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In situ measurements of thermally loaded rock and evaluation of an experiment with a 3D numerical model

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1. Introduction

Efficient and inexpensive energy storage systems undoubtedly play a significant role in the modern western-based sustainable energy strategy. The thermal energy storage, defined as the temporary storage of thermal energy at high or low temperatures,[1] appears to be the most appropriate method for correcting the mismatch sometimes occurring between energy supply and demand.[2] A comparison of several technologies for subsurface storage, including thermal, is given in.[3] The thermo-mechanical response of the rock massif subjected to temperatures of around 100 °C is also investigated in the context of high level radioactive waste disposal. Different types of in situ heater tests were published from the KAERI Underground Research Tunnel, the Stripa mine and Aspö in Sweden, the Grimsel Test Site and the Underground Research Laboratory of AECL.[4–8]

An in-situ experiment[9–11] was set up to evaluate the effects of cyclic heating and cooling on the thermo-hydro-mechanical characteristics of the granitic rock. The main objective of the experiment is to confirm or deny potential changes in the physical parameters of granitic rocks due to a thermal load of a maximum temperature of 95 °C. Careful attention is also paid to changes in the groundwater flow and the deformation of the rock massif caused by the cyclic heating. These are the key parameters necessary for the safe design and construction of underground structures intended for the storage of thermal energy or for radioactive waste disposal.

Numerical modelling was used to help plan, control, and evaluate the experiment, providing more knowledge from the data and a more efficient operation of the experiment. The presented thermal-stress model follows a previous simple thermal model[12] and precedes the authors' work aimed at the inclusion of fractures.[13]

Model analysis of a different type is included in some of the above-cited papers on experiments, referenced to work in the KAERI tunnel test, or processed and published separately (FEBEX test by[14]) – from analytical solutions with simplified geometry (Stripa) to 3D, non-linear, and/or coupled numerical simulations. Typically, simpler models are used for planning and dimensioning experiments and more complex models for evaluation (back analysis) of measured data. Other relevant works with complex models in the field of nuclear waste disposal include e.g.[15] with a comparison of several simulation codes on the Kamaishi mine heater test (3D or 2D axisymmetric), and[16] with a 3D elasto-plastic model of thermal induced rock damage in the Pillar Stability Experiment. Work in the field of heat storage is focussed on e.g. the theoretical optimization of equipment configuration or middle-scale laboratory experiments with rock-water interaction (1D model[17]).

Although the thermal models are generally believed to capture measurements well, for each particular study it is necessary to check the understanding of the process (e.g. exclusion of water advection heat transport) and the correspondence between laboratory determined and field-scale parameters. In the case of stress/deformation models, the main issues include nonlinearities (stress/strain curve, damage), inhomogeneities (in particular fractures), and the scale effect. Therefore, the choice and validation of the appropriate model is a challenge for each larger-scale in-situ experiment.

This contribution is limited to the following processes and issues

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related to the experiment (based on the suitable data): showing the relevance of the borehole stress measurement methods to capturing the stress and deformation phenomena (including the issue of deformation modulus determination); overall fitting of the numerical stress model to the measurements (linear elasticity with thermal expansion, considered as an appropriate starting step of the evaluation) by using an effective elastic modulus value; checking the mechanical process "reversibility" (elastic behaviour); verification of laboratory-determined data to a field scale (both thermal and mechanical); and demonstration of energy balance postprocessing for an evaluation of the storage/retrieval efficiency. Own procedures adapted for comparing the data for the model and the experiment are also introduced.

2. Experiment site, instrumentation and measurement methods

2.1. Experiment site

Granitic rock (tonalite) has recently been studied as a host rock of underground thermal energy storage in the Josef Underground Research Laboratory (the Josef URL), located in Central Bohemia. The Josef URL is situated in the exploration gallery of the Psí hory gold-bearing ore district[18] (Fig. 1). The rock massif is built by faulted/fractured granitic rocks of Sázava pluton, which belongs to the Central Bohemian Plutonic Complex. It is penetrated by dense swarms of quartz gold-bearing veinlets and deformation fissures filled with calcite. The crystallization age of the Sázava tonalite, determined by the conventional zircon U–Pb method, is 354.1 ± 3.5 Ma.[19] The Sázava pluton intruded into the low metamorphosed rocks of the neoproterozoic Teplá-Barrandien unit (a volcano-sedimentary sequence of the Jílové zone).[20] The experiment is located approximately 1.5 km from the entrance and is covered by an approximately 120 m thick layer of overburden.

