Failure and Deformation Behavior of Underground Geo-Structures: Advances in Geomechanics

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Editorial

Failure and Deformation Behavior of Underground Geo-Structures: Advances in Geomechanics

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1. Introduction

Underground geo-structures play a crucial role in various aspects of modern society for several reasons.

As urbanization continues to increase, surface land becomes increasingly scarce and expensive. Underground geo-structures provide an alternative means of accommodating infrastructure such as transportation networks, utilities, and storage facilities without consuming valuable surface space [1]. Furthermore, they can help mitigate environmental impacts by reducing surface disturbances.

With global population growth and economic development, the demand for energy and raw materials is rising. Subsurface energy storage, production, and disposal systems offer opportunities to meet this demand while also supporting efforts to decarbonize energy systems and achieve carbon neutrality goals.

Minerals and metals play integral roles in modern society, serving as essential raw materials for numerous applications, including renewable energy technologies. The projected significant increases in demand imply that the mining industry will be faced with developing underground mines that can sustain higher production rates and greater depths [2]. Mining at greater depths poses a set of challenges relating to high stresses and coupled deformations [3].

Meeting the growing energy demands of society through enhanced gas production from underground reservoirs necessitates continuous advancement in industry technologies. These advancements often require extensive experimental campaigns to investigate the effectiveness of various treatments and techniques. By conducting extensive experimental campaigns, researchers and industry practitioners can advance the state of the art in gas production technologies, improve reservoir management practices, and ensure the sustainable development of underground gas resources [4–6].

Underground storage facilities for hazardous materials indeed offer several advantages over above-ground storage options, particularly in reducing the risk of environmental contamination. The mechanical response of rock masses around storage caverns must be properly investigated to maintain seal integrity. Geomechanical data obtained from subsurface investigations are often subject to uncertainty. The interpretation of these data requires expertise in geological and geotechnical engineering to account for uncertainties and make informed decisions [7,8].

Fluid storage caverns are widely used to store natural gas, liquefied petroleum gas (LPG), and other gases in underground cavities, typically formed in salt domes or abandoned mines. Indeed, ensuring the stability of caverns for gas storage presents several challenges that must be carefully addressed to maintain the integrity and safety of a

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storage facility, including geological features, overburden pressure, and changes in fluid pressure [9,10].

Geothermal energy is a renewable energy source derived from the heat stored beneath the Earth's surface. Geothermal energy is considered a clean and sustainable energy source because it produces minimal greenhouse gas emissions and has a small environmental footprint compared to fossil fuels. Despite its environmental benefits, geothermal energy faces some challenges, including potential environmental impacts such as land subsidence and induced seismicity. Ongoing research and technological advancements are addressing these challenges and expanding the potential for geothermal energy development [11].

Drilling wellbores for carbon dioxide (CO_2) and acid gas storage in saline aquifers and depleted reservoirs is a crucial aspect of initiatives aimed at mitigating climate change. Saline aquifers and depleted reservoirs are considered viable storage sites due to their geological characteristics, such as porosity and permeability, which allow for the safe and secure containment of CO_2 and acid gas underground. The process typically involves drilling a wellbore deep into the subsurface rock formations, often thousands of meters below the Earth's surface, which serves as a structure for gas injection. Key considerations in the drilling and operation of these wellbores include ensuring the integrity and stability of the wellbore and preventing gas leakage into the atmosphere or groundwater. Advanced geomechanical models and technologies play a crucial role in addressing the challenges associated with ensuring wellbore integrity in these storage operations [12,13].

The need for efficient transportation in urban areas has led to innovative solutions such as constructing tunnels at narrow distances underground. The shallow depth of underground transportation systems in urban areas can present unique challenges and considerations, particularly regarding their interaction with buildings, facilities, and roads. It is crucial to consider the impact of tunnel construction on surrounding rock formations and ensure the safety and stability of underground spaces. An appropriate analysis of rock/soil damage is also essential for the stability of the opening and safety during service [14,15].

Ultra-long and ultra-deep mountain tunnels present significant challenges; they also offer promising opportunities for enhancing connectivity, accessing resources, and promoting sustainable and resilient infrastructure development. Effective planning, engineering expertise, and collaboration are essential for realizing the full potential of these ambitious projects [16].

This Special Issue highlights the variety of studies within the field of underground geostructures and emphasizes the exploration of analytical methods and emerging technologies. A brief overview is presented to encourage readers to delve deeper into the contents of the articles.

