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Numerical study of an abandoned mine repurposed for CAES systems

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Abstract

Balancing the supply and demand of energy is essential for ensuring grid stability and reducing dependence on fossil fuels. Among large-scale energy storage applications, Compressed Air Energy Storage (CAES) represents a promising solution due to its potential to integrate renewable sources efficiently. Repurposing existing underground infrastructure such as mine caverns, offers a cost-effective and less disruptive alternative compared to engineered cavities, taking advantage of pre-existing excavations characterized by high overburden and generally favourable rock mass conditions. However, besides these energy benefits, CAES implies a complex geotechnical challenge that requires an in-depth understanding of rock mass behaviour under cyclic loading. The potential reuse of underground spaces from a gold mine located in the Antioquia region, Colombia, is considered as a case study for CAES implementation. First, a brief review of CAES operating principles is presented, followed by a suitability assessment of the existing mine voids as storage reservoirs and the description of the mine's extraction process, which conditioned the geometry and spatial distribution of the abandoned cavities. The rock mass is then characterized, and fatigue-induced degradation behaviour under cyclic loading is assessed to evaluate its influence on the mechanical response of the surrounding rock mass. A three-dimensional numerical model based on finite difference method is developed to simulate the geomechanical behavior of the rock mass under typical CAES operating conditions. The results suggest that the rock mass remains largely stable, with displacements reaching 2.81 mm and major principal stresses of 9.89 MPa, supporting the feasibility of CAES system in the abandoned underground mines investigated. This preliminary assessment does not account for coupled thermo-hydro-mechanical processes which may influence long-term system performance.

Keywords

Numerical modelling, Underground energy storage, Compressed Air Energy Storage, Gold mine, Cyclic load.

1 Introduction

The transition toward low-carbon energy grid, requires large scale storage solutions to mitigate the intermittency of renewable energy sources. Among the available technologies, CAES has emerged as promising solution due to its capacity for large-scale storage and operational flexibility. However, cyclic pressurization induces repeated loading on the surrounding rock mass, potentially leading to stress redistribution, deformation accumulation and fatigue related damage. The use of abandoned mine cavities provides a cost-effective alternative for storage spaces, offering pre-existing volumes at depth. While CAES has been widely studied in salt caverns and porous media, applications in hard rock mines remain limited. This study assesses the feasibility of implementing CAES in an abandoned gold mine in Colombia by evaluating, through a numerical model the geomechanical response of the rock mass under cyclic loading conditions.

2 CAES technological solution and application to mines

2.1 CAES operational principles

CAES systems store energy by compressing air and injecting it into underground reservoirs. These systems operate from hourly to daily with a storage capacity ranging from 1MWh to 5000 MWh, approximately. With operating pressures between 5 MPa and 10 MPa. Existing operational sites and pilot projects comprehend buried depths from 110 to 1600 m (Wang et al. 2026).

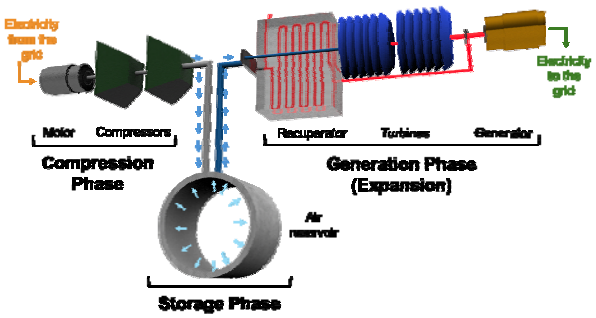


Fig. 1 Conceptual configuration of CAES system (adapted from Wang et al. 2026).

The performance of a CAES system is dictated by three main phases: compression (loading), storage and expansion (unloading). A simplified configuration of a CAES system is illustrated in Fig. 1. During loading phase, surplus electrical energy is used to compress air through a multistage compressor train. The compressed air is then stored in an underground reservoir, where the surrounding rock mass must withstand cyclic pressure variations. When demand rises, the air is released and expanded, converting stored energy back into mechanical and subsequently electrical energy (Bundt et al. 2016).

