1 Converting closed mines into giant batteries: Effects of cyclic loading on the

- 2 geomechanical performance of underground compressed air energy storage
- 3 systems
- 4 Falko Schmidt^a, Javier Menéndez^{b,*}, Heinz Konietzky^c, P. Pascual-Muñoz^d, Jorge Castro^e, Jorge Loredo^f,
- 5 Antonio Bernardo Sánchez^g.
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- 7 *a*Geotechnical Engineer, Santander, 39011, Spain
- 8 ^bHunaser Energy, Oviedo, 33005, Spain
- 9 Geotechnical Institute, TU Bergakademie Freiberg, 09599 Freiberg, Germany
- ^dDept. of Transports, Projects and Processes Technology, University of Cantabria, 39005 Santander, Span
- 11 Popt. of Ground Engineering and Materials Science, University of Cantabria, 39005 Santander, Spain
- 12 /Dept. of Mining Exploitation, University of Oviedo, Oviedo, 33004, Spain
- 13 ^gDept. of Mining Technology, Topography and Structures, University of León, León, 24071, Spain
- 14 *Corresponding author: jmenendezr@hunaser-energia.es

15 ABSTRACT

- 16 There are more than one million abandoned mines around the world. A large number of voids from closed 17 mines are proposed as pressurized air reservoirs for energy storage systems. A network of tunnels from
- an underground coal mine in northern Spain at 450 m depth has been selected as a case study to
- investigate the technical feasibility of adiabatic compressed air energy storage (A-CAES) systems. The
- rock mass in A-CAES plants is subjected on a daily base to mechanical cycling loading during the charge
- and discharge processes. Therefore, it is essential to analyze the behavior of the rock mass for the entire
- 22 service life. Two different lining options are analyzed, with 15 cm thick concrete lining and unlined
- tunnels, both with an internal synthetic seal to avoid air leakage through the lining and rock mass 23 24 fractures. In this paper, two 3D numerical models have been developed to analyze the geomechanical 25 performance of A-CAES plants. In the first model, deformations and plasticity state are studied assuming 26 pressure values of 5, 7.5 and 10 MPa and considering a storage space of 12,800 m³. Then, in the second 27 model, the cycling loading operation is simulated for 10,000 cycles (service life) for lined and unlined tunnels, considering a pressure range between 4 5 and 7.5 MPa. The results obtained show that the rock 28 29 mass surrounding the tunnels can resist the pressure with moderate deformations and small thickness of 30 plastic zones, while an increase of the initial volume of less than 0.5% has been observed by applying the
- 31 operating conditions. In addition, no fatigue failure is expected during the operation time. 32
- Key-Words: energy storage, closed coal mine, compressed air storage, underground storage, numerical
 simulation, cyclic loading, geomechanical performance;

35 **1 Introduction**

- The intermittent nature of variable renewable energies (VRE) such as wind and solar photovoltaic requires flexible energy storage systems (ESS) for balancing electricity supply and demand [1,2]. Estimates of abandoned mines around the world exceed one million [3]. Closed mines may be used as underground reservoir for underground pumped storage hydropower (UPSH) or compressed air energy storage (CAES) systems [4,5]. Pumped storage hydroelectricity (PSH) accounts for more than 99% of worldwide storage capacity with a round trip efficiency of about 70-80% [1,6-10].
- 42 A conventional diabatic CAES (D-CAES) system is composed of a compressor, a compressed air storage 43 system, a combustion chamber where natural gas is usually used to raise the temperature, a conventional 44 gas turbine and an electric generator. The compressed air is stored in a reservoir at a pressure that varies 45 between 4.5 and 7.5 MPa [11-13]. The system is based on the release of the compressed air from the 46 underground cavern, the air heating via combustion chamber using natural gas, and the expansion in a 47 gas turbine [11]. Currently, there are two D-CAES plants in operation in the world. The first CAES plant 48 was the 320 MW Huntorf plant, built in 1978 in Germany using a salt cavern. The Huntorf plant has a 49 usable volume of 310,000 m³ at a depth of 600 with an allowable pressure between 4 and 7 MPa on a daily