2. An Overview of Published Articles

"Influence of Preconditioning and Tunnel Support on Strain Burst Potential" by Delonca et al. (contribution 1) addresses the significant challenge of strain burst hazard in deep underground environments. This study emphasizes the importance of assessing the probability of strain burst occurrence and implementing effective mitigation measures to ensure workplace safety. While various methods have been proposed to assess strain burst potential, uncertainties in rock mass properties and physical processes necessitate additional defense measures. This paper investigates the impact of shotcrete, rockbolts support, and destress blasting on strain burst potential using two-dimensional numerical models of circular tunnels. The results indicate that the implementation of mitigation measures reduces the occurrence of strain bursts, but the hazard level persists, especially in cases of serious overbreak hazards. The combination of support systems and destress blasting shows promise in mitigating strain burst events, but its effectiveness varies across different scenarios.

"Application of Image Processing in Evaluation of Hydraulic Fracturing with Liquid Nitrogen: A Case Study of Coal Samples from Karaganda Basin" by Longinos et al. (contribution 2) investigates the microstructure and permeability evolution of coal following treatment with liquid nitrogen (LN2) for cryogenic fracturing compared to conventional hydraulic fracturing methods. This study utilizes high-resolution imaging techniques and image processing tools from the OpenCV Python library to analyze the 2D microstructure of bituminous coal samples before and after LN2 treatment. Digital images are processed to identify cracks and evaluate parameters such as crack density, total crack area, and average crack length. The results demonstrate a progressive increase in total crack area with longer freezing times and an increased number of freezing–thawing cycles. Crack density remains largely unaffected by freezing time alone but shows a significant increase after multiple freezing–thawing cycles. The study also highlights variations in crack density and number of cracks across different freezing times and cycles, with significant increases observed in certain treatment processes. Overall, the findings provide insights into the effectiveness of LN2 treatment for hydraulic fracturing in coal samples and demonstrate the utility of image processing techniques for analyzing microstructural changes in fractured materials.

"Interaction of Segmental Tunnel Linings and Dip-Slip Faults—Tabriz Subway Tunnels" by Ramesh et al. (contribution 3) addresses the behavior of segmental tunnel linings when intersecting with dip–slip faults, focusing on the Tabriz Subway Line 2 passing through the Baghmisheh Fault. Given the high costs of urban tunnel projects, understanding the performance of concrete structures under fault movement risks is crucial. This study employs advanced 3D numerical finite difference simulations with a plastic hardening constitutive model for soil to examine the behavior of straight and oblique segmented structures under large deformations. Fault–tunnel simulations are validated using centrifuge tests on segmental tunnels for normal faulting, showing a maximum difference of 15%. The results indicate that segmental structures outperform continuous structures during reverse fault movement, as they do not collapse but exhibit slight deformations. Among segmental structures, those with oblique joints demonstrate better behavior against faulting compared to those with straight joints. The findings suggest that utilizing oblique joints in segmental structures can enhance tunnel performance under fault movement conditions.

"Feasibility Study of Controlled-Source Electromagnetic Method for Monitoring Low-Enthalpy Geothermal Reservoirs" by Eltayieb et al. (contribution 4) discusses the importance of tracking temperature changes by measuring resulting resistivity changes within low-enthalpy geothermal reservoirs to ensure sustainable energy production and avoid early thermal breakthroughs. While the controlled-source electromagnetic method (CSEM) allows for the estimation of subsurface resistivity, its capability to monitor subtle resistivity changes typical of low-enthalpy reservoirs has not been proven. The study presents a feasibility study examining CSEM monitoring of 4–8 Ω·m resistivity changes in a deep low-enthalpy reservoir model, focusing on the TU Delft campus geothermal project. Utilizing a surface-to-borehole CSEM setup, this study investigates the sensitivity of CSEM data to disk-shaped resistivity changes to various radii and return temperatures. The results indicate that CSEM monitoring is robust against undesired effects such as random noise and survey repeatability errors. Modeled differences in electric field suggest successful detection of resistivity changes in the low-enthalpy reservoir, with greater changes in monitoring data observed with increasing resistivity change radius or magnitude. The findings suggest that CSEM could be a promising geophysical tool for monitoring small resistivity changes in low-enthalpy reservoirs, offering potential benefits for geothermal energy production.

"Feasibility Assessment of Acid Gas Injection in an Iranian Offshore Aquifer" by Cardu et al. (contribution 5) explores the feasibility of acid gas injection (AGI) operations in an offshore saline aquifer in Iran. AGI serves as a means of disposing of acid gas, primarily composed of H_2S and CO_2, often originating from petroleum production or processing. This study outlines a comprehensive procedure for evaluating the suitability of a field or formation for AGI, incorporating sensitivity analysis of various parameters to minimize costs and time. The key aspects of the feasibility assessment include examining reservoir properties, geomechanical aspects, caprock integrity, and gas plume dynamics. The Surmeh formation emerges as a promising candidate for AGI due to its composition of upper dolomite and lower carbonate rock formations. Geomechanical analysis reveals critical parameters such as pore pressure and fracture pressure, while caprock integrity, particularly within the Hith formation, is identified as crucial for containment and long-term stability. Seismic mapping is employed to assess variations in caprock thickness, which influence containment effectiveness. This study also highlights the role of capillary trapping in short-term gas entrapment and plume distribution, with numerical simulations being used to elucidate the impact of heterogeneous rock properties on these processes. The paper projects approximately 2 trillion cubic feet (TCF) of acid gas injection into the Surmeh formation, with a recommended injection rate of 180 million standard cubic feet per day (MMSCFD). The formation's tightness limits injectivity, with a maximum achievable rate of 7 MMSCFD at a permeability of 1 millidarcy (mD). However, higher porosity and permeability enable more efficient injection without fracturing the formation, necessitating the implementation of two injection wells, each with a capacity of 90 MMSCFD.

