Energy loss of compressed air storage in hard rock

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Abstract

Underground space provides opportunities for environmentally safe storage and retrieval of energy. Compressed Air Energy Storage (CAES) in underground caverns can be used to generate electrical power during peak demand periods. The excess power generation capacity, which is available when demand is low, is used to store energy in the form of compressed air. This energy is then retrieved during peak demand periods. The structural stabilities and leakage features of the air storage site determine the expected energy losses, efficiencies of energy conversions and the corresponding economics. Design examples of CAES systems are presented, their geomechanical and thermal responses to compression and air release cycles are considered, and the corresponding energy losses are estimated.

1 Introduction

Over the years, recently, the use of underground energy storage in hard rock, has been increasing worldwide. The use of mined caverns for strategic energy reserves is a typical example. Compressed Air Energy Storage (CAES) is done during slack hours by a compressor which discharges air into an underground cavern. The CAES, which has functions similar to hydraulic energy storage plants, improves the reliability of power supply at peak hours. During peak hours, the air flowing out of the reservoir is used to drive a gas turbine alternator. The power available from such a plant is typically 300–400 MW [1]. The process, known as CAES, has been in operation for over 20 years. Two facilities are currently operational: one in McIntosh, (Alabama, USA) and the other near Bremen in Germany. The 290 MW Huntorf plant in Bremen commenced
operation in 1978, and over a 10 year period showed 90% availability and 99% starting reliability. It is the world first commercial compressed-air storage installation. In Alabama, USA, a 110 MW CAES plant commenced operation in the early nineties. This plant provides enough electricity to supply the demands of 11,000 homes for 26 hours. In Israel the construction of a 300 MW CAES plant in Mount Sedom was considered [2]. The use of tunnels excavated in hard rock for this purpose, is conditional on short- and long-term stability and on prevention of loss of air pressure. A CAES pilot plant (capacity – 2 MW) built in Japan includes a tunnel 6 m in diameter and 57 m long [1]. The current experience in CAES systems demonstrated the effectiveness of this approach for energy supply, and as an instrument for strategic energy reserves.

2 Numerical modelling

2.1 General approach and structural data

2.1.1 General approach
The stability of single and multiple tunnel systems has been studied using the program FLAC [3]. In this context suitable constitutive elastic and elasto-plastic relations are selected for the description of mechanical behavior of intact rock. The Mohr-Coulomb failure criterion (shear yield function) with tension cutoff (tensile yield function) were adopted. The rock formation is assumed to constitute a half space. Measurements of horizontal stresses, at civil engineering projects and mining sites, show that the ratio of the average horizontal and vertical stresses decreases with depth, being highest at shallow depth levels [4,5].

Safe operating pressures for an underground reservoir depend on several geomechanical factors. These include in-situ stresses, pressure changes in the reservoir, and mechanical properties of the reservoir and surrounding material. A CAES system may consist of one large cavern, or alternatively of a group of small caverns or tunnels. The main factors used for determination the recommended cavern depth are: maximum air pressure; initial state of stress in the rock; tensile strength of the rock mass; rock mass deformability, and safety factors. The maximum acceptable tensile stress \( \sigma_{\text{max}} \) is as [6]:

\[
\sigma_{\text{max}} \leq \sigma_T / F
\]

where \( \sigma_T \) is tensile strength of the rock mass and \( F \) is the safety factor.

Stress analysis of lined and pressurized CAES tunnels that are excavated in rock is then demonstrated. The lining is considered as a monolithic structure and the analysis includes gravitational loading of the surrounding rock mass.

The objectives of this analysis are to simulate stress relaxation in the rock after excavation and prior to liner installation, and to examine the changes in these stresses due to air compression in the lined tunnels.

2.1.2 Mechanical properties
Mechanical parameters, which represent a typical rock mass in Israel, are available from literature [7–10]. We adopted the Geological Strength Index (GSI) proposed by Hoek and Brown [8]. The concrete liner, being represented by a continuous monolithic structure, is assumed to behave as a homogeneous,
isotropic, linearly elastic material with elastic modulus of 50,000 MPa and Poisson’s ratio 0.2. The analysis focuses on installation of a 1 m section of the liner. The concrete liner interacts with the rock as a structural element only.

