Journal of Rock Mechanics and Geotechnical Engineering 8 (2016) 314–328

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Design issues for compressed air energy storage in sealed underground cavities

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A R T I C L E I N F O

Article history:
Received 2 June 2015
Received in revised form
22 September 2015
Accepted 24 September 2015
Available online 28 October 2015

Keywords:
Compressed air energy storage (CAES)
Tunnels
Lining
Concrete plug
Feasibility assessment

A B S T R A C T

Compressed air energy storage (CAES) systems represent a new technology for storing very large amount of energy. A peculiarity of the systems is that gas must be stored under a high pressure ($p = 10–30$ MPa). A lined rock cavern (LRC) in the form of a tunnel or shaft can be used within this pressure range. The rock mass surrounding the opening resists the internal pressure and the lining ensures gas tightness. The present paper investigates the key aspects of technical feasibility of shallow LRC tunnels or shafts under a wide range of geotechnical conditions. Results show that the safety with respect to uplift failure of the rock mass is a necessary but not a sufficient condition for assessing feasibility. The deformation of the rock mass should also be kept sufficiently small to preserve the integrity of the lining and, especially, its tightness. If the rock is not sufficiently stiff, buckling or fatigue failure of the steel lining becomes more decisive when evaluating the feasible operating air pressure. The design of the concrete plug that seals the compressed air stored in the container is another demanding task. Numerical analyses indicate that in most cases, the stability of the rock mass under the plug loading is not a decisive factor for plug design.

1. Introduction

Very large amount of energy can be stored either with pumped hydroelectric storage (PHS) reservoirs or with compressed air energy storage (CAES) systems. PHS technology is commonly used and there are several examples in operation, while for CAES only two commercial projects have been undertaken in salt rock (Crotogino et al., 2001; Gardner and Haynes, 2007), as well as one demonstration project (Mansson and Marion, 2003) and one verification project in granite (Stille et al., 1994).

CAES systems have the peculiarity that gas must be stored under a high pressure ($p = 10–30$ MPa) in order to achieve greater efficiencies during energy recovery (withdrawal stage). Lined and unlined tunnels, shafts and caverns can all be used within this pressure range. The rock mass surrounding the opening resists the internal pressure while the lining or the natural hydraulic and geological conditions ensure gas tightness (Kovári, 1993). A lined rock cavern (LRC) is the most attractive option and the one most investigated over the past 20 years due to its wider application field, and there is no requirement for particular hydrogeological conditions or great depths of cover (Kovári, 1993).

From a geotechnical and structural point of view, the key factors to be considered in a feasibility assessment of CAES in lined cavities are: (1) uplift failure of the overlying rock up to the surface; (2) failure and loss of tightness of the sealing membrane; and (3) shearing of the plug closing the cavern. The loss of tightness of the cavity not only decreases the efficiency of the system, but also may impair stability (high air pressures within the overlying rock mass increase uplift risk). The lining concept most investigated for underground CAES is a composite structure consisting of an inner thin steel shell and an outer reinforced concrete shell (see Fig. 1). In this case, the sealing membrane is the thin steel shell. It may fail due to the bending that occurs when it is squeezed into cracks in the outer concrete lining, buckling during depressurization, the tensile stress developing during cavity expansion or the fatigue induced by cyclical loading (Damjanac et al., 2002; Okuno et al., 2009).

However, few works have analysed these aspects, and in most cases only for site-specific geotechnical conditions. Recent analyses of the uplift problem include those of Kim et al. (2012), Perazzelli et al. (2014) and Tunsakul et al. (2014). Kim et al. (2012) suggested a limit equilibrium model assuming that the full shearing resistances of the rock mass act along the vertical slip surfaces. This assumption is uncertain in view of the tensile stress field developing

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2015.09.006

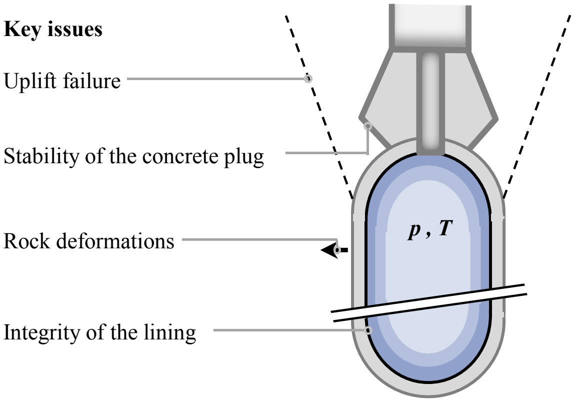

Fig. 1. Key design issues for a lined CAES rock cavity.

around the expanding cavity. Perazzelli et al. (2014) performed small and large strain numerical analyses of a continuum rock mass model and showed that the deformations at failure are very large in the case of weak rocks, thus necessitating a geometrically nonlinear formulation in order to obtain the ultimate uplift pressure. Tunsakul et al. (2014) developed a numerical method based on the element-free Galerkin (EFG) method with a cohesive crack model to simulate the fracture propagation patterns in a continuum medium around the pressurised tunnel; the authors found a qualitative agreement between physical model tests and numerical results and they emphasised that the in situ stress ratio has a strong influence on both the crack initiation location and the propagation path.