"Application of Bonded-Block Models to Rock Failure Analysis" by Lemos (contribution 6) explores the use of bonded-block models in the analysis of rock failure processes. Discrete element models, particularly bonded-particle models, have been widely utilized for this purpose, but bonded-block models have emerged as a promising alternative in recent years. These models employ polygonal or polyhedral elements instead of circular or spherical particles. The paper outlines the fundamental principles of bonded-block models and their application in simulating failure in rock materials. It identifies critical governing parameters and discusses their influence on the modeling outcomes. Additionally, the calibration procedure of the models based on laboratory tests is described. An application example is provided to demonstrate the effectiveness of bonded-block models in analyzing underground excavation problems. The example utilizes a simple bonded-block model comprising rigid blocks and a bilinear softening contact model. The simulation results illustrate the model's ability to accurately reproduce observed failure modes, including block fractures. Overall, the paper highlights the potential of bonded-block models as a powerful tool in the numerical simulation of rock failure processes.

"Analysis of Deformations of the Tunnel Excavation Face via Simplified Calculation Methods" by Kalantar and Oreste (contribution 7) focuses on ensuring the stability of the excavation face during tunnel construction, which is essential for ensuring the safety of workers and the progress of the project. This study utilizes simplified numerical calculation methods and analytical techniques to analyze the stability conditions of the tunneling face, particularly focusing on the extrusion of the face as an indicator of the mechanical behavior of the rock ahead. One notable aspect is the comparison between the numerical method and the hemispherical method, demonstrating the reliability of the latter for such analyses. By conducting an extensive parametric analysis, considering various geometric and geomechanical parameters typical of tunnel excavation in weak rock, this study determines the extent of face extrusion and its dependence on these parameters. Moreover, comparing the extrusion values obtained from calculations with established limit values from the scientific literature enables a rapid assessment of face stability. Additionally, a specific investigation of the role of pressure applied to the face provides insights into defining the intensity of main stabilization systems, such as TBM (Tunnel Boring Machine) thrust and longitudinal fiberglass bolts, to prevent face collapse. Overall, this study contributes to enhancing our understanding of the mechanical behavior of tunnel faces in weak rock conditions and provides insights for optimizing stability assessments and implementing appropriate stabilization measures during tunnel excavation projects.

"Numerical Modeling and Back-Analysis Approach on a Monitored Underground Cavern for the Extraction of Marble for Ornamental Uses" by Oreste et al. ((contribution 8) focuses on the significance of the Cava Madre of Candoglia, an underground rock cavern in northwest Italy, which is renowned for its historical importance and as a source of marble used in the ongoing renovation of the Milan Cathedral. As the cavern expanded over time, significant horizontal stresses necessitated the construction of robust support structures to stabilize the side walls. To ensure ongoing safety and stability, a sophisticated monitoring system is employed. To enhance the reliability of geomechanical characterization and the numerical model used to analyze stress and strain behavior within the cavern, the researchers developed a back-analysis approach. This involved calibrating two key geomechanical parameters: the elastic modulus of the marble at the problem scale and the lateral thrust coefficient at rest (k0), which had significant uncertainty. By refining these parameters through back-analysis, the accuracy of the numerical model was improved, leading to a more precise understanding of the cavern's behavior. The refined numerical model facilitated a comprehensive examination of the support and stabilization structures within the cavern's walls. This analysis enabled the verification of the effectiveness of these structures and informed careful planning for future mining activities to continue extracting marble from the existing bench. By leveraging insights gained from the back-analysis and numerical modeling, the project can proceed with confidence, ensuring the sustainable exploitation of the valuable marble resource while prioritizing safety and stability.