2.2 Modelling sequence results and discussion

One dimensional array of parallel tunnels (Safety factor \( F = 1.0 \)) The stability of a one dimensional array of parallel tunnels in massive dolomitic rock was analysed, using a configuration of three parallel tunnels set at the same depth with center to center spacing of 2b and 3b, where \( b \) denotes the tunnel diameter. The array was set 35 m below surface and tested at excavated diameters of 6, 9 and 12 m, and fixed 1 m thick liner. Here the rock is assumed at equilibrium under the prevailing gravity loading, e.g., prior to excavation as well as after its completion. Furthermore, it is assumed that there is sufficient time delay between excavation and liner installation, so as to permit relaxation of the perturbed stress field toward equilibrium. Note that \( F = 1.0 \) was applied as a reference case. After the liner is installed, the tunnels are pressurized. Pressure levels from 4 to 8 MPa were applied. Thus, in this model, liner installation is assumed to precede pressurization. Results for an array of three parallel tunnels, 12 m diameter each and spaced at 2b, 35 m below surface, are presented (at different levels of internal pressure).

Internal pressure 8 MPa Fig. 1 shows that the region of tensile-stress (in units of kPa) reaches all the way to the ground surface. At this pressure level many yield zones (not shown) develop around the tunnels. However, no tension induced failure zones exist. The observed radial displacement of the tunnel wall did not exceed, the rather small level of 3.1 mm.

![Figure 1: Distribution of principal and tensile stresses (internal pressure 8 MPa, tunnel spacing of 2b). One region of tensile stress (extending to the surface) is enclosed by a single contour around the array of tunnels.](image-url)
One dimensional array of parallel tunnels (F=3.0 and F=10.0) The effect of changing the safety factor from 1 to 3 and then to 10 is described next. Using a safety factor of 3 showed that at 4 MPa, virtually no tension induced failure exist (plot not shown). In contrast, setting the internal pressure at 8 MPa produced many zones around the tunnels that exhibit yield tension (plot not shown), and the the maximum wall displacement increased to 8.74 mm. Note that further increase of internal pressure is expected to generate additional failure zones and crack propagation around the tunnels. This can lead to emergency situations. Note that a possible countermeasure against these effects is increase of the tunnel depth.

The maximum operating pressures in air storage reservoirs is limited by their characteristic level of tensile fracture and stresses at which faulting, or mechanical damage, may be induced in the reservoir, caprock and overburden. Tensile fracturing can occur when the fluid pressure within the excavated reservoir is increased above the minimum in situ stress [11]. From this point on a hydraulic or pneumatic fracture is generated followed by its propagation. The hydraulic fracture pressure provides an absolute limit to the operating reservoir pressure, as fracturing through the caprock, and gas leakage into overlying permeable formations, must be avoided. The above analysis of the arrays of three tunnels shows that they are expected to be mechanically stable under 4 to 8 MPa operating pressures [12]. The number of tunnels will depend of the needed energy capacity.

3 Energy storage capacity

The CAES capacity, i.e. the mechanical energy which may be obtained during expansion of the compressed gas, depends on the cavern or tunnel volume, initial and final gas pressure and conditions of its expansion. If during expansion the gas temperature remains constant and equal to that of the surrounding rock, then the dimensionless isothermal energy capacity factor can be expressed as:

\[ w = \ln \left( \frac{P_0}{P_f} \right) \]

where air is assumed to behave as an ideal gas in the 1 to 10 MPa pressure range, and the process temperature.

The adiabatic counterpart of eq. 1 is given by,

\[ w = \frac{1}{k-1} \left[ 1 - \left( \frac{P_0}{P_f} \right)^{1/(k-1)} \right] \]

where \( w = W/(P_0 V) \); \( W \) denotes the free energy or energy capacity of the air; \( P_0 \) and \( P_f \) - initial and final expansion pressure; \( V \) – volume of air; \( k = C_p / C_v \) - ratio of specific heats at fixed pressure and fixed volume.