50 cycle with 2-3 h of discharge period at full load [12, 13]. The second is the 110 MW unit built 1991 in 51 McIntosh, Alabama, with a volume of 538,000 m³ at a depth of 450 m, in which the air pressure varies 52 between 4.5 and 7.6 MPa with a discharging time at full load of 24 h [14, 15]. McIntosh D-CAES power 53 plant is characterized by the regenerative heat recovery of the exhaust gas, reduction of fuel consumption 54 and improvement of global efficiency. To avoid using fossil fuels (natural gas) and consequently to reduce 55 the CO₂ emissions, adiabatic CAES (A-CAES) plants have been proposed in recent years. A-CAES systems 56 store the heat from the compression process during the charge using thermal energy storage (TES) 57 systems. The heat recovery may be used to raise the compressed air temperature during the generation 58 phase in the gas turbine. The global efficiency of CAES plants is defined as the ratio of the electrical energy 59 generated in the expansion by the gas turbine and the sum of the electrical energy required by the 60 compressor and the fuel chemical energy [16]. The cycle efficiency of D-CAES plants is 54% and 42% for 61 McIntosh and Huntorf D-CAES power plants, respectively [17]. A-CAES is expected to have higher round 62 trip energy efficiency than conventional D-CAES plants [18-20]. Globally, the A-CAES round trip efficiency 63 exceeds 70-75% [16]. In addition the CO_2 emissions are also reduced.

64 Compressed air reservoirs of CAES plants are subjected to high pressures and different loading conditions, 65 even with daily or hourly cyclic periods. For this reason, it is essential to analyze the effect of high air 66 pressures and mechanical cycling loading of storage systems during the operation time. Recently, some studies have been made in rock caverns [21-24]. However, rare investigations have been carried out to 67 model the behavior of the rock mass in coal mines considering both, high pressures and cyclic mechanical 68 69 loading. Rock salt formations are appropriate places for constructing underground cavities of CAES plants 70 and natural gas storages, because of their low permeability and adequate mechanical properties [25,26]. 71 In rock salt caverns, the temperature variation during the operation time affects the rate of creep 72 deformation and changes the cavern closure rate [27,28] Rock caverns excavated in two mines with a volume of 1,600 m³ at a depth of 450 m were investigated in Japan. Experimental data was presented for 73 74 a lined cavern with backfilling concrete and reinforced concrete in Ishihata [29]. Leakage rates of about 0.5% per day were observed at a pressure of 0.9 MPa. Nakata et al. [30] studied an unlined blast-excavated 75 76 cavern with a volume of 200 m³ at a depth of 1,000 m with a pressure that varies from 0.6 MPa to 77 atmospheric conditions in about five hours. The leaks were traced to the piping. Rutqvist et al. [31] 78 investigated the coupled thermodynamic and geomechanical performance of underground CAES in concrete-lined rock caverns. They concluded that 96.7% of the energy injected during compression could 79 80 be recovered during subsequent decompression, while 3.3% of the energy was lost by heat conduction to the surrounding media. Khaledi et al. [32] carried out an analysis of compressed air storage caverns in 81 82 rock salt considering thermo-mechanical cycic loading. The study concludes that both stability and 83 serviceability are highly affected by the operating pressure and the increased creep rate accelerates the 84 volume convergence. Damjanac et al. [33] performed numerical stress analysis for the Halmstad 85 Demonstration Plant (a 50 m high lined rock cavern in granite) under cycling loading. The results showed an increase in the magnitude of the displacements in the rock mass with the cycles. In situ tests were 86 87 carried out in a 9 m high shaft at 50 m depth in granite. The shaft diameter increased with the loading 88 cycles [34]. Perazzelli et al. [35] conducted numerical analysis of a continuum rock mass for CAES tunnels 89 and the analysis concluded that the deformations are very large in the case of weak rocks. The British 90 Geological Survey (BGS) estimated that the available salt caverns in the Cheshire Basin (UK) could support 91 up to 100 CAES storage facilities [36]. Zhou et al developed analytical [37] and numerical [38] studies for 921 mechanical responses induced by temperature and air pressure in lined rock caverns for CAES systems 93 and concluded that the temperature sharply fluctuates only on the sealing layer and the concrete lining.

