Hypergravity Experiments on Solute Transport in Fractured Rock and Evaluation Methods for Long-Term Barrier Performance

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Abstract

Hyper-gravity experiment enable the acceleration of the long-term transport of contaminants through fractured geological barriers. However, the hyper-gravity effect of the solute transport in fractures are not well understood. In this study, the sealed control apparatus and the 3D printed fracture models were used to carry out 1 g and N g hyper-gravity experiments. The results show that the breakthrough curves for the 1 g and N g experiments were almost the same. The differences in the flow velocity and the fitted hydrodynamic dispersion coefficient were 0.97-3.12% and 9.09-20.4%, indicating that the internal fractures of the 3D printed fracture models remained stable under hyper-gravity, and the differences in the flow and solute transport characteristics were acceptable. A method for evaluating the long-term barrier performance of low-permeability fractured rocks was proposed based on the hyper-gravity experiment. The solute transport processes in the 1 g prototype, 1 g scaled model, and N g scaled model were simulated by the OpenGeoSys (OGS) software. The results show that the N g scaled model can reproduce the flow and solute transport processes in the 1 g prototype without considering the micro-scale heterogeneity if the Reynolds number (Re) critical Reynolds number (Recr) and the Peclet number (Pe) the critical Peclet number (Pecr). This insight is valuable for carrying out hyper-gravity experiments to evaluate the long-term barrier performance of low-permeability fractured porous rock.

Full Text

Preamble

Hyper-gravity experiment of solute transport in fractured rock and evaluation method for long-term barrier performance

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Hyper-gravity experiments enable the acceleration of long-term contaminant transport through fractured geological barriers. However, the hyper-gravity effect on solute transport in fractures remains poorly understood. In this study, sealed control apparatus and 3D printed fracture models were used to conduct 1 g and N g hyper-gravity experiments. The results show that breakthrough curves for the 1 g and N g experiments were almost identical. Differences in flow velocity and fitted hydrodynamic dispersion coefficient ranged from 0.97–3.12% and 9.09–20.4%, respectively, indicating that internal fractures in the 3D printed models remained stable under hyper-gravity and that differences in flow and solute transport characteristics were acceptable. Based on these hyper-gravity experiments, we propose a method for evaluating the long-term barrier performance of low-permeability fractured rocks. Solute transport processes in the 1 g prototype, 1 g scaled model, and N g scaled model were simulated using OpenGeoSys (OGS) software. The results demonstrate that the N g scaled model can reproduce flow and solute transport processes in the 1 g prototype without considering micro-scale heterogeneity if the Reynolds number (Re) < critical Reynolds number (Recr) and the Peclet number (Pe) < the critical Peclet number (Pecr). This insight is valuable for conducting hyper-gravity experiments to evaluate the long-term barrier performance of low-permeability fractured porous rock.

1. Introduction

Deep geological disposal is an internationally recognized safe, reliable, and technically feasible method to prevent high-level radioactive waste leachate from escaping into the environment [?, ?, ?, ?]. Granite is a typical low-permeability fractured porous medium and serves as a key geological barrier. Since the design service life of an engineered barrier is approximately 1000 years, the long-term barrier performance of a deep disposal repository depends strongly on the granite barrier. However, the ability of the geological barrier to provide long-term service is directly related to the quality of the surrounding hydrogeological environment. Field monitoring of long-term transport processes is not feasible. Therefore, hyper-gravity experiments provide a means to accelerate contaminant transport through geological barriers.

In a 1/N-scale centrifuge model, seepage path lengths are 1/N times shorter than in actual conditions, while the self-weight of pore fluid is N times larger under a centrifugal force of N g (i.e., at 500g, water weighs 500 times its weight at 1g). Consequently, the local seepage velocity at any point is N times faster than in the prototype, and advective processes occur N^2 times faster in the model than in the prototype [?, ?, ?, ?]. For example, a 14.6-day modeling period at 500 g can simulate advective transport processes requiring more than ten thousand years in the prototype (14.6 days × 500^2 = 10,000 h). Thus, hyper-gravity experiments can accelerate transport processes in small-scale models at stress levels similar to those experienced by the prototype.

The use of hyper-gravity experiments to simulate contaminant transport began in the late 1980s. Researchers studied the similitude of contaminant transport simulations, derived eight dimensionless groups of contaminant transport, explained similarity conditions, and demonstrated the feasibility of simulating contaminant transport through hyper-gravity experiments [?, ?, ?, ?, ?, ?, ?, ?]. For instance, Hensley and Schofield (1991) conducted hyper-gravity experiments on long-term NaCl transport in silt. The test lasted 27 h under 100 g centrifugal acceleration, simulating 31 years of solute transport in a landfill. Lo et al. (2005) simulated one-dimensional transport of adsorptive inorganic contaminants (such as cadmium) in saturated and unsaturated soils. Zhang and Hu (2006) studied long-term transport behavior of light non-aqueous phase liquids (LNAPLs) in unsaturated soil, with results showing that hyper-gravity experiments accurately simulated LNAPL transport processes. Zeng (2015) performed a 72-h hyper-gravity experiment under 50 g centrifugal acceleration to simulate Pb2þ transport through a kaolin liner using a ZJU-400 centrifuge developed by Zhejiang University. The continuous test reproduced 22.8 years of solute breakthrough in a 2-m thick compacted clay layer, verifying the long-term barrier performance of the clay barrier. Subsequently, Zhan et al. (2022) conducted tests at 100 g for 43.8 h to simulate 50 years of contaminant transport in soil-bentonite walls and loess-amended soil-bentonite walls, verifying the 50-year long-term barrier performance of the loess-modified barrier. These studies demonstrate that hyper-gravity experiments are effective for predicting long-term barrier performance of fractured rock masses with low permeability.