"Sensitivity Analysis of Wellbore Mud Pressure towards Anisotropic Shale Properties, Pore Fluid Pressure and Far Field Stresses" by Deangeli et al. (contribution 9) investigates the mud pressure required to maintain the stability of wellbores drilled in transversely isotropic shale. This is accomplished through sensitivity analyses conducted using both analytical and numerical modeling techniques, specifically employing the FDM (Finite Diffrence Method). The anisotropic strength of the Tournemire shale is interpreted using two distinct criteria: the Weakness Plane Model (WPM) and the modified Hoek–Brown criterion (HBm). The sensitivity analyses are performed on synthetic case studies, revealing varying trends in mud pressure predictions between the two criteria. Notably, the WPM and HBm may predict different mud pressures in certain scenarios, with some cases showing higher pressures with the WPM and vice versa. The HBm predictions are found to be more sensitive to changes in the anisotropy of far field stresses across all inclinations of the weakness planes. Conversely, the WPM occasionally predicts anomalously low mud pressures over a wide range of weak plane inclinations. Furthermore, the frictional component of strength exhibits a decrease with increasing pore fluid pressure for both criteria. However, the mud pressure predicted by the WPM demonstrates greater sensitivity to changes in frictional strength compared to the HBm. Given the change in trends observed with variations in the input data, caution is advised in the selection of the strength criterion. The paper suggests a simple solution for predicting safe and reliable mud pressure with a minimal number of laboratory tests, aiming to provide practical guidance for engineering applications in shale drilling scenarios.

"Application of a Finite-Discrete Element Method Code for Modelling Rock Spalling in Tunnels: The Case of the Lyon-Turin Base Tunnel" by Martinelli and Insana (contribution 10) investigates brittle failure, or spalling, around excavations in hard rock masses with high in situ stresses. This phenomenon occurs due to the nucleation and growth of cracks induced by stress redistribution following excavation. Modeling this process is challenging, but the hybrid finite–discrete element method (FDEM) can capture emergent discontinuities associated with brittle fracturing processes by bridging the continuum and discontinuum domains. In this study, FDEM is applied using a commercial code to model brittle behavior around deep underground excavations, specifically focusing on the Torino–Lyon Base tunnel under three stress conditions. The results show that cracking occurs immediately after excavation, leading to extended spalling around the tunnel. This highlights the need for carefully designed support systems to prevent blocks from falling from the tunnel boundary. The findings are consistent with the previous literature, but this study reveals deeper spalling caused by gradual stress redistribution and shape changes. This emphasizes the importance of using a code capable of identifying crack propagation, opening, and the formation of loose blocks, which progressively alter the tunnel contour. Overall, this study demonstrates the applicability of FDEM in modeling brittle behavior around deep underground excavations and underscores the importance of accurately predicting spalling to ensure the safety and stability of tunneling operations.

"Improvements in Rock Mass Description for Stope Design by Geophysical and Geochemical Methods" by Rinne et al. (contribution 11) delves into the critical aspect of stope design in mine planning, which aims to optimize ore recovery, minimize ore dilution, control production costs, and ensure safety. It presents the main findings of research aimed at introducing novel techniques for characterizing the ore body and surrounding rock mass before stope excavation. The research involves a comprehensive literature review and a survey of mining professionals to evaluate current stope design practices. This research identifies critical areas for improvement in stope design, including geotechnical data collection, software enhancements, and better integration of design into mine planning processes. The empirical part of this study proposes innovative techniques for rapid data acquisition. Laser-induced breakdown spectrometry (LIBS) is developed for on-site measurements at the tunnel face and from core boxes to provide mineralogical and geometallurgical data. Ground-penetrating radar (GPR) studies are conducted to enhance discontinuity characterization, while rapid photogrammetric methods are suggested for efficient tunnel geometry characterization. Although these techniques already have industrial applications, this study highlights their potential for adoption and further development to enhance ore and rock mass characterization for stope design. By leveraging these advanced technologies, mining operations can improve the accuracy and efficiency of stope design, leading to enhanced productivity, safety, and cost-effectiveness.

3. Conclusions

This compilation of articles devoted to underground geo-structures and related operations encompasses a diverse range of research, elucidating the richness of the research field. This is also reflected in the different methodologies adopted for these studies, ranging from analytical and numerical models to lab tests and in situ measurements.

Regarding subject, tunnels (both road and subway) have garnered considerable interest, with five papers focused on this topic. This attention could stem from various reasons, such as their significance in transportation, their engineering challenges, or their potential impacts on the surrounding environment and communities.

Mining and related operations are the focus of two papers within this Special Issue, each addressing distinct subjects. These papers collectively contribute to a comprehensive understanding of different aspects of mining and related activities.

In the realm of geo-energy and acid gas/CO_2 storage, four papers are highlighted within this Special Issue, each tackling different aspects of these topics. These papers collectively contribute to advancing understanding and technologies related to geo-energy production, acid gas/CO_2 storage, and the utilization of subsurface resources.

Overall, underground structures play a vital role in meeting the increasing demands of modern society while addressing environmental, safety, and resource challenges. Their versatility, resilience, and efficiency make them indispensable for sustainable population growth and economic development.

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