2.2 Integration of abandoned spaces for CAES systems

Suitable geological formations for CAES include salt caverns, porous media and hard rock. While salt caverns are the most mature solution, hard rock environments allow the reuse of engineered or mined cavities. Abandoned mine excavations offer existing underground spaces, reducing construction costs and environmental impact (Álvarez-Fernández et al. 2020). However, the geometry and support systems of these excavations depend on past mining activities, require reassessment for high pressure applications.

3 Description of the case study

3.1 Site and geological setting

The study site is an underground gold mine in the Colombian Andes Region, located within the Antioquia Batholith (Duque-Trujillo et al. 2019). The deposit is hosted in competent diorite with excavations reaching the 430 m of depth and a steeply dipping shear zone requiring vertically distributed production levels for the extraction of mineralized bodies. Discontinuities are characterized by millimetric hard infillings composed by carbonates and quartz, with no significant evidence of active aperture. Overall, these structural conditions indicate significant depth, low permeability and favourable mechanical interlocking, providing suitable conditions for these types of storage systems.

3.2 Mining method: long-hole stoping

The mine was developed using the long-hole stoping method for hard rock mining and presents a system of abandoned cavities used as accesses and bypasses. These cavities are here assessed as potential air reservoirs. This mining method is executed in four distinct operational phases, illustrated in Fig. 2.

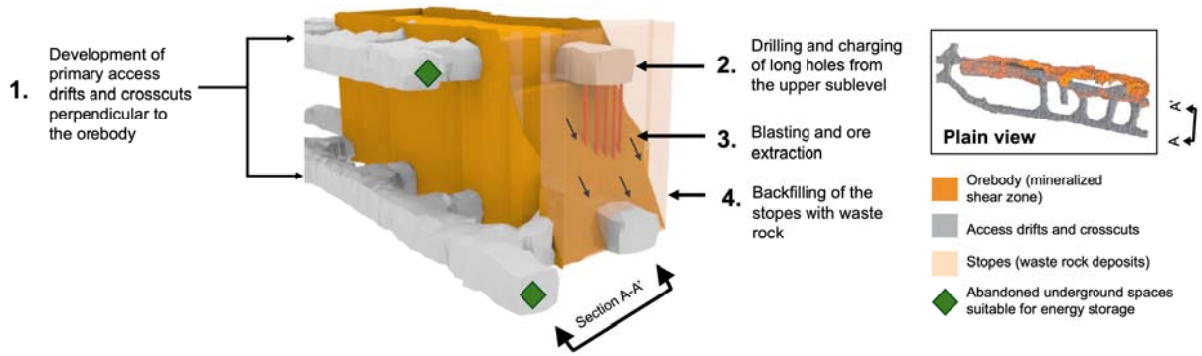


Fig. 2 Potential abandoned spaces suitable for CAES implementation from long hole stoping method.

Production stopes are typically backfilled after excavation and thus become inaccessible. Nevertheless, other excavations can remain available since are excavated to form redundant access drifts or crosscuts, or from zones initially interpreted as potentially mineralized and further determined to be non-economic. These spaces are considered as potential reservoirs due to their stability and structural integrity. Backfilled stopes were excluded due to uncertainties associated with fill material permeability and mechanical behaviour.

4 Numerical model

4.1 Model set up and boundary conditions

To perform a preliminary assessment of the mechanical integrity of an abandoned excavation under potential CAES operation, a three-dimensional numerical model (Fig. 3) of a representative drift was developed using the finite-difference code FLAC 3D (Itasca 2022). The in-situ stress field was initialized as a function of depth, assuming an earth pressure coefficient (K_0) of 0.73, in agreement with the parameters established during the mine characterization phase. The model dimensions were selected to minimize boundary effects, and the mesh discretization was performed using graded zoning with progressive refinement toward the excavation. This drift is located at a sufficient distance from the shear zone so that the influence of this structure can be neglected as first-order approximation, treating the rock mass as a homogeneous domain.