However, due to discontinuity and heterogeneity of fractured rock masses, creating models with prototype materials is difficult, and no suitable similar material exists for preparing scaled models. Only a few studies have reported hyper-gravity experiments of flow and solute transport in fractured media [?, ?, ?, ?, ?, ?, ?, ?]. Levy et al. (2002, 2003) investigated the potential of geotechnical centrifuges as experimental tools to study dense non-aqueous phase liquid (DNAPL) infiltration into fracture systems. They analyzed microscopic fractures [?] and observed excellent agreement between scaled tests and prototype data when inertial force effects were negligible. Subsequently, Jones et al. (2017) conducted hyper-gravity experiments on potassium permanganate crystal flow in a single plexiglass fracture model under different flow rates at 20 g, proving that hyper-gravity experiments could simulate and observe fracture flow processes. Jones et al. (2018) performed Lugeon tests using geotechnical centrifuge modeling to investigate flow behavior through an inclined smooth single-fracture model, finding that the width of the dominant flow path increased with inflow pressure. However, measured flow velocities were large, with Re ranging from 169 to 698, and a nonlinear relationship existed between pressure and flux. Therefore, similarity of flow velocity remains to be analyzed. Additionally, Gurumoorthy and Singh (2004) simulated molecular diffusion of Cs in integrated granite or a single fracture using hyper-gravity experiments, but considered only molecular diffusion while ignoring convection and mechanical dispersion. Nishimoto and Sawada (2016; 2017) conducted near-field hyper-gravity experiments to evaluate geomechanical properties in rock surrounding a high-level radioactive waste geological disposal reservoir. Tests were performed under 30 g centrifugal force in isotropic stress-constraint conditions with confining pressures of 5–10 MPa and pore water injection at the model bottom. Conducted continuously for 67 days, these tests reproduced flow, mechanics, and temperature conditions of the prototype over 165 years, demonstrating feasibility of simulating long-term characteristics of geological disposal reservoirs containing high-level radioactive waste and long-term solute transport processes in fractured media using hyper-gravity experiments.

In summary, current hyper-gravity experiments of contaminant transport have only been conducted in soil media. Few experimental studies report on flow and solute transport in fractured rock masses, and the hyper-gravity effect and similarity of solute transport in fractures remain poorly understood. Therefore, studying the hyper-gravity effect on solute transport in fractured rock masses is necessary to develop experimental methods and provide theoretical support for subsequent hyper-gravity experiments of solute transport in low-permeability fractured rock masses.

This study investigates solute transport in fractured rock masses using hyper-gravity experiments and develops an evaluation method for long-term barrier performance. 3D-printed fracture models and a custom-made sealed control apparatus were used to conduct normal gravity and hyper-gravity experiments of solute transport in fractured rock masses. The feasibility of 3D printed fracture models for hyper-gravity experiments of solute transport was evaluated, and the influence of hyper-gravity on solute transport was analyzed. A method for evaluating long-term barrier performance of low-permeability fractured rocks is proposed based on hyper-gravity experiment results. Solute transport processes in the 1 g prototype, 1 g scaled model, and N g scaled model were simulated using OpenGeoSys (OGS) software. The results provide guidance for verifying long-term barrier performance of deep-earth projects, such as high-level waste storage in geological disposal reservoirs.

2.1. Experimental setup

Solute transport tests of 3D-printed fractured rocks were performed using a hyper-gravity experimental apparatus to investigate fluid flow and solute transport in fractured rock masses. The device was developed by researchers at Zhejiang University [Figure 1: see original paper]. The apparatus consists of a centrifuge (ZJU400), a sealed control unit containing the fractured rock, an upstream solute control unit, an upstream water level control unit, an effluent reservoir, a waste liquid collection reservoir, a valve control unit, and a data acquisition unit. The sealed control unit containing the fractured rock has six boundary interfaces and can simulate a maximum pore pressure of 5 MPa under a maximum centrifugal force of 100 g. It accommodates cube specimens with a maximum length of 200 mm. The device can simulate in-situ stress of large-scale rock engineering in a reduced geo-mechanical model, specifically the vertical stress gradient induced by gravity. Hyper-gravity results from high-speed rotation of the centrifuge. As shown in Fig. 1, the upstream water level was maintained by several Mariotte bottles [**?**, **?**, **?**], which automatically provided continuous solution supply during centrifuge rotation. The downstream water level was controlled by a spillway in the downstream water level control unit. Hydraulic head was maintained by adjusting Mariotte bottle height. The upstream water level was higher to create flow, and outflow solution was collected in the effluent reservoir.

