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Numerical simulation of thermal–mechanical processes observed at the Drift-Scale Heater Test at Yucca Mountain, Nevada, USA

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Abstract

Results from the 4-year-long heating phase of the Drift-Scale Heater Test at the Exploratory Studies Facility at Yucca Mountain, Nevada, USA, provide a basis to evaluate conceptual and numerical models used to simulate thermal–mechanical coupled processes expected to occur at the potential geologic repository at Yucca Mountain. The objectives of the evaluation were to investigate coupled processes associated with (i) temperature effects on mechanical deformation and (ii) effect of thermal–mechanical processes on rock-mass permeability. Two-dimensional numerical models were built to perform the thermal–mechanical analyses. Thermal–mechanical simulations were predicated on a continuum representation of a deformation-permeability relationship based on fracture normal stress. The estimated trend of permeability responses using a normal stress-based deformation-permeability relationship compared reasonably to that measured in the coupled thermal–mechanical analyses.

Keywords: Thermal–mechanical process; Thermally induced mechanical deformation; Fracture normal stress; Fracture permeability; Fracture closure; Rock-mass permeability; Heater Test

1. Introduction

An understanding of, and the ability to predict, the thermal–hydrologic–mechanical–chemical processes are the major challenges to performance and safety assessment of a nuclear waste geologic repository in fracture rocks. The nuclear waste represents a heat source which is active over an extended period of time. This thermal input induces buoyant fluid flow and rock expansion [1]. The thermally induced rock expansion may cause closure of fractures in some portion of the rock mass and opening of fractures in other portion of the rock mass. Fracture closure or opening will affect fracture permeability. The thermal load may also have an effect on long-term degradation of rock material and cause changes in chemical sorption and retardation capability.

The Drift-Scale Heater Test at the Exploratory Studies Facility at Yucca Mountain, Nevada, is a planned 8-year-long in situ heater test, with 4 years of heating followed by 4 years of cooling. The test has been monitored using a vast array of instrumentation to measure, or infer, changes in temperature, saturation, displacement, and chemistry. The 4-year heating phase was initiated in December 1997 and completed in January 2002. Results from the Drift-Scale Heater Test contribute to the basis for evaluating the capability of coupled-processes codes to simulate thermal–mechanical–hydrological–chemical processes in partially saturated fractured rock. Thermal–mechanical coupled processes and their effects on fracture permeability are analyzed in this paper.

For the modeling study presented here, thermally induced mechanical deformation in the rock was

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simulated for the 4-year heating phase of the Drift-Scale Heater Test. This paper presents the modeling results of (i) temperature effects on mechanical deformation and (ii) effect of thermal–mechanical processes on rock-mass permeability and their comparison with the measured data. These modeling studies are an important part of the process of assessing and developing confidence to independently evaluate the safety case for the potential geologic repository at Yucca Mountain. The modeling analyses reported in this paper were conducted as part of coupled-processes comparative studies of the DECOVALEX III program.

2. Drift-Scale Heater Test description

The Drift-Scale Heater Test is located in the Topopah Spring middle nonlithophysal (Tptpmn) unit, within the horizon of the potential repository at Yucca Mountain [2]. The Tptpmn unit is approximately 30–40 m thick at the location of the Drift-Scale Heater Test, overlain by the Topopah Spring upper lithophysal (Tptpul) unit and underlain by the Topopah Spring lower lithophysal (Tptpll) unit. The Drift-Scale Heater Test block was characterized prior to the onset of heating. Onsite characterization of the local geology and in situ hydrology was supplemented with laboratory tests of thermal–hydrological and thermal–mechanical properties.

A plan-view schematic of the relative placement of the heated drift to the observation drift is shown in Fig. 1. The 5-m-diameter, 47.5-m-long heated drift is closed at the east end by a thermal bulkhead. Approximately 12 m of the west end of the heated drift is lined with cast-in-place concrete ground support. Mesh and rock bolts provide support for the remainder of the drift. Concrete inverts were placed along the entire floor of the heated drift to provide a flat surface. Thermal sources consist of 9 canister heaters, placed end to end on the floor of the heated drift, and 50 wing heaters (25 on either side), emplaced in horizontal boreholes drilled perpendicular into the sidewalls of the heated drift about 0.25 m below the springline. The wing heaters are spaced 1.83 m apart. Each wing heater has two segments, both 4.4 m long, separated by 0.66 m with a larger power output to the outer segment [3]. The inner wing heater segment is separated from the heated drift wall by 1.67 m.

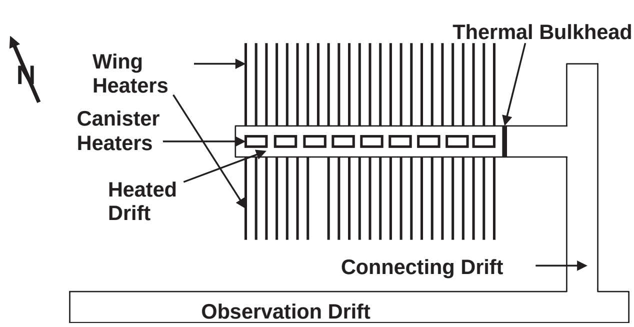

Fig. 1. Plan-view schematic of the Drift-Scale Heater Test.

3. Conceptual models

The approach used to simulate thermal–mechanical coupled processes in the fractured rock at the Drift-Scale Heater Test was to first determine the effects of temperature on deformation of the rock, then to determine the change in permeability in response to deformation. In deformable rocks, changes in matrix permeabilities are likely to be small, consequently contributions of the rock matrix deformation-induced permeability change to the overall permeability are likely to be small. With this understanding, only the effects of mechanically induced fracture deformation on the rock-mass permeability were considered and a continuum model was used to represent fracture permeability. The thermal–mechanical analyses were conducted in two dimensions based on a single continuum model using the FLAC code [4]. Following are descriptions of thermal–mechanical conceptualization.

3.1. Continuum thermal–mechanical model

FLAC uses a time-marching method to solve a set of algebraic equations of motion and constitutive relations. In a continuous solid body, the equation of motion can be generalized as follows:

$$\rho \frac{\partial \dot{u}_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i, \quad (1)$$

where ρ is the mass density, t is time, $\dot{u}_i$ are components of the velocity vector, x_j are components of the coordinate vector, σ_{ij} are components of the stress tensor, g_i are components of the gravitational acceleration, and indices i and j are components in a Cartesian coordinate system.

The strain rate associated with the equation of motion may be derived from the velocity gradient using the following:

$$\dot{e}_{ij} = \frac{1}{2}\left[\frac{\partial \dot{u}_i}{\partial x_j} + \frac{\partial \dot{u}_j}{\partial x_i}\right], \quad (2)$$

where $\dot{e}_{ij}$ are strain-rate components. With the strain-rate known, the constitutive relation that describes the stress-strain relationship of a deformable body for an isotropic elastic material can be represented by

$$\Delta\sigma_{ij} = \{\delta_{ij}[K - \tfrac{2}{3}G]\dot{e}_{kk} + 2G\dot{e}_{ij}\}\Delta t, \quad (3)$$