94 In this paper, the stability of closed coal mines in NW Spain during the operation time of A-CAES plants is 95 analyzed considering daily cyclic compression and decompression of air in the coal mine drifts. 96 Geomechanical numerical modelling is conducted to study the technical feasibility of using underground 97 infrastructure from closed mines as storage system for A-CAES plants. In a first step, a 3D numerical 98 model, which includes two deep-levels of drifts from a closed mine, is developed to investigate the stability 99 of the rock masses subjected to 5, 7.5 and 10 MPa of pressure. In a second step, a different 3D numerical 100 model is built to simulate the cyclic loading operation resulting from the charge and discharge processes 101 during 10,000 cycles (service life). The air pressure in the drifts fluctuates between 4.5 and 7.5 MPa over

102 the entire service life. In particular, the stress evolution in the concrete lining and surrounding rock 103 formation as well as the deformations and the damage evolution are studied.

104 2 Methodology

105 2.1A-CAES scheme and study area

106 A simplified scheme of an A-CAES plant in a closed mine is shown in Fig. 1a. The study area is located in

107 the Asturian Central Coal Basin (ACCB), NW Spain. Fig. 1b shows the 370 m thick modeled lithological

108 sequence considering two mining levels and the existing formations in the study area (sandstone, shale

and coal seams). The cross section of cross-cuts and coal mine drifts is in the range of 9-12 m². The

exploitation drifts normally have a support system consisting of steel arches (21 kg m⁻¹), wood and wire meshes. Geologically, shales and sandstones are present with abundant seams of bituminous and

subbituminous coal and some limestones located close to the base [39].



- **Fig. 1.** (a) Simplified scheme of the A-CAES plant in a closed mine. Compression of ambient air (power in), underground compressed air reservoir at pressures of 4.5-7.5 MPa in coal mine drifts, heat storage, heat exchanger, expansion in a gas turbine
- 116 and alternator (power out); (b) Stratigraphic profile used in the numerical model

117 2.2 Numerical modelling

113

118 2.2.1 Model geometries, meshes and boundary conditions

119 The numerical simulations were conducted using the finite difference code FLAC^{3D} [40]. To analyze the 120 technical feasibility of the underground infrastructures during the operation time of CAES plants, two 121 different 3D models have been developed. Fig. 2 illustrates the geometry of the considered models: model 122 A (Fig. 2a), which includes two deep-levels with cross-cuts and coal drifts to study the effect of the high 123 pressure; and model B (Fig. 2b), where a detailed area of level 1 in model A has been selected to analyze 124 the cyclic loading. Level 1 and level 2 are at a depth of 450 m and 530 m, respectively. Model A is 198 m 125 long, 198 m wide and 370 m high. The usable storage volume of air in model A is 12,800 m³ in unlined 126 tunnels. The number of zones of the model is 910,000. Model B is 30 m long, 30 m wide and 30 m high, 127 and the number of zones is 104,000. In model B, the air is stored in a tunnel with concrete lining (thickness 128 of 15 cm), and the total storage capacity is about 480 m³. Fig. 4b shows the study section of model B with

- 129 2 m thick coal seam located at the left wall and a total of twelve observation points within the concrete
- 130 lining and around the study section in the rock mass. The study section is the most critical section where
- 131 the geomechanical conditions are less favorable to withstand high pressures.



Fig. 2. Geometry of the 3D models. (a) Model A. Level 1 and level 2 of cross-cut and coal drifts; (b) Model B. Lined coal drift and cross-cut in sandstone and shale formations.

135 Computational domains, discretization and boundary conditions for both models are shown in Fig. 3 and

136 Fig. 4. The cross-section of the considered coal drifts is about 9.4 m². The coal drift has a height of 3 m and

137 a width of 3.6 m, and its roof has a semi-circular form with a radius of 1.8 m. To increase the accuracy of

the calculations, the mesh is refined close to the excavations and becomes gradually coarser outwards. In

both models roller boundaries are applied at the bottom and along the vertical outer boundaries. That means displacements are restrained normal to these boundaries. On the upper boundary of the models a

- 141 vertical load of 6.5 and 11.2 MPa is applied on model A and model B, respectively, which corresponds to
- 142 the overburden weight.

132



Fig. 3. (a) Geometry, mesh and boundary conditions of model A; (b) Detail of the level 1 and cross section of the existing coal drifts.



Fig. 4. (a) Geometry, mesh and boundary conditions of model B; (b) Detail of study section with twelve observation points in shale, sandstone and concrete lining.

