在核廢料處置場的緩衝材料發生水-力耦合及熱-水-力耦合行為之數值分析：利用巴塞羅那基本模式模擬應用在 Mont Terri URL 之 EB 試驗及在 Grimsel 試驗場址之 FEBEX 試驗

Lee,C., Lee,J., Kim,GY., 2021. Numerical analysis of coupled hydro-mechanical and thermo-hydro-mechanical behaviour in buffer materials at a geological repository for nuclear waste: Simulation of EB experiment at Mont Terri URL and FEBEX at Grimsel test site using Barcelona basic model. *International Journal of Rock Mechanics & Mining Sciences*, **139**,104663

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報告日期：2022/12/30

摘要

本研究使用 TOUGH2-MP/FLAC3D 模式，以重現 Opalinus 粘土為岩體的工程障壁試驗(EB test)之水-力耦合行為，以及結晶岩為岩體的全尺度工程障壁試驗(FEBEX test)之熱-水-力耦合行為，來探討耦合熱彈塑性模型的適用性(本篇為 DECOVALEX-2019 計畫中 Task D 的一部分)。在數值模式中，分別採用達西定律、菲克定律和傅立葉定律來表示流體的移流、蒸氣的擴散和熱流傳導的流通量。此外，本研究使用力學組成律，藉由彈性模式和巴塞羅那基本模式了解溫度、孔隙壓力、吸力和應變變化之影響。總的來說，模式成功地重現膨潤土緩衝材料在兩個長期現地實驗中溫度、相對濕度、總應力和位移的演變及空間分佈的耦合行為。在模式模擬飽和度、含水量及乾密度之結果，與現地試驗結束拆除後之結果有不錯的吻合成果。

關鍵字: 膨潤土緩衝材料、水-力耦合行為、熱-水-力耦合行為、巴塞羅那基本模型、TOUGH2-MP/FLAC3D

International Journal of Rock Mechanics & Mining Sciences 139 (2021) 104663

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

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

Numerical analysis of coupled hydro-mechanical and thermo-hydro-mechanical behaviour in buffer materials at a geological repository for nuclear waste: Simulation of EB experiment at Mont Terri URL and FEBEX at Grimsel test site using Barcelona basic model

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ARTICLE INFO

Keywords:
Bentonite buffer materials
Coupled hydro-mechanical behaviour
Coupled thermo-hydro-mechanical behaviour
Barcelona basic model
TOUGH2-MP/FLAC3D

ABSTRACT

We investigated the applicability of a thermo-elasto-plastic model using a TOUGH2-MP/FLAC3D simulator to reproduce the coupled hydro-mechanical behaviour at the engineered barrier emplacement experiment in Opalinus Clay and the coupled thermo-hydro-mechanical behaviour at the full-scale engineered barrier experiment in a crystalline host rock, as part of the DECOVALEX-2019 project Task D. In the numerical models, we adopted Darcy's law, Fick's law, and Fourier's law for the advective flux of fluid, vapour diffusion, and conductive heat flux, respectively. We also used the mechanical constitutive law, which explicitly considers the effects of temperature, pore pressure, suction, and strain changes using the elastic model and the Barcelona basic model. In general, the numerical models in the simulator successfully represented the coupled behaviour in bentonite buffer materials at the two long-term *in situ* experiments in terms of evolution and spatial distribution for temperature, relative humidity, total stress, and displacement. The performance of the models for the dismantling of the *in-situ* experiments is globally satisfactory compared with the post-mortem results for saturations, water contents, and dry density.

1. Introduction

Coupled thermo-hydro-mechanical and chemical (THMC) processes occur in deep geological repositories for high-level radioactive waste disposal (Fig. 1). Decay heat from spent nuclear fuel increases the temperature of the repository and differential thermal expansion induces thermal stress in the disposal system. Meanwhile, the increased temperature decreases the saturation of the buffer material near the canister in the waste repository, which leads to water evaporation, while the saturation in the buffer materials near the host rock is increased by water intake from the rock mass. These hydraulic processes lead to shrink/swell behaviour in the buffer materials. Consequently, change in stresses occur in the engineered and natural barrier system. Transient pore pressure induced by the fluid flow also affects the changes in the effective stresses of the disposal systems. In addition, geochemical alterations and reactions cause variations in the hydrological property of the near field, such as porosity, fracture aperture, and permeability, which can affect the ground water flow and transport processes near the disposal tunnels and deposition holes.[2] Therefore the coupled THMC processes must be understood for the safe disposal of spent nuclear fuel, because they play important roles in the design, construction, and operation of a repository in deep geological formations during its lifespan.[3] Moreover, because the THMC processes are integral to the performance and safety assessment of disposal systems, they should be predicted using the state-of-the-art numerical models and other techniques.

However, it is difficult to combine the complex coupled THMC processes (Fig. 2) into efficient models and develop numerical techniques to simulate them. It is also a challenging task to verify the numerical models and techniques, and validate the simulation results against laboratory tests and *in situ* experiments. To solve these problems, an international cooperative project called DECOVALEX (acronym for DEvelopment of COupled THM models and their VALidation against EXperiments) was initiated in 1992.[5–8] Since its initiation, the DECOVALEX project has completed seven phases.

Regarding the development and validation of the THM models and

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https://doi.org/10.1016/j.ijrmms.2021.104663
Received 18 March 2020; Received in revised form 13 January 2021; Accepted 13 January 2021
Available online 5 February 2021
1365-1609/