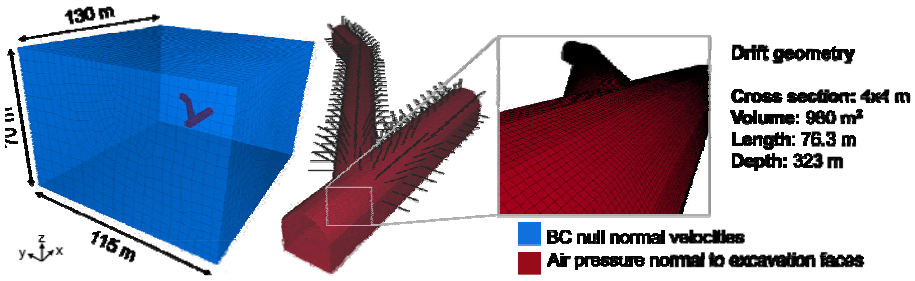


Fig. 3 Model mesh, geometry and boundary conditions.

4.2 Rock mass characterization and material properties

The excavation is developed within a type II-IIIA diorite rock mass (Bieniawski 1989). The mechanical properties of the intact rock were derived from laboratory tests performed during the mine characterization phase, including triaxial compression and uniaxial compressive strength tests. The constitutive behaviour can be described using the generalized Hoek-Brown (H-B) failure criterion and the resulting input parameters adopted for the rock mass in the model are exposed in Table 1. The tensile strength of the rock mass was assumed equal to zero, this assumption follows the approach adopted during the original geomechanical characterization performed for the mining operation, in which the tensile strength was not explicitly considered in the design analyses.

Given the rock mass quality and expected stress redistribution, systematic reinforcement using friction split-set bolts is installed. Two configurations were adopted: 2.13 m long bolts at the intersection and 1.52 m long bolts along the remaining sections (Fig. 3). All bolts have a diameter of 39 mm and a yield strength of 445 MPa.

Table 1. Rock mass properties for modelling CAES operation.

	γ [kN/m3]	E_i [GPa]	ν [-]	σ_{ci} [MPa]	GSI	D [-]	m_b [-]	a [-]	s [-]
Diorite	27.00	64.50	0.24	95.00	65	0.80	2.49	0.50	0.00497

To account for potential fatigue-induced degradation associated with cyclic pressurization, S-N (Stress to Number of cycles) curves were implemented. These curves correlate, in a semi-logarithmic scale, the ratio between cyclic strength (σ_{max}) and monotonic strength (σ_{mon}) with the number of applied cycles (N). Considering that CAES systems typically operate daily and are generally designed for up to 10,000 loading cycles, cyclic degradation may lead to progressive strength reduction, the development of new plasticized zones and increased displacements around the excavation boundary. For granodiorite, which has similar mechanical behaviour and mineralogical composition to diorite, Vaneghi et al. (2020) proposed a S-N correlation (see Eq.1), derived from the regression of multiple experimental datasets available in literature, and adopted for this study.

$$\frac{\sigma_{max}}{\sigma_{mon}} = -1.477\ log_{10}(N) + 90.532 \quad (1)$$

A concrete lining or any sealing system was not considered in the present configuration due to the classification of the rock mass as good, which ensures sufficient self-supporting capacity. Nevertheless, a sealing layer would be required in practical applications to ensure air tightness and operational efficiency.

4.3 Simulation procedure

The numerical model was implemented following the standard workflow for underground excavation numerical analyses (Fig. 4). To reproduce CAES operation, cyclic internal pressure corresponding to the loading and unloading phases from 2 MPa to 10 MPa was applied progressively to the excavation boundary for 10,000 cycles.

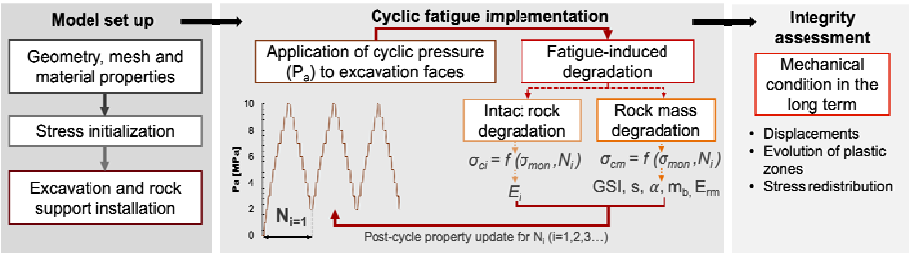


Fig. 4 Workflow to simulate CAES operation and rock mass fatigue-induced damage.