2.2. Monitoring devices

As shown in Fig. 1, four micro-pore water pressure sensors (PPSs) (HC-25, \$±\$0.1% accuracy) were attached to the inlet and outlet of the sealed control unit to monitor fracture model inlet and outlet pressure, respectively. Two micro-pore water pressure sensors, one temperature sensor (Pt-100, \$±\$0.1% accuracy), and one conductivity meter (EC-510, \$±\$1.5% accuracy) were attached to the effluent reservoir. These three sensors performed real-time monitoring of water level, temperature, and cumulative conductivity of the outflow solution.

2.3. 3D printed fracture model

A method was developed to create 3D-printed models of rock masses with a single fracture and fracture networks. Due to high 3D printing costs, only key parts of the fracture model were printed, with other parts replaced by aluminum alloy. Fig. 2a [Figure 2: see original paper] shows the variable-aperture single-fracture model (200 mm long × 200 mm width × 20 mm high). The initial fracture aperture was 0.5 mm due to 3D printing accuracy limitations. The printed rubber hardness in the model was 65. This hardness level and selected structure could produce realistic fracture model deformation under given confining stress. It should be noted that this study’ s objective is to clarify hyper-gravity effects on flow and transport processes in fractures; for simplicity, the rock matrix effect is not considered, printing with impermeable resin material.

Fig. 2b shows the 3D printed variable-aperture fracture network model (200 mm long × 100 mm wide × 100 mm high). The initial fracture aperture of each single fracture in the fracture network model was set the same (0.5 mm), and the rubber hardness (65) was the same as in the single-fracture model. The model consisted of the fracture network and matrix. Several single fractures crossed the matrix and were connected by rubber, enabling deformation by confining stress. The matrix supported the fracture network and had a hollow interior filled with sand and sealed with high-strength bolt plugs on the surface. This design substantially reduced manufacturing cost while ensuring structural strength of the 3D printed model.

Fig. 3 [Figure 3: see original paper] shows the assembled 3D-printed fracture model and layout scheme in the sealed control unit. The assembled fracture model experienced deformation under confining stress exerted by the pressurization mechanism on both sides, limiting fracture aperture to 0–0.5 mm. Implementation steps for the sealed control unit were as follows. First, the fracture of the assembled model was placed in the vertical direction, parallel to the centrifugal force direction under hyper-gravity. This setting ensured formation of a water pressure gradient at the fracture boundary and prevented secondary deformation under hyper-gravity. Second, after assembling and sealing the six sides of the sealed control unit, a flow test was conducted to observe flow changes. If permeability was too high, confining stress was adjusted to control fracture aperture or permeability.

2.4. Experimental plan

Normal gravity flow experiments were first conducted to design hyper-gravity solute transport experiments in the 3D printed fracture model. Fig. 4a [Figure 4: see original paper] shows the relationship between pressure drop and flow rate/Reynolds number (Re) during flow experiments in the single-fracture model. Results indicated a linear relationship between flow rate and pressure drop, with Re ranging from 0.25 to 1.061. Thus, Darcy' s law is applicable. The average equivalent hydraulic fracture aperture was 2.18 \$±\$5 m, and permeability was 3.96 \$×\$10 \$×\$4 m/s.

Based on flow experiment results, three groups of solute transport experiments with different pressure differences and g levels were designed under normal gravity and hyper-gravity (Table 1). Normal gravity experiment pressure differences were 100, 200, and 300 kPa, with corresponding hyper-gravity experiment g levels of 20, 40, and 60 g to evaluate hyper-gravity influence on solute transport in the 3D printed single-fracture model.

Fig. 4b shows the relationship between pressure drop and flow rate/Re during flow experiments in the fracture network model. Results also suggested a linear relationship, with Re ranging from 1.659 to 3.828. Therefore, Darcy' s law is valid in this experiment. The calculated average equivalent hydraulic fracture aperture was 2.85 × $±$5 m, and permeability was 6.76 $×$10 $×$4 m/s. As shown in Table 2 , three groups of normal gravity experiments and one hyper-gravity experiment at 80 g were designed. A comparison experiment with 400 kPa pressure difference under normal gravity and 80 g hyper-gravity was conducted to evaluate hyper-gravity influence on solute transport in the 3D printed fracture network model.

3.1. Test 1: Single-fracture model

3.1.1. The effect of hyper-gravity on flow behavior

Pore water pressure difference between fracture model inlet and outlet and pore water pressure/water level in the effluent reservoir under normal gravity and hyper-gravity are shown in Fig. 5 [Figure 5: see original paper]. Pressure differences were relatively stable in normal gravity experiments (S1, S2, and S3) (Fig. 5a), with a range of $±$2 kPa, indicating stable supply pressure. As shown in Fig. 5c, pore pressure/water level of S1, S2, and S3 increased over time, indicating continuous solution flow into the effluent reservoir. Water level increased linearly, with slope increasing as pressure difference increased.

In hyper-gravity experiments, pressure difference ΔP was calculated by average pressure between inlet and outlet, Pin - Pout, where Pin = (P1+P2)/2 and Pout = (P3+P4)/2. Results are shown in Fig. 5b. The effluent reservoir was equipped with PPSs 5 and 6 to monitor real-time pressure P5 and P6, with results shown in Fig. 5d–e. Slopes of pore pressure and water level were similar, suggesting relatively stable flow velocity in the 3D printed single-fracture model under hyper-gravity. Hyper-gravity experiment results also show that slopes increased, indicating flow velocity in the fracture model increased with g level.

Findings show that flow characteristics of solute transport in the 3D-printed single-fracture model were similar under 1 g and N g. Flow velocity and equivalent hydraulic fracture aperture under different experimental conditions are listed in Table 3 . Difference in equivalent hydraulic fracture aperture obtained from normal gravity and hyper-gravity experiments was small, with maximum flow velocity difference of 3.12%, demonstrating similar flow characteristics of the 3D printed single-fracture model under hyper-gravity and normal gravity. Flow velocity under different conditions increased N times with pressure difference or centrifugal acceleration g level, and Re was less than 1, indicating similar flow processes under hyper-gravity and normal gravity.

Additionally, relationships between flow pressure difference and flux from normal gravity and hyper-gravity transport experiments were compared with those from normal gravity flow experiments, as shown in Fig. 4a. Data obtained from transport experiments were within the fitted curve derived from flow experiments.

3.1.2. The effect of hyper-gravity on transport behavior

Fig. 6 [Figure 6: see original paper] shows cumulative conductivity/concentration curves and breakthrough curves (BTCs) derived from normal gravity and hyper-gravity experiments for the single-fracture model. The conductivity sensor in the outlet effluent reservoir monitored cumulative conductivity continuously. Duration time when conductivity was measured in S1, S2, S3 and C1, C2, C3 shortened as pressure increased (Fig. 6a), i.e., solute transport breakthrough time in the fracture model was shortened. Unlike in normal gravity experiments, conductivity exhibited slight fluctuations under hyper-gravity because the environment affected conductivity sensor working performance.

Based on concentration evolution, the solute transport process can be divided into three stages:

Stage I -solute infiltration: In the initial stage, water level in the effluent reservoir rises, but conductivity does not change because solute flows into the inlet water chamber from the fracture inlet. At this time, the fracture model is flooded by inflowing solution, which flows from the fracture outlet to the effluent reservoir. However, solute has not yet reached the fracture outlet. Therefore, conductivity in the effluent reservoir is the background value of pure water, and cumulative solute mass is 0.

Stage II - solute breakthrough: In this stage, the conductivity curve exhibits a breakpoint, and conductivity increases. At this time, solute has infiltrated the fracture model, migrated to the fracture outlet, and flowed into the effluent reservoir. Outflow concentration and cumulative solute mass increased, resulting in increased cumulative conductivity.

Stage III - solute saturation: Water in the inlet/outlet water chamber and fracture is gradually replaced by solute, and outflow concentration reaches peak concentration or approaches solution concentration. The rate of conductivity increase slows significantly, but cumulative solute mass continues increasing. It is worth noting that although outflow concentration has reached peak value, cumulative conductivity continues rising. At this time, outflow solution is diluted due to water in the effluent reservoir, and cumulative solution concentration in the effluent reservoir has not yet reached maximum value.

Fig. 6 shows that cumulative concentration curve characteristics are similar under 1 g and N g. BTCs are slightly different, but overall difference is small, indicating that solute transport characteristics in the 3D-printed single-fracture model are the same under hyper-gravity and normal gravity.

We used the breakthrough standard in the Technical Code for Geotechnical Engineering of Domestic Waste Landfill (CJJ176-2012). Breakthrough time, t0.1, of solute transport in the fracture is defined based on solute transport speed in the fracture model. Table 3 shows calculated breakthrough time t0.1 and Pe for different experimental cases, indicating that solute breakthrough time decreases with increasing pressure or g level.

The Advection-Diffusion (ADE) model was used to fit normalized BTCs depicted in Fig. 6b to compare solute transport characteristics under different conditions. Results are shown in Fig. 7 [Figure 7: see original paper]. Hydrodynamic dispersion coefficient Dh and coefficient of determination R2 are listed in Table 3. R2 values are greater than 0.99, and Dh increases with increasing pressure or g level. Relative difference in Dh between normal gravity and hyper-gravity experiments ranges from 9.09% to 20.4%.

Temperature in the centrifuge chamber increases with centrifugal acceleration (g level) and operation time, changing solution temperature in experiments and affecting fluid dynamic viscosity coefficient. Therefore, a temperature sensor was placed in the effluent reservoir to monitor outflow liquid temperature to evaluate possible liquid temperature influence on results. Fig. 8 [Figure 8: see original paper] shows fluid temperature in C1, C2, and C3 experiments. Temperature increases over time and with g level. Maximum temperature difference between different conditions is 0.9-1.4°C, indicating that liquid temperature influence on hydrodynamic viscosity coefficient can be ignored.

3.2. Test 2: Fracture network model

3.2.1. The effect of hyper-gravity on flow behavior

Fig. 9 [Figure 9: see original paper] shows pore water pressure/water level in the effluent reservoir for the fracture network model under normal gravity and hyper-gravity. As shown in Fig. 9a, pressure and water level in N1, N2, and N3 experiments increase linearly, with slope increasing as pressure difference increases, the same as for the single-fracture model. Fig. 9b shows that slopes of pore pressure and water level increase linearly, indicating flow velocity in the model remains unchanged. This result shows that internal fracture structure of the 3D printed fracture network model remains relatively stable under hyper-gravity.

As shown in Fig. 4b, data obtained from transport experiments conform to the fitting curve obtained from flow experiments in the fracture network model, indicating that flow characteristics of solute transport in the 3D printed fractured network models are the same under 1 g and 80 g.

Flow velocity and equivalent hydraulic fracture aperture under different experimental conditions are listed in Table 4 . Equivalent hydraulic fracture aperture is similar in normal gravity and hyper-gravity experiments. Difference in flow velocity between N2 and D1 is 0.97%, demonstrating that flow characteristics of the 3D printed fracture network model are the same under hyper-gravity and normal gravity.

3.2.2. The effect of hyper-gravity on transport behavior

Fig. 10 [Figure 10: see original paper] shows cumulative conductivity/concentration curves and BTCs from normal gravity (N2) and hyper-gravity experiments (D1) for the fracture network model. As shown in Fig. 10a, conductivity curves exhibit fluctuation under 80 g hyper-gravity. Sudden decrease at the end of the cumulative concentration curve may be due to high centrifugal acceleration, which significantly affects conductivity sensor working performance. Additionally, cumulative concentration curve characteristics are similar under 1 g and 80 g. BTCs are slightly different, but overall difference is small, indicating that solute transport characteristics in the 3D printed fracture network model are similar under hyper-gravity and normal gravity.

Calculated breakthrough time t0.1 and Pe for different experimental cases are given in Table 4. Solute breakthrough time decreases with increasing pressure in normal gravity experiments.

Fitting results of normalized BTCs for N2 and D1 are shown in Fig. 11 [Figure 11: see original paper], and ADE fitting Dh and R2 are listed in Table 4. R2 values are greater than 0.98, and Dh increases with increasing pressure. Relative difference between N2 and D1 is 9.58%.

Outflow liquid temperature in the D1 experiment is shown in Fig. 12 [Figure 12: see original paper]. Temperature increases over time. Although centrifugal acceleration was high, experimental duration was short. Thus, maximum temperature difference was only 0.8°C, indicating that temperature influence on hydrodynamic viscosity coefficient can be ignored.

In summary, based on scaling laws from previous studies [?, ?, ?, ?, ?], a small-scale hyper-gravity fracture model can achieve water pressure gradient boundary conditions of a large-scale prototype, making it possible to reproduce prototype flow and transport processes. Hyper-gravity effect on flow and solute transport characteristics of the 3D-printed single/fracture network models is small or non-existent for the range of G-levels tested, for accelerations up to 80 g. This is expected because flow and transport characteristics are related to fracture model properties (fracture aperture, roughness, geometry, etc.), and despite some structural variations due to compression during centrifuge spinning, Darcy' s law represented by permeability k and solute transport mechanism represented by Df (diffusion coefficient) are not affected by gravity in a hyper-gravity environment. Furthermore, to the authors' knowledge, applying water pressure gradient boundary conditions to scaled models is difficult when conducting 1 g scaled experiments. However, unlike 1 g scaled model experiments, hyper-gravity experiments efficiently reproduce prototype gradient boundary conditions, such as water pressure gradient and hydraulic boundary conditions. Therefore, long-term contaminant migration in in-situ fractured rock masses can be simulated in an N g scaled model under hyper-gravity conditions, and contaminant breakthrough curves at different outflow positions can be obtained to predict contaminant breakthrough time. Thus, our results provide new insights into experimental studies of contaminant transport in complex fracture models under hyper-gravity conditions.

4.1. Method

Based on hyper-gravity experiment results, we propose a long-term barrier performance evaluation method for low-permeability fractured rock masses, as shown in Fig. 13 [Figure 13: see original paper]. The main steps are as follows:

Step 1: Determine input parameters, including geometric parameters (length, width, depth) of the research object, hydrogeological conditions, fracture geometric parameters (fracture trend, length, density, and size), key solutes or contaminants, and simulation parameters.

Step 2: Establish a simplified three-dimensional fracture network model according to fracture geometric parameters. Determine whether influence of rock matrix around fractures and sorption and decay processes should be considered.

Step 3: Carry out OpenGeoSys (OGS) simulation to obtain flow and concentration fields, BTCs, and breakthrough time (Tt) or maximum breakthrough concentration (Cmax). Assess whether Re and Peclet number (Pe) meet the following conditions in hyper-gravity experiments according to previous studies [**?**, **?**, **?**, **?**, **?**]: Re $<$ Recr (=1) and Pe $<$ Pecr (=1). If conditions are met, proceed to Step 4; otherwise, optimize and adjust the fracture model or boundary conditions, such as decreasing fracture aperture (or hydraulic permeability) of the model or decreasing hydraulic gradient between model inlet and outlet.