Analysis of the rock mass deformations in pressurised lined cavities can be found in Stille et al. (1994), Sofregaz US Inc. and LRC (1999), Brandshaug et al. (2001), Damjanac et al. (2002), Johansson (2003), and Okuno et al. (2009). Stille el al. (1994) and Johansson (2003) presented monitoring results from in situ tests in the Grängesberg Pilot Plant (a 9 m high shaft of 4.4 m in diameter, 50 m deep in granite). Okuno et al. (2009) presented the results of in situ tests at the Gas Storage Pilot Plant in the Kamioka mine (a 400 m deep, 6 m in diameter tunnel in sedimentary rocks). Both works showed that the cavern diameter increases with the loading cycles. Sofregaz US Inc. and LRC (1999), Brandshaug et al. (2001) and Damjanac et al. (2002) investigated the rock deformations for the Grängesberg Pilot Plant and for the Halmstad Demonstration Plant (a 50 m high cavern with 37 m in diameter, 115 m deep in granite, pressurised at 20 MPa) by numerical stress analysis of continuum rock mass models. In these studies, the rock mass is taken as a homogeneous, continuous, linearly elastic-perfectly plastic, no-tension material ($\sigma_t = 0$) obeying the Mohr–Coulomb yield criterion, and the effect of the cycling loading is not investigated. Damjanac et al. (2002) also performed numerical stress analysis of discontinuum rock mass models for the Halmstad Demonstration Plant considering the cycling loading. These analyses indicate a small increase in the magnitude of the rock mass displacements with the cycles.

Buckling and fatigue failures of the steel lining in CAES and gas storage caverns were investigated in very few works. Results of buckling analysis were presented by Okuno et al. (2009), but the computational model adopted in this work remains unclear. Verifications of fatigue can be found in Damjanac et al. (2002).

Concrete plug stability has been investigated mostly in the context of PHS systems. Auld (1983) and Ilyushin (1988) described different types of underground plugs, analysed the factors to be considered in design, and suggested a simple design formula addressing the possible failure modes in the plug, in the rock mass or at the interface – but without analysing the stability of the rock mass explicitly (the equation suggested considers the bearing capacity of the rock as an input parameter). Hökmark (1998) evaluated the stability of the rock around the concrete plug by introducing a safety factor based on an elastically computed stress field and the Mohr–Coulomb failure criterion. Park et al. (2001) performed a numerical investigation of the mechano-hydraulic behaviour of concrete plugs taking a fixed air pressure and assumed elastic behaviour for the plug concrete. They also considered the elastic-perfectly plastic behaviour according to the Mohr–Coulomb failure criterion for the rock, and elastic-perfectly plastic Mohr–Coulomb behaviour for the rock–plug interface. Their computations showed the influence of several factors (e.g. the shape, depth and in situ horizontal stress coefficient K_0) on stresses and displacements in the rock mass and the plug.

Studies on the stability of concrete plugs in CAES systems are to be found in Song and Ryu (2012) and in Pedretti et al. (2013). The approach of Song and Ryu (2012) is similar to that of Hökmark (1998). Pedretti et al. (2013) performed numerical stress analyses on the plug of a planned CAES test plant in Switzerland and evaluated the safety margin against failure by iteratively reducing the strength parameters of the rock mass.

The present paper investigates the above-mentioned design problems for underground CAES by means of numerical stress analyses, taking tunnels and shafts above the water table of 4 m in diameter with a thin steel shell under a wide range of geotechnical conditions. As in Sofregaz US Inc. and LRC (1999), Brandshaug et al. (2001) and Damjanac et al. (2002), we consider the rock mass as a homogeneous, continuous, linearly elastic-perfectly plastic, no-tension material ($\sigma_t = 0$), obeying the Mohr–Coulomb yield criterion.

We show in detail how the stress field in the surrounding rock and the displacements change during the pressurisation of a CAES cavity and we define an uplift safety criterion based on the extension of the tensile failed zone above the cavity (Section 2).

Rock mass deformations at the walls of the cavity are shown for a wide range of geotechnical conditions and a maximum operating pressure of 20 MPa (Section 3). These values are computed assuming a monotonic increasing of the air pressure. The behaviour of the adopted rock mass model in the case of loading cycles is discussed by a computational example (Section 4).

We show the stress and strain in the steel lining during pressurisation and depressurisation of the cavity and we clarify why buckling and fatigue failures can occur (Section 4). Verifications of these failures are presented (Section 4). Critical buckling loads are here computed by means of nonlinear buckling analysis, while critical stress ranges are taken from the literature.

We analyse the interaction between a site-specific rock mass and plugs of different geometries (Section 5) by means of a computational model similar to the one of Park et al. (2001). The stability of the rock around the concrete plug is investigated evaluating the relation between the pressure in the cavity and the displacement of a control point of the plug.

2. Uplift

2.1. Computational model

Uplift failure is investigated by numerical stress analyses using plane strain and axisymmetric models for the tunnels and shafts, respectively. Fig. 2 shows the computational domains and boundary conditions. The analyses were performed using the finite difference code FLAC (Itasca, 2001) under the assumption of small strains. The effect of this assumption on the assessment of the limit pressure will be discussed in Section 2.3.

The rock mass is considered to be a linearly elastic-perfectly plastic, no-tension material obeying the Mohr–Coulomb yield criterion and a non-associated flow rule with dilatancy angle equal to zero. The lining is not introduced into the numerical model because