in Mining Engineering (2024) from Universidad Católica del Norte, Antofagasta, Chile. He is currently a Ph.D. candidate in Mining at the same university (since 2024).

Since 2022, he has taught courses and laboratory sessions related to Rock Mechanics and Rock Engineering at the undergraduate level in the Mining Engineering program of the Department of Metallurgical and Mining Engineering, Universidad Católica del Norte. Since 2024, he has also held the position of Laboratory Technician at the Rock Mechanics Laboratory at the same university.

His current doctoral research focuses on the analysis of rock dilatancy and its relationship with the scale effect, aiming to develop a mathematical model capable of describing dilation angle behavior based on laboratory compression tests.

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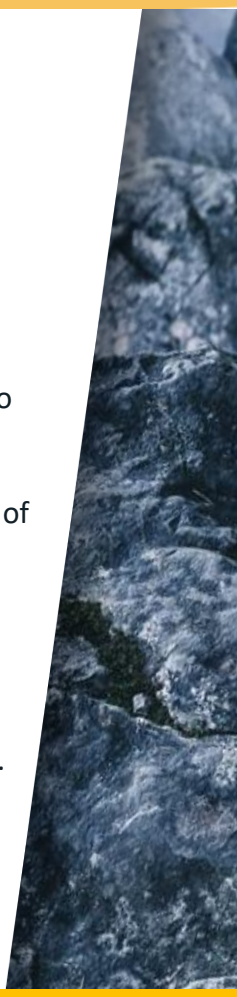
Engineering Behavior of Soft Rock Masses in Costa Rica: Recent Research and Practical Applications



Abstract

This work summarizes recent research on the engineering behavior of soft and heterogeneous rock masses in Costa Rica and their application to tunnel engineering. Two previous investigations are considered as antecedents. The first addresses numerical experiments on synthetic samples to estimate the deformability modulus and strength parameters of a conglomeratic formation, based on laboratory and field characterization of its constituents, as presented by Jiménez (2015). The second focuses on the mechanical characterization of volcaniclastic breccias, evaluating the influence of clasts and scale effects on strength and deformability through laboratory testing, as reported by Vindas (2018).

Based on the concepts and findings of these studies, the present work applies numerical modeling using the Finite Element Method to a tunnel excavated in weak, fractured tuffs. The results highlight the limitations of relying solely on intact rock properties and demonstrate the importance of integrating experimental characterization, empirical observations, and numerical modeling for the assessment of tunnel behavior in soft rock masses.

Speaker

Isaac Núñez Morales is a Geotechnical Engineer with experience in slope stabilization, foundation design, and hydrological analysis. Since 2019, he has contributed to major infrastructure and energy projects, including geotechnical monitoring for hydroelectric facilities. Since 2024, he has been part of the Instituto Costarricense de Electricidad (ICE), where he has also worked on the characterization of volcanic rocks for renewable energy generation. He holds a Master's Degree in Geotechnical Engineering with honors from the University of Costa Rica, supported by applied experience in tunnel reinforcement, dam instrumentation, and advanced geotechnical design.