Step 4: Create a 3D-printed fracture model and conduct hyper-gravity experiment to evaluate long-term barrier performance of low-permeability fractured rock mass. Analyze experimental results from two aspects: (1) If contaminants are conservative solutes (such as chloride ions), BTCs and breakthrough time (Tt) obtained from experiments can be directly compared with numerical simulation results to verify long-term barrier performance of low-permeability fractured rock mass. (2) If contaminants are non-conservative solutes (such as heavy metal ions and nuclides), additional theoretical analysis of experimental results is necessary based on contaminant sorption and decay parameters. Predict prototype BTCs, breakthrough time (Tt) or maximum breakthrough concentration (Cmax) to verify long-term barrier performance of low-permeability fractured rock mass.

4.2. Case study

We conducted a case study in Xinchang, Beishan, Gansu Province, using the proposed method to evaluate 10,000-year nuclide transport through the geological barrier in high-level waste disposal. A simplified 3D fracture network model was generated based on the Monte Carlo simulation method. Solute transport processes were simulated in the normal gravity 1 g prototype (Fig. 14a [Figure 14: see original paper]), hyper-gravity 500 g scaled model (Fig. 14b), and normal gravity 1 g scaled model (Fig. 14c) using OGS software. Solute transport was compared under different conditions to analyze feasibility and required conditions for simulating solute transport in fractured rock masses with hyper-gravity models.

4.2.1. Numerical model and physical parameters

Fig. 15 [Figure 15: see original paper] shows the simplified randomly generated 3D fracture network model and corresponding mesh. The generation method has been described in detail by Hu et al. (2021). The model is 500 m long × 500 m wide × 500 m high. Since simulating pore structure characteristics of rock matrix around fractures using 3D printing is difficult, such as porosity and nuclide decay, we only considered advection and dispersion in the fracture network in the hyper-gravity experiment. Influences of sorption, decay, and other factors were predicted by analyzing results.

Table 5 summarizes simulated cases. Only advection and dispersion were considered in fracture networks of the 1 g prototype, 500 g scaled model, and 1 g scaled model. However, different physical and chemical processes were considered in the 1 g prototype to compare factor influences on solute transport processes and determine long-term geological barrier performance. In all cases listed, pollution sources with concentration of 1 mol/L are continuously injected from the left boundary surface. Pollution source parameters, such as sorption allocation coefficient and decay coefficient, were selected from JNC-H12 (2000).

4.2.2. Case study results

We use outflow position P1, p (500 m, 139 m, 409 m) as an example. BTCs considering matrix diffusion, sorption, decay, and other physicochemical processes in the 1 g prototype are shown in Fig. 16 [Figure 16: see original paper]. Generally, BTCs exhibit rightward shift when diffusion, adsorption, and decay are considered. At concentration of C/C0 = 10%, breakthrough time is 39.7 years when only advection and dispersion are considered. When advection and dispersion of fracture network and surrounding matrix are considered, breakthrough time is 41,200 years because molecular diffusion in the matrix significantly extends contaminant breakthrough time. Breakthrough time is 729,300 years when advection, diffusion, and sorption are considered. Contaminant breakthrough time is prolonged by fracture-matrix interface and matrix sorption of contaminants. When advection, diffusion, adsorption, and decay are considered, breakthrough time does not change much, but maximum breakthrough concentration of contaminants is reduced by 47% due to decay.

Therefore, evaluating long-term barrier properties of low-permeability fractured rock mass by considering only advection and diffusion effects in the fracture network is feasible. The scaled model can be used for hyper-gravity experiments for comparison and verification, and matrix effects, sorption, and decay can be evaluated by numerical simulation. We assessed numerical simulation results of the 1 g prototype, 500 g scaled model, and 1 g scaled model to determine hyper-gravity experiment feasibility.

Fig. 17 [Figure 17: see original paper] shows pressure, velocity, and concentration fields derived from the model at 80 years of prototype time. Pressure and concentration fields of the 1 g prototype and 500 g scaled model are identical, and velocity field is similar (model: prototype = 500:1). However, simulation results of the 1 g prototype and 1 g scaled model are significantly different.

We created BTCs for outflow positions of prototype model P1, p (500 m, 139 m, 409 m), P2, p (500 m, 157 m, 110 m), scaled model P1, m (1 m, 0.278 m, 0.818 m), and P2, m (1 m, 0.314 m, 0.220 m) to quantify solute concentrations for different cases. Results of the 1 g scaled model and 500 g scaled model were scaled according to the N^2 (model: prototype) time similarity ratio, as shown in Fig. 18 [Figure 18: see original paper]. Trends of BTCs of the 1 g prototype and 500 g scaled model are identical. However, trend of BTC of the 1 g scaled model differs substantially from that of the 1 g prototype because flow field differences in the 1 g scaled model resulted in different concentrations. Results show that simulating flow and solute transport processes in the 1 g prototype with the 1 g scaled model is difficult.