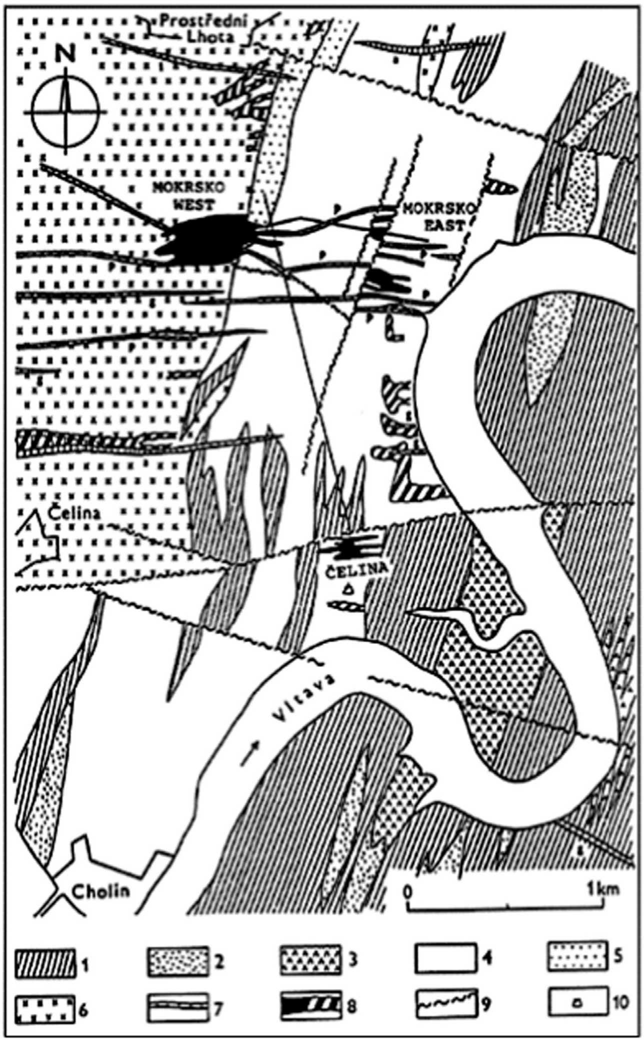

Fig. 1. Geological map of the Josef URL after Morávek.[27] 1 – alkaline and intermediate metavolcanites, 2 – silicic metavolcanites, 3 – albitic granites, 4 – volcano-sedimentary formation, 5 – shales and wackes, 6 – tonalite, 7 – dyke rock, 8 – gold-bearing ore mineralization, 9 – faults, 10 – adit.

2.2. Experiment regime and instrumentation

The cyclic thermal load of rocks is simulated by repeated heating and cooling from a large-diameter borehole. A short, two-week "preheating" cycle preceded the main experiment to test the instrumentation of the experiment. The duration of the first main cycle of heating-cooling lasted eleven months, of which the heating phase to achieve as high a thermal loading of the rock as possible lasted approximately nine months. In practice, it is of course not possible to reach the maximal rock loading (the steady state time of the heating process – in terms of measurement precision – has been estimated by the numerical model to be approximately ten years). The second cycle lasted five months (three months of heating and two months of cooling). The third cycle lasted approximately one month (sixteen days of heating and seven days of cooling). Additional short cycles followed to simulate the practical working regime of the system, which should cover energy production peaks. The heating/cooling experiment was switched off at the end of 2014.

2.2.1. Heater/cooler unit

The heater/cooler unit consists of an electric boiler, a heat pump, a tank, circulating pumps and PEX-AL-PEX tubes. The tubes are coiled in a horizontal borehole with a diameter of 0.85 m (the so-called "heating borehole") from a depth of 1.7–2.2 m, behind the tunnel face. The contact between the tubes and the rock is provided by a geo-polymer layer. The first 1.7 m of the heating borehole is tightly insulated against heat exchange by bags filled with cellular glass insulation (FOAMGLAS). The scheme of the heater/cooler installation is shown in Fig. 2. The temperature of the water, which is used as the heat transport medium, switches between 10 °C (for the cooling phase) and 95 °C (for the heating phase); it is set to the desired value and then controlled (within a certain range) by the boiler automation thermostat module.

2.2.2. Measurement instrumentation, stress measurement

The experiment is aimed to capture complex processes of the heat transport, the induced stress (or the deformation) and the groundwater flow, using a variety of sensors with data recording. The complex monitoring description lies beyond the scope of this paper.

The rock massif is monitored in roughly 10 m surroundings of the heating borehole. Monitoring boreholes (from 0.4 m to 10.5 m long, with about 130 m total length) are used for an application of non-destructive measurement methods, particularly for the monitoring of thermal, geotechnical, hydraulic, and microseismic quantities (Fig. 3). The data collection has been provided by the online transfer to the local server.

Temperature has been measured by Pt1000A resistance thermometer. Geotechnical and hydraulic monitoring covers stress and strain changes in rock matrix (by stress meters, strain gages), groundwater pressure (by piezometers) and displacements induced along fractures (by micro and 3D crackmeters). We focus on stress changes in the rock matrix, due to their large extent.

In-situ stress changes induced by thermal loading were measured by vibrating wire stress meters (Geokon, Model 4300BX Hard Rock). Each stress meter is equipped with a thermistor, which enables the temperature to be measured simultaneously. The temperature value is used for thermal correction, avoiding the influence of temperature changes