裂隙內寬與滲透率演變於雙孔隙介質之水-力耦合模型技術開發

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摘要

對於高放射性廢棄物最終處置場的設計，國內主要採用深地層處置概念以防止放射性核種外洩造成生物與環境危害。然而，處置母岩本身與受力產生之裂隙，為放射性核種外釋的主要通道。由於地層中的裂隙可能受到壓溶作用與自由面溶解的影響，使得裂隙內寬(Aperture)與滲透率發生變化，進而影響核種傳輸特性。因此，瞭解裂隙內寬與滲透率受到外在條件影響而隨時間發生之變化，有助於評估放射性核種外釋可能性，進而確保放射性廢棄物處置場之安全性。本研究採用 Liu et al. (2006)之岩體裂隙幾何運算方式，藉多重物理量耦合分析軟體(COMSOL Multiphysics®)建置二維水力-力學雙孔隙介質機制模型，將水-力數值模擬結果引入商業數學軟體 MATLAB®中進行裂隙幾何變化計算，再將裂隙演變結果代回數值模式中進行迭代運算，以模擬石灰岩裂隙在受到壓溶作用與自由面溶解下，裂隙內寬隨時間變化的情形，並針對其結果計算等效水力傳導係數(K_{eq})以評估該區域之流體傳輸特性。研究顯示，在本研究設定條件下，在每 1 小時為時間間隔進行 1500 小時之模擬中，當僅考慮壓溶作用之影響時，其等效水力傳導係數值下降約 11%；當僅考慮自由面溶解之作用時，由於裂隙內寬在溶解過程中不斷增寬，導致裂隙粗糙點間不再相互接觸而產生水流通道，至終造成等效水力傳導係數值上升約 7 個數量級；當同時考慮兩者之作用時，由於自由面溶解之作用較壓溶作用顯著，因此裂隙內寬將持續增寬，其等效水力傳導係數值增加約 47%。未來將透過考慮岩體於不同環境條件下之影響進行參數計算，以建置完整裂隙演變幾何模型，並期望能應用於現地的安全評估工作中。

關鍵字: 岩體裂隙內寬、壓溶作用、自由面溶解、滲透率、水-力耦合、等效水力傳導係數。

Development of a Coupled Hydro-Mechanical Model for Fracture Aperture and Permeability Evolution in Dual-Porosity Media

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Abstract

For the design of high-level radioactive waste (HLW) disposal sites, most countries currently adopt the deep geological disposal concept to prevent the leakage of radioactive nuclides, which could pose risks to both biological systems and the environment. However, fractures in the bedrock caused by stress are main pathways for radionuclide migration. These fractures may be influenced by pressure solution and free surface dissolution, leading to changes in fracture aperture and permeability, thereby affecting radionuclide transport characteristics. This study employs the fracture geometry simulation method proposed by Liu et al. (2006) and utilizes the multiphysics coupling analysis software (COMSOL Multiphysics®) to establish a coupled two-dimensional hydro-mechanical model in dual-porosity media. Numerical simulation results for hydro-mechanical interactions are imported into the commercial mathematical software MATLAB to calculate the geometric changes in fractures under stress. The results of fracture evolution are then iteratively fed back into the numerical model to simulate the temporal changes in fracture aperture under the combined effects of pressure solution and free surface dissolution. The equivalent hydraulic conductivity (K_{eq}) is calculated to evaluate the fluid flow characteristics of the rock mass. In the simulation conducted over 1,500 hours with hourly intervals under the setting of models, the results indicate that: 1) When considering only the effects of pressure solution, the equivalent hydraulic conductivity decreases by approximately 11%. 2) When considering only free surface dissolution, the continuous widening of the fracture aperture during the dissolution eliminates contacting asperity, forming fluid channels that result in an increase in equivalent hydraulic conductivity by approximately seven orders of magnitude. 3) When both effects are considered simultaneously, free surface dissolution is more dominant than pressure solution, the fracture aperture continues to widen and the equivalent hydraulic conductivity increases by approximately 47%. Future research can involve conducting sensitivity analyses of rock masses under different environmental conditions to further understand the underlying mechanisms. This study aims to develop geometric models of fracture evolution and hopes to contribute to the safety assessment of in-situ applications.

Keywords: Fracture aperture, Pressure solution, Free surface dissolution, Permeability, Coupled hydro-mechanical model, Equivalent hydraulic conductivity.