Table 6 lists average flow velocity, Re, and Pe values for different cases. Re for all three cases were smaller than Recr = 1, conforming to flow similarity assumption. Average velocity ratio between 500 g scaled model and 1 g prototype was 501.3:1, similar to theoretical flow rate (model: prototype = 500:1). Pe of the 500 g scaled model was also smaller than Pecr = 1. These findings, combined with concentration field and BTCs, show that mechanical dispersion was similar for the 500 g scaled model and 1 g prototype.

Based on these results and fracture aperture similarity, feasibility and required conditions for hyper-gravity experiments of solute transport in fractured rock masses are summarized in Table 7 . In smooth fracture models, the advection process is characterized by laminar flow, and hydrodynamic dispersion is dominated by molecular diffusion when fracture aperture similarity ratio between prototype and model is 1:1 (permeability coefficient similarity ratio is 1:1), and Re and Pe are less than critical values. Mechanical dispersion can be ignored; thus, 500 g scaled experiments can reproduce flow and solute transport processes of the 1 g prototype. Therefore, if flow and solute transport processes are similar, long-term barrier performance of low-permeability fractured rock masses can be verified by hyper-gravity experiments to reveal long-term solute transport through geological barriers and improve theoretical models.

5. Conclusions

Normal gravity and hyper-gravity experiments of solute transport in fractured rock were conducted with a sealed control apparatus containing 3D-printed single/fracture network models. Flow and solute transport characteristics of fracture models were obtained under different pressures and g levels. Flow velocity, cumulative concentration curves, and BTCs under normal gravity and hyper-gravity were compared, and BTC fitting results were discussed. Subsequently, a new method for evaluating long-term barrier performance of low-permeability fractured rock masses using hyper-gravity experiments was proposed. Feasibility of this method to simulate nuclide transport in deep geological disposal reservoirs was discussed. The following conclusions were obtained:

(1) Pore water pressure and water level increased linearly over time, indicating unchanged flow velocity in the model. Difference in flow velocity between normal gravity and hyper-gravity experiments ranged from 0.97 to 3.12%, suggesting that internal fractures of 3D printed single/network fracture models under hyper-gravity were relatively stable and flow characteristics remained the same. Trends of cumulative concentration were consistent in normal gravity and hyper-gravity experiments, and BTCs were slightly different. Difference in fitted hydrodynamic dispersion coefficient between experiments ranged from 9.09 to 20.4%, demonstrating that solute transport characteristics in 3D printed single/network fracture models under hyper-gravity were within acceptable range.

(2) Results of normal gravity and hyper-gravity experiments showed that solute transport in fractured rock masses was affected by fracture aperture, roughness, and geometry but not by hyper-gravity. Therefore, hyper-gravity experiments can be used to simulate water pressure gradient, hydraulic boundary conditions, and solute transport in fractured rock masses.

(3) OGS software was used to simulate and analyze flow and solute transport in the 1 g prototype, 1 g scaled model, and 500 g scaled model. BTCs of the fracture network model were compared at different outflow locations and simulation conditions. Results showed that hyper-gravity experiments could reproduce flow and solute transport in normal gravity prototype when Re < Recr and Pe < Pecr. Our results provide technical support for studying solute transport characteristics in large-scale complex fracture network models and predicting contaminant breakthrough such as nuclides in fractured rock masses. The proposed method is suitable for verifying long-term barrier performance of deep earth projects, such as deep geological disposal.

In this study, to systematically investigate hyper-gravity effects on fluid flow and solute transport in fractured rock, we only considered parallel fracture models. However, under real conditions, rough-walled fractures are more frequent [?, ?, ?, ?, ?, ?, ?]. Therefore, more realistic conditions considering fracture roughness in rough-walled fractures are needed for future studies. More importantly, hyper-gravity similarity in rough-walled fractures remains an open question. Before applying geotechnical centrifuge modeling techniques to replicate flow and transport processes in real fractured rocks, continued research on similarity of flow and transport in complex fractured rocks is necessary. Additionally, further research is required for higher G-levels of centrifuge gravity or different flow regimes such as non-Darcy’ s flow.

References

Arulanandan, K., et al., 1988. Centrifuge modeling of transport processes for pollutants in soils. Journal of Geotechnical Engineering-ASCE 114 (2), 185-205.

Brouwers, L.B., Dippenaar, M.A., 2018. Partially Saturated Flow from Sand into a Discrete Smooth Open Vertical Fracture at the Soil-Rock Interface: Experimental Studies. Bulletin of Engineering Geology and the Environment.

Chen, Y., Han, C., Ling, D., Kong, L., Zhou, Y., 2011. Development of geotechnical centrifuge ZJU400 and performance assessment of its shaking table system. Chin. J. Geotech. Eng. 33 (12), 1887-1894.

Costin, L.S., 1997. Site Selection and Characterization Processes for Deep Geologic Disposal of High Level Nuclear Waste. Office of Scientific & Technical Information Technical Reports.