- 149 The rock mass behaves linearly elastic perfectly plastic, obeying the Mohr-Coulomb (M-C) failure
- 150 criterion. In the classical M-C model the strength properties of the materials are assumed to remain
- 151 constant after the onset of plastic failure. This assumption means that the material is able to support a 152 stress equal to the failure strength even after reaching the failure envelope. The M-C failure criterion is
- stress equal to the failure stregiven by Eq. (1).

$$\frac{1}{2}(\sigma_1 - \sigma_3) = c \cos \phi - \frac{1}{2}(\sigma_1 + \sigma_3) \sin \phi$$
(1)

154 where σ_1 and σ_3 are the total maximum and minimum principal stresses, respectively, in MPa, ϕ is the 155 friction angle, in degrees, and *c* is the cohesion, in MPa.

156 *2.2.2 Material properties*

157 The physical and mechanical properties of the rocks were determined by laboratory testing of intact rock 158 samples following the suggested methods of the International Society for Rock Mechanics (ISRM) [41]. 159 Laboratory tests were performed on 60 core samples from the considered site at the University of Oviedo 160 (Mechanical Laboratory). Brazilian tensile tests, unconfined compressive strength (UCS) tests, triaxial 161 compression tests and direct shear tests of discontinuities were conducted on the prepared samples to 162 obtain intact rock properties. Rock mass engineering properties for each lithology are obtained by means 163 of the Geological Strength Index (GSI), a specific rock mass classification scheme under consideration of a 164 disturbance factor (D), which depends upon the degree of disturbance to which rock mass has been 165 subjected by blast damage during the excavation phase. Disturbance factors of D = 0.8 for coal formation 166 and D = 0 for shale and sandstone rock masses were considered.

167 Unit weight (γ), intact uniaxial compressive strength (σ_{ci}), intact modulus (E_i), intact rock constant (m_i), 168 *GS* and the parameters used by the generalized Hoek-Brown (H-B) failure criterion (m_{b} , s and a) are given 169 in Table 1. H-B's constants were obtained by applying Eq. (2)-(4). The rock mass properties such as 170 uniaxial tensile strength (σ_{tmass}) and deformation modulus (E_{mass}) were calculated by applying Eq. (5) and 171 (6). The H-B failure criterion has been used to obtain the equivalent M-C strength parameters (cohesive 172 strength and friction angle of rock masses) [42]. The corresponding rock mass properties are given in

173 Table 2.

$$m_b = m_i exp\left(\frac{GSI - 100}{28 - 14D}\right) \tag{2}$$

$$s = exp\left(\frac{GSI - 100}{9 - 3D}\right)$$

$$a = \frac{1}{2} + \frac{1}{6} \left[exp\left(\frac{-GSI}{15}\right) - exp\left(\frac{-20}{3}\right) \right]$$

$$E_{mass} = E_i \left(0.02 + \frac{1 - D/2}{1 + exp^{((60 + 15D - GSI)/11)}} \right)$$

$$\sigma_{tmass} = \frac{-s \ \sigma_{ci}}{m_b}$$

(6)

(5)

(3)

174

175 Table 1

176 Model parameters: intact rock properties, GSI and Hoek-Brown constants.

Parameter	Shale	Sandstone	Coal
Unit weight, γ (kN m ⁻³)	22.68	25.87	15.00
Intact modulus, E _i (MPa)	21000	43650	32900
Intact uniaxial comp. strength, σ_{ci}	35	150.8	8.0
Intact rock constant (m _i)	9.2	15.4	8.0
GSI	35	50	51
m_b	0.903	2.582	0.433
S	0.00073	0.00386	0.00059
<u>a</u>	0.5159	0.5057	0.5053

177 Table 2

178 Rock mass properties used for modelling of CAES plant operation.

Lithology	Young's modulus (MPa)	Poisson's ratio	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (°)
Shale	2381	0.27	0.028	0.67	37.7
Sandstone	13409	0.25	0.226	2.02	52.7
Coal	3200	0.32	0.011	0.25	20.0
Concrete	23000	0.27	2.000	5.00	40.0

179 2.2.3 Simulations procedure

For both models, the following steps have been performed to simulate the effects of applying high pressures and cyclic loading on the underground infrastructure. Due to tectonics, the horizontal components are often equal or even higher than the vertical component. Therefore, the virgin in-situ stress field should have horizontal components between about 60% of vertical component and 200% of vertical component. Finally, an isotropic stress field has been chosen as a compromise ($\sigma_{xx}=\sigma_{YY}=\sigma_{ZZ}$). The initial primary stress in model A is between 6.5 MPa on the upper side and 15.5 MPa on the bottom of the

186 model. For model B, the initial primary stress is 11.2 MPa.