To address the gap between laboratory scale observations and rock mass scale behaviour, two degradation methodologies were implemented. In the first approach, fatigue-induced degradation was applied to σ_{ci} and respectively to deformability modulus of the intact rock, representing damage at the material. In the second approach, considering the model in an equivalent continuum medium, degradation was applied directly to the rock mass compressive strength (σ_{cm}) influencing directly the Geological Strength Index (GSI) and therefore H-B constants, accounting for scale effect and influence of structural features.

5 Results and discussions

5.1 Stress redistribution after excavation

The excavation stage induces a redistribution of the in-situ stress field, resulting in localized zones of yielding, as shown in Fig. 5. The plastic zone reaches up to 0.57 m along the sidewalls, 0.52 m at the invert and 0.14 m at the roof, reflecting the influence of the in-situ stress ratio. At the drift intersection,

the plastic zone extends up to 0.97 m, highlighting the stress perturbation within the complex geometry. The effect on the installed split-set bolts remains minimal, this observation is consistent with their primary role of controlling potential block detachment and with the modelling assumption of an equivalent homogeneous medium.

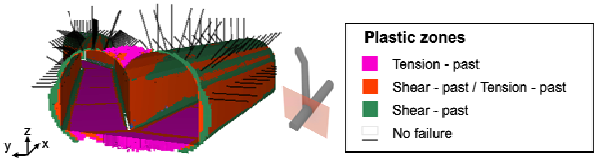


Fig. 5 Plastic zones around the drift due to excavation.

Additionally, the excavation induces a limited mechanical response in the surrounding rock mass. A maximum total displacement of approximately 4.51 mm is observed at the roof of the intersection. The relatively small magnitude of displacement indicates the high stiffness and competence of the diorite rock. Stress concentrations develop at the bottom corners of the excavation due to geometric transition between the sidewalls and the invert. At these locations, the principal stresses reach values of approximately 12 MPa and 36 MPa, while stresses along the sidewalls reach about 18 MPa.

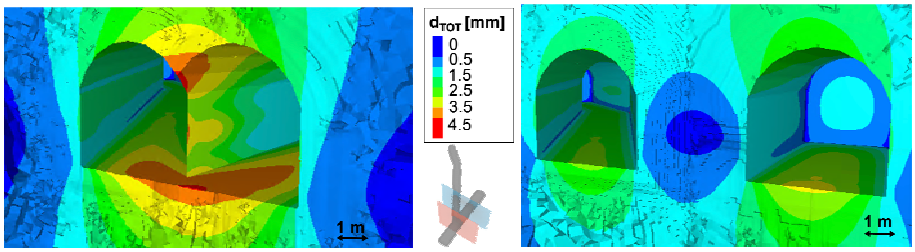


Fig. 6 Total displacement [mm] after excavation stage.

5.2 Displacement evolution and fatigue degradation under cyclic loading

To evaluate effect of CAES operation and rock fatigue-induced degradation, total displacement and principal stresses were assessed at different distances from the excavation boundary. Fig. 7 illustrates the displacement evolution referenced to the beginning of CAES operation at different observation points. The cyclic response is characterized by an initial transient phase followed by the stabilization of displacement amplitudes. Differences between the two degradation approaches remain minimal, with peak displacements of 2.73 mm and 2.81 mm for the intact rock and rock mass approaches respectively, indicating that the overall mechanical response is more influenced by stiffness degradation than by the scale at which damage is applied, whether at the intact rock (laboratory scale) or rock mass scale.

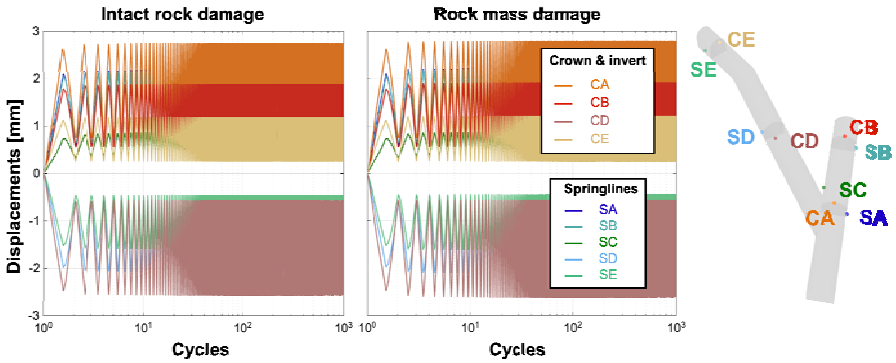


Fig. 7 Total displacement at the crown, invert and spring lines during CAES operation.

Moreover Fig. 8presents the evolution of the principal stress states during CAES operation for cycles 1, 2, 5, 10 and 100, considering both fatigue-induced damage approaches. The stress paths are illustrated for three representative conditions: (i) the initial system state, without internal pressure, (ii) full loading condition (in Fig. 8 distinguished between first and subsequent cycles), and (iii) an intermediate operation stage, when the system is unloaded to 2 MPa of applied pressure. Under peak CAES operating conditions, the major and minor principal stresses at points near the excavation

boundary reach 9.89MPa and 6.95 MPa respectively. The main stress redistribution occurs during the first cycle, whereas from cycle 2 onward the response stabilizes and becomes repeatable, confirming that cycle 1 primarily governs the initial redistribution from excavation induced stresses. Computed stress states remain generally below the rock mass strength envelope, indicating predominantly elastic behaviour. The stress state after excavation is closer to the failure envelope than the state obtained once the pressurisation of the cavity is activated. The internal pressurization during CAES operation, indeed, shifts the stresses away from failure. Plastic zones are limited as well as the effects on the support system.

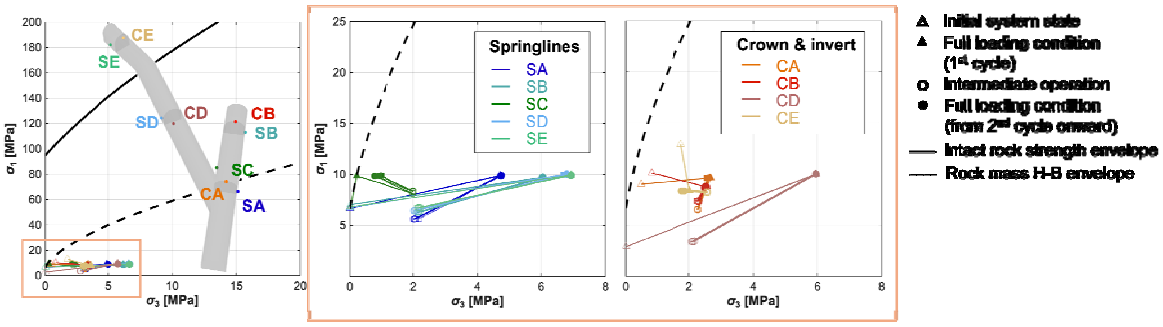


Fig. 8 Principal stress path at crown, invert andspringlines during CAES operation.

6 Concluding remarks

This study explores the feasibility of repurposing abandoned mine spaces for compressed air energy storage (CAES) systems. Despite accounting for fatigue-induced degradation, the computed displacements and additional plastic zones remain limited, and the principal stresses shift away from failure envelope, suggesting that the rock mass can accommodate the operational loading cycles without significant deterioration. The use of rock masses with moderate fatigue susceptibility is advantageous for underground energy storage applications, from a mechanical perspective, fewer interventions are required, as the stress redistribution and localized deformations remain manageable. Nevertheless, this study represents a preliminary assessment, and several aspects were not explicitly considered, including the excavation damage zone, discontinuity behaviour and temperature variations. While the adopted assumptions provide a conservative baseline for feasibility evaluation, future research should incorporate thermo-hydro-mechanical coupled analyses and detailed characterization of discontinuities to capture the long-term response of underground CAES systems.

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