Dou, Z., Sleep, B., Zhan, H., Zhou, Z., Wang, J., 2019. Multiscale roughness influence on conservative solute transport in self-affine fractures. Int. J. Heat Mass Tran. 133, 375-387.

Griffioen, J.W., Barry, D.A., 1999. Centrifuge modeling of unstable infiltration and solute transport. J. Geotech. Geoenviron. Eng. 125 (7), 556-565.

Gurumoorthy, C., Singh, D.N., 2004. Centrifuge Modeling of diffusion through rock mass. J. Test. Eval. 33 (1), 44-50.

Hensley, P.J., Schofield, A.N., 1991. Accelerated physical modelling of hazardous-waste transport. Geotechnique 41 (3), 447-466.

Huang, N., Jiang, Y., Liu, R., Li, B., Sugimoto, S., 2019. A novel three-dimensional discrete fracture network model for investigating the role of aperture heterogeneity on fluid flow through fractured rock masses. Int. J. Rock Mech. Min. Sci. 116, 25-37.

Jones, B.R., Brouwers, L.B., Tonder, W.D.V., Dippenaar, M.A., 2017. Assessing geotechnical centrifuge modelling in addressing variably saturated flow in soil and fractured rock. Environ. Sci. Pollut. Res. Int. 24 (15), 1-21.

Jones, B.R., Van Rooy, J.L., Dippenaar, M.A., 2018. Lugeon Tests at Partial Saturation: Experimental and Empirical Contributions. Rock Mechanics and Rock Engineering.

Kumar, R.P., Singh, D.N., 2012. Geotechnical centrifuge modeling of chloride diffusion through soils. Int. J. GeoMech. 12 (3), 327-332.

Laverov, N.P., Omelianenko, B.L., Velichkin, V.I., 1994. Geological Aspects of the Nuclear Waste Disposal Problem. Office of Scientific & Technical Information Technical Reports.

Levy, L., Culligan, P., Germaine, J., 2003. Modelling of DNAPL behavior in vertical fractures. International Journal of Physical Modelling 3 (1), 1-19.

Levy, L.C., Culligan, P.J., Germaine, J.T., 2002. Use of the geotechnical centrifuge as a tool to model dense nonaqueous phase liquid migration in fractures. Water Resour. Res. 38 (8), 34-1-34-12.

Lo, I.M.C., Hu, L.M., Meegoda, J.N., 2004. Centrifuge modeling of light nonaqueous phase liquids transport in unsaturated soils. J. Geotech. Geoenviron. Eng. 130 (5), 535-539.

Makedonska, N., et al., 2016. Evaluating the effect of internal aperture variability on transport in kilometer scale discrete fracture networks. Adv. Water Resour. 94, 486-497.

Mckinley, I.G., Alexander, W.R., Blaser, P.C., 2007. Development of geological disposal concepts. Radioact. Environ. 9 (6), 41-76.

Ng, C.W.W., 2014. The state-of-the-art centrifuge modelling of geotechnical problems at HKUST. Journal of Zhejiang University. A. Science 15 (1), 1-21.

Nishimoto, S., Sawada, M., Okada, T., 2016. New rapid evaluation for long-term behavior in deep geological repository by geotechnical centrifuge. Part 1: test of physical modeling in near field under isotropic stress-constraint conditions. Rock Mech. Rock Eng. 49 (8), 3323-3341.

Sawada, M., Nishimoto, S., Okada, T., 2017. New rapid evaluation for long-term behavior in deep geological repository by geotechnical centrifuge—Part 2: numerical simulation of model tests in isothermal condition. Rock Mech. Rock Eng. 50 (1), 267-285.

Schofield, A.N., 1980. Cambridge geotechnical centrifuge operations. Geotechnique 30 (3), 227-268.

Soga, K., Kawabata, J., Kechavarzi, C., Coumoulos, H., Waduge, W.A.P., 2003. Centrifuge modeling of nonaqueous phase liquid movement and entrapment in unsaturated layered soils. J. Geotech. Geoenviron. Eng. 129 (2), 173-182.

Taylor, R.N., 1995. Geotechnical Centrifuge Technology. CRC Press.

Wang, J., Chen, L., Su, R., Zhao, X., 2018. The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: planning, site selection, site characterization and in situ tests. J. Rock Mech. Geotech. Eng. 10 (3), 411-435.

Ye, Z., Liu, H., Jiang, Q., Liu, Y., Cheng, A., 2017. Two-phase flow properties in aperture-based fractures under normal deformation conditions: analytical approach and numerical simulation. J. Hydrol. 545, 72-87.

Zhan, L., et al., 2022a. Effects of multiscale heterogeneity on transport in three-dimensional fractured porous rock with a rough-walled fracture network. Comput. Geotech. 148, 104836.

Zhan, L., You, Y., Zhao, R., Chen, C., Chen, Y., 2022b. Centrifuge modelling of retardation migration in loess-amended soil-bentonite barriers. Int. J. Phys. Model. Geotech. 1-35.

Zou, L., Cvetkovic, V., 2020. Inference of transmissivity in crystalline rock using flow logs under steady-state pumping: impact of multiscale heterogeneity. Water Resour. Res. 56 (8).

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