The isothermal and adiabatic discharge conditions present the maximum and minimum levels of \( w \) available from a lossless expansion of an ideal gas from \( P_0 \) to \( P_f \). Table 1 shows data of \( w \) for different values of \( P_0 / P_f \).
Actual values of energy capacity are expected to exist between the isothermal and adiabatic extremes, and they depend on heat transfer between the gas and its surroundings and the rate of discharge. For example, if the volume of one CAES tunnel (diameter 12 m, length 100 m) is 11,310 m³, then setting the initial pressure at $P_o = 10$ MPa and final pressure at $P_f = 1$ MPa gives $(1.36-2.6) \times 10^8$ kJ, as the possible range for the energy capacity. Assuming a discharge time of 3 hours gives 12.6–24.1 MW as the power rating of one tunnel. If $P_o$ is changed to 8 MPa then the corresponding results are $(1.01-1.88) \times 10^8$ kJ and to 9.35–17.41 MW. The number of tunnels will depend of the needed energy capacity.

### 4 Air temperature and temperature gradients on the tunnel wall during charge and discharge

During charge and discharge, the air temperature inside the tunnel changes due to the change in pressure and heat transfer across the tunnel walls. It is assumed that: i) the air is an ideal gas; ii) uniform air temperature and pressure prevail across the tunnel volume; iii) the tunnel has a cylindrical shape, it is long and set deep enough so that end and surface effects can be neglected. Using these assumptions the evolution of air temperature may be described by the following equation:

$$\frac{dT}{d\tau} = \frac{T}{P} \left(1 - \frac{1}{k}\right) \frac{dP}{d\tau} + \frac{qS}{\rho c_p V}$$

where $T$ is absolute temperature of the tunnel air, $\tau$ - time, $P$ - absolute pressure, $k$ - ratio of specific heats of the air, $q$ - heat flux across the tunnel wall, $S$ - surface area of the tunnel wall, $\rho$, $c_p$ - density and specific heat at constant pressure of the air, $V$ - tunnel volume.

The value of $q$ may be found from solution of the unsteady conjugate heat transfer problem between the air and the surrounding rock [13].

Numerical solution of the problem provides the air temperature, and the temperature gradient in the surrounding rock, during charge and discharge. Calculated results for a cylindrical tunnel 12 m in diameter and 100 m long are presented in Figs. 2 and 3. Calculations for the charge phase were performed using: initial absolute pressure of 0.1 MPa and 1 MPa, and final pressure 8 MPa;
initial temperature of the surrounding rock +10°C; charge and discharge time 6 hours, and idle interval between the charge and discharge processes 6 hours. A linear increase of air pressure during the charge phase was assumed. Figs. 2 and 3 show a fast increase in air temperature during the initial phase of charging. This fast temperature rise may be explained by the assumed linear increase of the air pressure. If the initial pressure \( P_0 \) in the tunnel is sufficiently small, the ratio \( P/P_0 \) which determines increase in air temperature rises very fast at the initial charging stage. For example, if \( P_0 = 0.1 \text{ MPa} \) then after the first 12 min the pressure increases 3.5 times. Neglecting heat losses in the rock, an increase of the air temperature up to 131°C is obtained. If heat losses are accounted for the result is \( \approx 70°C \) (Fig. 2). Higher air temperature generates increased heat losses to the rock. This results in a temporary decrease of the air temperature. Further increase of the pressure leads to a slower rise of the air temperature (Fig. 2) or nearly stable temperature (Fig. 3). The temperatures at the end of the charge phase are 81°C and 23°C for initial pressure 0.1 MPa (Fig. 2) and 1 MPa (Fig. 3), respectively.

Figure 2: Air temperature and pressure vs. time during the charging and discharging phases (charging and discharging time 6 h; initial pressure 0.1 MPa).

Figure 3: Air temperature and pressure vs. time during the charging and discharging phases (charging and discharging time 6 h; initial pressure 1 MPa).
During the idle interval (6–12 h) the air temperature decreases slowly because of heat losses to the surrounding rock and slow pressure loss. During the discharge the air temperature falls due to the decrease in pressure and the continued heat flux to the rock. For an initial pressure of 0.1 MPa, and 1 MPa, the air temperature falls down to ~ -50°C (Fig. 2) and -7°C (Fig. 3) respectively. Upon completion of the discharge period the air temperature rises again following the heat flux from the warmer surrounding rock. A plot of the charge-idle-discharge cycle in the $P - T$ plane is shown in Fig. 4. Note that final point of the diagram (5) doesn't coincide with the initial point (1). This reflects the effect of the residual heat in the rock.

![Figure 4: A plot of the charge-idle-discharge cycle in the $P - T$ plane (initial pressure 0.1 MPa).](image)

Calculated temperature gradients in the rock at the tunnel wall are shown in Fig. 5. The curves reflect the features of the charge-discharge process described above. Peak gradients are ~-700 K/m for $P_0 = 0.1$ MPa and ~-50 K/m for $P_0 = 1$ MPa. These temperature gradients are caused by the rapid increase in air temperature during the charge phase and the low temperature during the final stage of discharge. The case of initial pressure 0.1 MPa is calculated in order to find the range of possible temperatures and gradients. In reality a minimal initial pressure should meet the characteristics of the used air turbines which must exceed the atmospheric pressure 0.1 MPa. Fig. 5 shows that the peak temperature gradients, for the case of initial pressure 1 MPa do not exceed 50 K/m. Nevertheless, these temperature gradients may cause substantial thermal stresses in the surrounding rock and lining materials.
Energy losses during charge – discharge cycle

Energy losses during a charge – discharge cycle arise due to heat flux from the heated air to the surrounding rock. The energy, transferred to the rock in one cycle may be expressed as:

\[ Q = \int_{0}^{t} S \lambda G \, dt \]  

where \( t \) is cycle time, \( \lambda \) - heat conductivity of the rock, \( G \) – temperature gradient in the rock at the tunnel wall, and \( S \) surface area where \( G \) exists.

The specific energy loss is defined as follows:

\[ \bar{Q} = \frac{Q}{P_{\text{max}} V} \]  

where \( Q \) denotes energy, transferred to the rock in a single cycle; \( P_{\text{max}} V \) is the peak free energy of the compressed air at the point where the pressure reaches maximum.

Specific energy losses were calculated for three tunnel diameters (6, 9 and 12 m) and three charge periods (3, 6 and 12 h), using the numerical model developed in [13]. Fig. 6 shows specific energy losses as function of number of cycles for three charge periods. The specific losses decrease with an increase in the number of cycles. This may be explained by the accumulation of heat in the surrounding rock and subsequent decrease of the temperature gradient in the following cycles.
Figure 6: Specific energy losses vs. number of charge-discharge cycles (tunnel diameter 6 m; discharge time 10 hours).

Fig. 7 shows a plot of the specific losses vs. the charge time. Increase of the charge time decreases the energy losses. In this context the energy losses increase with increase of the tunnel diameter. This reflects the increase in the temperature gradient at the wall and the surface area of the tunnel that results from increasing the tunnel diameter.

Figure 7: Specific energy losses during a charge-discharge cycle vs. charging time (discharging time 10h; after 70 days of CAES operation).

6 Summary and conclusion

Underground CAES systems are technically feasible and potentially attractive for future peak and intermediate load power generation. The analysis presented here provides an example of the expected effect of applied loads on the stability of underground array of tunnels as part of a CAES system. Estimates of tunnel stability in hard rock have been obtained for different array spacing. The limiting
value for rock fracture can be avoided if the tunnel excavation depth is sufficiently large. At 100 m (given $\sigma_T$) a lower safety factor applies.

The capacity of a CAES facility, i.e. the mechanical energy which may be obtained during expansion of the compressed air, is considered. This capacity depends on the cavern volume, initial and final air pressure and the conditions governing its expansion. One CAES tunnel (12 m diameter and 100 m long) operating at initial pressure of 8 MPa and final pressure 1 MPa provides up to $1.88 \times 10^8$ kJ of stored energy. If a discharge time of 3 hours applies, then the maximum theoretical power rating of one tunnel is 17.41 MW.

Dependence of specific energy losses on the charge time was estimated. Increase of the charge time decreases the energy losses. If a charge time of 12 hours applies, then the specific energy losses do not exceed 20%. Decreasing the time to 3 hours increases the specific energy losses to 32–33%. The energy losses increase with increase of the tunnel diameter and decrease with an increase in the number of cycles.

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References