- 187 For model A, the following simulation steps were performed: (1) Generation of primary stress field by
- 188 initializing vertical and horizontal stresses, (2) Excavation of level 1 and level 2, and (3) Application of air
- 189 pressures values of 5, 7.5 and 10 MPa. Plasticity states, maximum and minimum principal stresses and
- deformation values due to the application of air pressures were analyzed on level 1 and 2.
- 191 For model B, the following simulation steps were performed: (1) Generation of primary stress field by
- initializing vertical and horizontal stresses, (2) Excavation of coal mining drifts, (3) Installation of 15 cm
- thick concrete lining after excavation, (4) Resetting of displacements in order to measure pressure effects,
- and (5) Application of cyclic loads resulting from the charge and discharge processes at pressure values between 4.5-7.5 MPa during 10,000 cycles. Plasticity states, displacements and stress evolution in the
- 195 between 4.5-7.5 MFa during 10,000 cycles. Flasticity states, displacements and stres196 concrete lining as function of cyclic loading have been investigated.
- 197 To consider the gradual rock mass deterioration with ongoing cyclic loading, according to the Eq. (7),
- reduction of resistance and deformation properties is carried out depending on the number of the cycles
- according to Dobromil et al. [43].

$$f_c = 1 - (0.0022 \cdot Ln(C_i))$$

(7)

where f_c is a correction factor and C_i is the cycle number *i*. This reduction is only applied to plastified zones around the void, leaving other zones far away from the excavation untouched. M-C parameters such as friction angle, cohesion and tensile capacity are affected by the reduction. The final reduction after 10.000th cycles is 2%. There is no fatigue data available for these materials at this stage of investigation, therefore this approach using the M-C constitutive model is carried out.

205 **3 Results and discussion**

206 3.1 Effects of high pressure on unlined infrastructure

207 Fig. 5 shows deformation and plasticity state for level 2 at a maximum air pressure of 10 MPa. The 208 maximum displacement is 12.1 mm and occurs at the floor of the right tunnel. The maximum displacement 209 is reduced down to 10 mm at the right wall of the left tunnel. Extent and type of plastification of the rock 210 mass around the tunnels located at level 2 is shown in Fig. 5b. A combination of shear and tensile plastifications are observed mainly in the roof, floor and left wall of the left tunnel. In the right tunnel, the 211 212 plasticity state changes and tensile failure, located at the floor, is practically irrelevant. The thickness of the plastic zones reaches up to 2,5 m at the tunnels roof. Table 3 shows deformation, maximum and 213 214 minimum principal stresses near tunnels as well as plasticity types and extent for 5, 7.5 and 10 MPa air

215 pressure loading. Note that the higher deformation values and plastifications are associated to the coal 216 seam that is crossing the section (Fig. 3).





219 Table 3

220 Deformation, maximum and minimum principal stresses, thickness of plastic zones and plasticity type for air pressure of 5, 7.5 221 and 10 MPa.

Danamatan	5 MPa		7.5 MPa		10 MPa	
Falameter	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
Deformation (mm)	5.2	5.5	8	9	11	12.1
Maximum principal stress, σ_1 (MPa)	22.8	35.6	14.4	19.7	14.2	16.9
Minimum principal stress, σ_3 (MPa)	10.1	14.3	8.2	8.2	9.3	10.
Thickness of plastic zones (m)	1.8	1.9	2.2	2.2	2.4	2.5
Plasticity type	Shear		Shear/Tensile		Shear/Tensile	

222 With decreasing the air pressure, displacements and thickness of plastic zones decrease significantly. At

an air pressure of 5 MPa the maximum displacement is reduced down to 5.5 mm and the extent of the

- 224 plastic zones reaches 1.9 m at level 2. At an air pressure of 7.5 MPa shear and tensile plastifications are
- obtained, while at 5 MPa, only plastification in shear has been observed. The increase of the usable storage
- space has been estimated after applying the operating pressures. The initial storage volume is 12,800 m³,
- increasing by 0.24, 0.37 and 0.52% at pressure values of 5, 7.5 and 10 MPa. Fig. 6 shows the principal
- stresses concentration at a pressure of 10 MPa around the tunnels on level 2. The maximum principal
- stress (σ_1) and the minimum principal stress (σ_3) reach 16.9 and 10.6 MPa, respectively. At a pressure of
- 230 5 MPa, the maximum and minimum principal stresses are 35.6 and 14.3 MPa at level 2.



Fig. 6. Effects of applying a pressure of 10 MPa on the coal drifts located at level 2. (a) Maximum principal stress; (b) Minimum principal stress.

234 3.2 Analysis of cyclic loading

The cycling loading is analyzed for lined and unlined tunnels for 10,000 cycles. Compression and decompression cycles have been simulated for a typical A-CAES operation, with the tunnel pressure ranging from 4.5 to 7.5 MPa.

Fig. 7 presents - on a logarithmic scale - the evolution of displacements for unlined (Fig. 7a) and lined tunnels (Fig. 7b), during a simulation over 10,000 daily pressure cycles, equal to more than 30 years of continuous operation. The results obtained show that the displacements remains constant over the entire 10,000 cycles of simulation time. Maximum and minimum values of displacements are obtained at P5 and P7 (Fig. 4b), respectively. P5 and P7 are located at the rock wall, near the rock-concrete interface, on the left (coal formation) and right (sandstone formation) sides of the tunnel, respectively. At point P5, the total displacements vary from 9.86 mm at a pressure of 4.5 MPa to 12.10 mm at a pressure of 7.5 MPa for

245 unlined tunnels. The total displacements decrease significantly in the case of lined tunnels, varying from

8.42 mm at a pressure of 4.5 MPa to 9.68 mm at a pressure of 7.5 MPa. The maximum displacement also

occurs in the coal formation and is reduced by 20% when a concrete lining is applied. A detail of the total

248 displacements at P5 is shown in Fig. 8 for 10 air pressure cycles.



Fig. 7. Results of simulations for 10,000 air pressure cycles for an A-CAES in a coal mine drift. See Fig. 4 for the location of observation points. (a) Total displacements considering unlined case; (b) Total displacements considering 15 cm thick concrete lining.

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Fig. 8. Detail of total displacements at P5 for 10 air pressure cycles. (a) Considering unlined case; (b) Considering 15 cm thick concrete lining.

256 Fig. 9 shows - on a logarithmic scale - the evolution of total maximum (Fig. 9a) and minimum (Fig. 9b) 257 compressive principal stresses for lined tunnels at P2, P7 and P10. P2 and P10 are located in sandstone 258 formation and within the concrete lining, respectively, on the top and roof of the tunnel. During the 259 pressurization of the tunnel (compression phase), the maximum compressive stress increases up to -18 260 MPa at P7 (negative number signify compressive stress), while the minimum compressive stress reaches 261 -8 MPa. At P10, within 15 cm concrete lining, the maximum and minimum principal stresses decrease 262 down to -7.45 and -3.8 MPa, respectively. As it is shown in Fig. 9b, the minimum principal stress at P 10 263 becomes positive (tensile stress) reaching 1.67 MPa.



264 265 266 267

Fig. 9. Results of simulations for 10,000 air pressure cycles for an A-CAES in a coal mine drift. See Fig. 4 for the location of observation points. (a) Total maximum principal stress considering lined case; (b) Total minimum principal stress considering lined case.



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Fig. 10. Detail of principal stresses in concrete lining (P 10) for 10 pressure cycles. (a) Total maximum principal stress; (b) Total minimum principal stress.

Fig. 11a depicts extent and type of plastification during cyclic loading operation at 7.5 MPa. Plastification in shear occurs mainly at the left wall, in the coal formation, while a combination of shear and tensile plastifications develop in the concrete lining. Irrelevant tensile plastifications have also been obtained in the coal formation. Tensile plastifications are obtained at the floor. Fig. 11b shows the tensile stresses in the concrete lining. The tensile stresses in the concrete lining reach up to 1.8 MPa at the floor of the tunnel. Since the concrete lining shows peaks of tensile stress, fiber reinforced shotcrete could also be applied.



277

278 Fig. 11. Effects of cyclic air loading at 7.5 MPa on the study section. (a) Plastified zones; (b) Tensile stresses in concrete lining.

The variation of the usable storage volume (ΔS_v) during the mechanical cyclic loading phase (4.5-7.5 MPa) is evaluated considering two scenarios: (1) unlined tunnels and (2) tunnels with 15 cm thick concrete

281 lining. The variation of the storage volume of the network of tunnels is calculated by applying Eq. (8):

$$\Delta S_{v} = \frac{V_{s0} - V_{si}}{V_{s0}}$$
(8)

where V_{s0} and V_{si} are the initial defined volume (480 m³) and the usable storage volume after each pressure cycle (i), respectively. Fig. 12a shows, on a logarithmic scale, the change in storage volume during normal operating conditions of an A-CAES plant. As it is observed, the storage volume increases in both scenarios. An increase in storage volume between 0.30% and 0.38% has been estimated considering unlined tunnels. Finally, the increase of volume is reduced down to 0.22% and 0.29% when a 15 cm thick concrete lining is considered. A detail of the variation of usable volume for 10 air pressure cycles is shown in Fig. 12b.



Fig. 12. Variation of usable storage volume for lined and unlined tunnels during 10,000 air pressure cycles; (b) Detail of variation of usable volume for 10 pressure cycles.

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To validate the numerical model, an analytical solution for deformations of a circular tunnel in perfectly elastic material subjected to internal pressure can be obtained following Eq. (9):

$$u_{ie} = \frac{r_0(1+v)}{E_m} (P_0 - P_i)$$

where, u_{ie} is the inward radial elastic displacement, E_m is the Young's modulus or deformation modulus, v

is the Poisson's ratio of the rock, r_0 is the tunnel radius, P_0 is the far field stress and P_i is the internal support pressure. Considering the values indicated in the article, the displacements caused by the pressure change from 4.5 MPa to 7.5 MPa should be around 0.5 mm for sandstone and 2 mm for shale assuming only elastic deformations.

301 The deformations obtained from the numerical simulations are within the range of those expected 302 analytically, considering that the simulations consider more details like plastified zones and a non-

303 uniform presence of shale, coal and sandstone material in the drift section.

304 4 Conclusions

Abandoned mines around the world have a great potential for ESS. In this work, a technical feasibility 305 306 analysis of using disused mining structures from a closed coal mine at 450 m depth as underground CAES 307 system is presented. The main objective of this work is a preliminary design for the necessary reinforcement in tunnels subjected to high pressure cyclic loading. Then, based on this information, it is 308 309 planned to build a small-scale pilot plant in the study area to experimentally investigate the behavior in 310 situ. During the normal operating conditions of A-CAES plants, the storage systems are subjected to daily mechanical cyclic loading at high pressure values. Therefore, to ensure the feasibility of the storage 311 312 systems, it is essential to investigate the stability of the rock masses and concrete lining during the 313 operation time. To accomplish this, two 3D numerical models have been developed in order to obtain deformations and plasticity states around the existing tunnels. 314

315 The results obtained show that existing underground infrastructures can resist loading scenarios of A-316 CAES plants. Moderate deformation values and small extent of plastic zones have been obtained in unlined 317 tunnels at pressure values of 5, 7.5 and 10 MPa. At an air pressure of 10 MPa, the maximum displacement 318 is 12.1 mm and occurs at the floor of the tunnels locates at level 2. The maximum displacements is reduced 319 down to 5.5 mm at a pressure of 5 MPa. The maximum thickness of plastic zones is 2.5 m for an air 320 pressure of 10 MPa, and it is reduced to 1.9 m for 5 MPa. Regarding the cyclic loading operation, the 321 maximum displacements are reached at the left wall in the coal formation. The displacements vary from 322 9.68 mm to 12.1 mm when the air pressure fluctuates between 4.5-7.5 MPa in unlined tunnels. The 323 maximum displacements remain constant during the cyclic loading and are reduced by 20% when concrete lining is considered. Regarding the high storage air pressure and the safety aspect, shaft plugs 324 325 are an essential feature, and subject to further investigations. Finally, the variation of the storage volume 326 has been estimated during the operation time. An increase of the usable storage volume less than 0.5% 327 has been obtained by the simulations.

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