International Journal of Rock Mechanics & Mining Sciences 83 (2016) 149–161

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Coupled thermal-hydrological-mechanical behavior of rock mass surrounding a high-temperature thermal energy storage cavern at shallow depth

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ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
6 November 2015
Accepted 8 January 2016
Available online 15 January 2016

Keywords:
Thermal-hydrological-mechanical coupled analysis
Thermal energy storage
Rock cavern
TOUGH-FLAC simulator

ABSTRACT

We numerically model the thermal-hydrological-mechanical (THM) processes within the rock mass surrounding a cavern used for thermal energy storage (TES). We consider a cylindrical rock cavern with a height of 50 m and a radius of 10 m storing thermal energy of 350 °C as a conceptual TES model, and simulate its operation for thirty years. At first, the insulator performance are not considered for the purpose of investigating the possible coupled THM behavior of the surrounding rock mass; then, the effects of an insulator are examined for different insulator thicknesses. The key concerns are hydrothermal multiphase flow and heat transport in the rock mass around the thermal storage cavern, the effect of evaporation of rock mass, thermal impact on near the ground surface and the mechanical behavior of the surrounding rock mass. It is shown that the rock temperature around the cavern rapidly increases in the early stage and, consequently, evaporation of groundwater occurs, raising the fluid pressure. However, evaporation and multiphase flow does not have a significant effect on the heat transfer and mechanical behavior in spite of the high-temperature (350 °C) heat source. The simulations showed that large-scale heat flow around a cavern is expected to be conduction-dominated for a reasonable value of rock mass permeability. Thermal expansion as a result of the heating of the rock mass from the storage cavern leads to a ground surface uplift on the order of a few centimeters, and to the development of tensile stress above the storage cavern, increasing the potentials for shear and tensile failures after a few years of the operation. Finally, the analysis shows that high tangential stress in proximity of the storage cavern can some shear failure and local damage, although large rock wall failure could likely be controlled with appropriate insulators and reinforcement.

1. Introduction

The effective management of existing energy resources is as important as the development of new energy sources. Energy storage systems make it possible to use renewable energy sources for heating and cooling, in addition to power generation when required, by remedying the problems resulting from their intermittent and variable characteristics. An energy storage system can balance the energy demand and supply, thus improving the overall efficiency and flexibility of energy systems.

Thermal energy storage (TES) is an energy storage technology, which stores thermal resources, such as solar energy, geothermal energy and industrial waste heat, without converting the thermal resource into different forms of energy. In general, above-ground TES has been commercially used in concentrating solar power (CSP) plants, but little attention has been paid to the applicability of a rock cavern to large-scale high-temperature thermal energy storage, except for a few studies.[1,2] As opposed to aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) which use the underground environment as a storage medium, cavern thermal energy storage (CTES) which utilizes a cavern as a thermal energy storage tank, is technically feasible even under poor geological conditions, and it can be customized for various purposes and storage temperatures. Moreover, the increasing needs for large-scale high-temperature TES for industrial purposes can make CTES superior to above-ground TES systems. Underground spaces can offer a viable and economical alternative for large-scale storage because the surrounding rock functions as a heat insulator due to its low thermal conductivity.[1] A numerical study of the heat loss characteristics of rock cavern TES and above-

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http://dx.doi.org/10.1016/j.ijrmms.2016.01.007
1365-1609/

ground TES[2] showed that the heat loss rate of the rock cavern TES approached a certain value with time, whereas that of the above-ground TES system remained constant over the operation period. It was also observed that, in terms of the long-term operation period, the heat loss of the rock cavern TES system exhibited less sensitivity and less dependent behaviors related to the insulator performance compared with those of the above-ground TES system, which suggests that regarding the thermal insulator, the initial construction cost and the risk of possible failure according to the cyclic thermal load can be reduced in the underground space. However, at present, only limited applications of CTES are available because of the high investment costs and the environmental impacts. An exception is the Lyckebo rock cavern used for storing hot water of 40–90 °C for a heating system in Sweden, which has been operating since 1983.[3] In the case of the CTES for high temperatures above 100 °C, feasibility studies on the technologies for high-temperature and large-scale rock caverns have been conducted by the Korea Institute of Geosciences and Mineral Resources (KIGAM) from 2012 to 2014.[4–6]

The estimation and control of the thermal, hydrological and mechanical behaviors of storage caverns and the surrounding rock mass is one of the key issues that should be addressed in the development of technologies for CTES. The repeated thermal charging and discharging could potentially cause temperature changes in the surface water and groundwater and consequent effects on vegetation and the biosphere. Thermally induced mechanical instability of the storage caverns and the surrounding rock mass as well as the long-term characteristics of hydro-thermal multiphase flow and heat transport are also important issues to be investigated.

