Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Comparative Validation of the Discontinuum-based Numerical Simulator for Modelling the Coupled Hydro-Mechanical Processes of Near-Field Rock

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Keywords : Numerical simulation, Discontinuum, Coupled processes, Multi-barrier system, Geological disposal

1. Introduction

Near-field rock, surrounding the engineered barrier system within the deep geological repository of high-level radioactive waste disposal, contains numerous discontinuities including natural joints and excavation-induced fractures. Under the disposal conditions involving the high temperature, high pressure and groundwater inflow, the discontinuous rock exhibits the complicated elasto-plastic deformation as a result of the coupled thermo-hydro-mechanical (THM) processes.

The TOUGH-3DEC simulator has been developed to describe the THM processes of discontinuous rock and validated by analytic benchmark models and experimental models as part of a DECOVALEX-2023 (DEvelopment of COupled models and their VALidation against EXperiments-2023) project [1]. In the experimental analysis, the synthetic specimen including single fracture is modelled, and then rotatable polyaxial stress conditions are applied to demonstrate the true-triaxial stress condition of disposal conditions. Additionally, flow tests are simulated to validate the permeability changes under the changing polyaxial stress. The mechanical and hydraulic responses from the experimental analyses are compared to the simulation results obtained from the other continuum-based numerical tools in the DECOVALEX-2023 project.

2. Methods and Results

2.1 Numerical Tools: TOUGH-3DEC simulator

TOUGH-3DEC simulator links TOUGH2, the integral finite difference method (IFDM) for thermo-hydraulic analysis of geological media [2], and 3DEC, the block-based distinct element method (DEM) for mechanical analysis of discontinuous rock mass [3], using the sequential coupling algorithm. This allows TOUGH-3DEC to describe the coupled THM processes of the discontinuum model [4]. TOUGH-3DEC simulator can reflect the stress-dependent change of the hydraulic properties by updating the hydraulic aperture as a result of mechanical equilibrium in every timestep (Fig. 1).

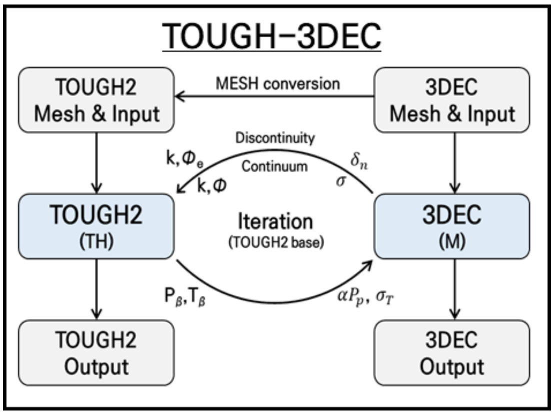
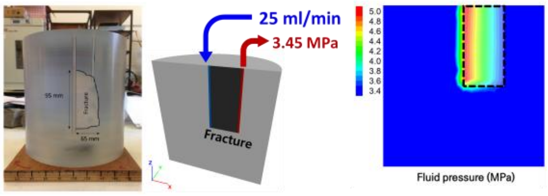


Fig. 1. Layout of the TOUGH-3DEC simulator [4]

2.2 Experimental Analysis: the GREAT cell

DECOVALEX-2023 Task G aims to numerically simulate the mechanical behavior of fractured rock under hydraulic and thermal conditions using the HM and TM experimental analysis. As a HM experimental analysis, the polyaxial compression test and fluid flow test through a single fracture in GREAT (Geo Reservoir Experimental Analogue Technology) cell, invented by the University of Edinburgh to generate a true triaxial stress field in the lab-scale specimen [5], are simulated by five different modelling teams. As preliminary simulations, the polyaxial compression tests with the intact and single fracture specimens are modelled. The circumferential strain extracted from the experiments is compared to the strain data calculated from the mechanical simulations.

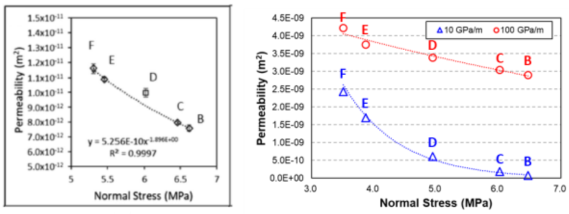
To validate the HM simulation performance of the TOUGH-3DEC, the flow tests performed in the GREAT cell [5] are modelled. The flow tests are proceeded under the five different true-triaxial stress conditions with monitoring the permeability changes calculated from the pressure changes between the injection and production wells. In the numerical model, 25 ml/min of constant injection rate of is applied on the elements representing the injection well and the production well elements are fixed as 3.45 MPa of back pressure. The fluid flow is allowed only through the fracture plane between two wells (Fig. 2a, b).



(a) (b) (c)

Fig. 2. (a) Fractured specimen for flow tests [5], (b) layout of the flow tests, and (c) pressure distribution extracted from the numerical simulations

Under the five different polyaxial stress conditions of which axial stress is 12 MPa and lateral stress varies from 4 to 7 MPa, the fluid injection is simulated until the steady-state. The equivalent permeability of fracture is calculated by the flow rate and averaged pressure difference between injection and production elements. Fig. 3 compares the permeability trends depending on the applied normal stress extracted from the experiment and the TOUGH-3DEC simulations. The exponential curves of the stress-dependent permeability are well shown from both experimental and numerical results. The slope of the permeability trend highly depends on the assigned normal stiffness of fracture, so the accurate fracture property should be measured for the quantitative validation.



(a) (b)

Fig. 3. Permeability changes by the applied normal stress extracted from (a) the GREAT cell experiment [5] and (b) TOUGH-3DEC simulations

3. Conclusions

GREAT cell flow tests are modelled by the TOUGH-3DEC simulator to validate the hydro-mechanical simulation performance, and the exponential relationship between the permeability and applied normal stress on the fracture is depicted in the numerical results. Based on comparative validations with the experiments and a variety of numerical codes, the TOUGH-3DEC simulator could be applied to demonstrate more complicated coupled processes and geological conditions of discontinuous media such as the multi-barrier system of the geological repository for high-level radioactive waste.

ACKNOWLEGEMENTS

The authors appreciate and thank the DECOVALEX-2023 Funding Organisations Andra, BASE, BGE, BGR, CAS, CNSC, COVRA, US DOE, ENRESA, ENSI, JAEA, KAERI, NWMO, NWS, SÚRAO, SSM and Taipower for their financial and technical support of the work described in this research. The statements made in the research are, however, solely those of the authors and do not necessarily reflect those of the Funding Organisations. This work was also supported by a National Research Foundation (NRF) grant funded by the Korean government (MSIP) (No. 2021M2E1A1085193).

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