In terms of the simulation of coupled thermal-hydrological-mechanical (THM) phenomena in geological media, considerable efforts have been made in the field of rock and soil mechanics and oil and gas reservoir engineering. As promoted by the multi-disciplinary projects such as geological nuclear waste disposal, geothermal energy development and underground CO_2 sequestration, the importance of the development of a reliable simulation code for THM process is increasingly recognized.[7] A number of academic and commercial codes have been developed, including FRACON,[8] FLAC,[9] VISAGE™,[10] TOUGH-FLAC,[11] ABAQUS-COORES,[12] GeoSys/Rockflow.[13]

The present study is aimed at examining coupled THM behavior in the rock mass around a high-temperature thermal energy storage cavern using TOUGH-FLAC simulator. The multiphase ground water flow and heat transfer in the rock mass surrounding a rock cavern storing thermal energy of 350 °C were analyzed using the TOUGH2-EOS4 module, which can consider water/air mixtures with vapor pressure-lowering effects.[14] The coupled processes between the hydro-thermal flow and the mechanical behavior were predicted by FLAC3D.[15]

2. Numerical model

2.1. TOUGH-FLAC simulator

The TOUGH-FLAC simulator was initially developed[9] as pragmatic approach for modeling of THM processes in porous and fractured geological media. It is based on the linking of two existing codes, TOUGH2 and FLAC3D. The TOUGH2 code is a well-established code for multi-dimensional fluid and heat flows of multiphase, multicomponent fluid mixtures, whereas FLAC3D is a widely used commercial code for rock and soil mechanics with thermo-mechanical and hydro-mechanical interactions. The respective merits of both codes have allowed the TOUGH-FLAC simulator to be widely applied to many THM problems in geological media, such as nuclear waste disposal, CO2 injection, geothermal reservoir engineering and energy storage in rock caverns.[16–19] In this technique, TOUGH2 and FLAC3D are executed for a compatible numerical mesh, and the calculation results are transferred mutually and repeatedly through external coupling modules. Multiphase pressures and temperatures calculated by the TOUGH2 code are transferred to FLAC3D, and then a quasi-static mechanical analysis is conducted with FLAC3D at the TOUGH2 Newton iteration level. When a quasi-static state is reached, FLAC3D provides stress and strain states of each element to TOUGH2 and the changes in porosity, intrinsic permeability and capillary pressure are updated for the next calculation in TOUGH2. The procedures to link the two codes are provided in detail in Ref. 11 In TOUGH-FLAC simulator, the pressures and temperatures are only calculated by the TOUGH2, and the hydro-mechanical and thermo-mechanical couplings are implemented in the mechanical analysis by FLAC3D.

The general formulation of the constitutive equation for thermo-hydro-mechanical interaction used in FLAC3D is expressed as[15]:

$$\breve{\sigma}_{ij} + \alpha\frac{\partial P}{\partial t}\delta_{ij} = H(\sigma_{ij},\ \xi_{ij} - \xi_{ij}^{T},\ k) \tag{1}$$

where $\breve{\sigma}_{ij}$ is the corotational stress rate, α is the Biot coefficient, P is the pore-pressure and δ_{ij} is the Kronecker delta. H is the functional form of the constitutive law, σ_{ij} is total stress, ξ_{ij} and ξ_{ij}^{T} are the mechanical and thermal strain rates and k is a history parameter that takes into account the history of loading. The corotational stress-rate is equal to the material derivative of the stress as it would appear to an observer in a frame of reference attached to the material point and rotating with it at an angular velocity equal to the instantons value of the angular velocity of the material.[15]

The quantity on the left-hand side of Eq. (1) is Biot's effective stress; the pore pressure is positive in compression, whereas the stress is negative in compression in FLAC3D; effective stresses are used in all of elastic and plastic models.

The thermo-mechanical interaction is accomplished by reformulating the incremental stress-strain relations to add the portion due to temperature change to the total strain increment. Because free thermal expansion results in no angular distortion in an isotropic material, the shearing-strain increments are unaffected. The thermal strain rates associated with free expansion are expressed as follows:

$$\xi_{ij}^{T} = \alpha_t\frac{\partial T}{\partial t}\delta_{ij} \tag{2}$$

where α_t is the linear thermal expansion coefficient and T is the temperature.

When using an isotropic material, the hydraulic properties such as porosity and permeability can be expressed as a function of volumetric strain or mean effective stress.[11,20] The functions of porosity and permeability used in the present study are the empirical exponential models suggested in [21] and slightly modified and applied in[11]:

$$\phi = \phi_r + (\phi_0 - \phi_r)\exp(a \times \sigma'_M) \tag{3}$$

where ϕ is porosity, ϕ_0 is porosity at zero stress, ϕ_r is residual porosity at high stress, σ'_M is mean effective stress and the exponent a should be experimentally determined.

$$k = k_0\exp\left[c\ \times (\phi/\phi_0 - 1)\right] \tag{4}$$

where k is permeability, k_0 is permeability at zero stress and the exponent c should be experimentally determined.

The capillary pressure is modified with permeability and porosity according to the function by Leverett[22]: