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Nonlinear Dynamics of Gas Migration in Water-Saturated Compacted Clay

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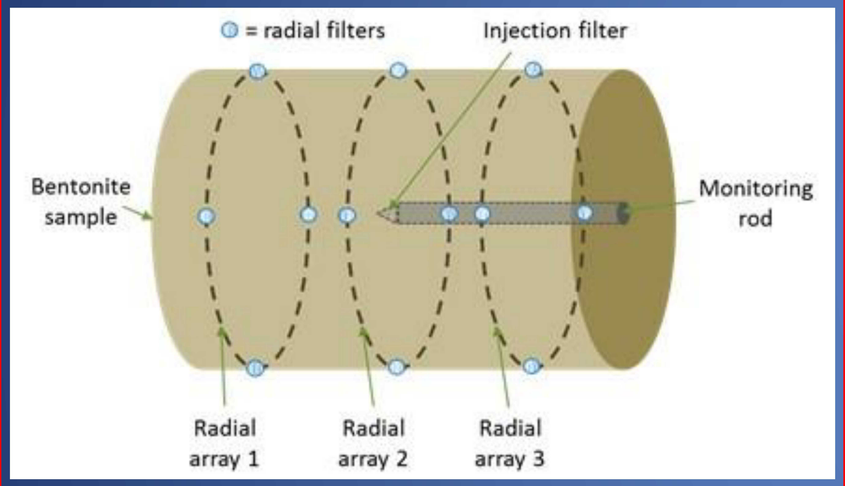
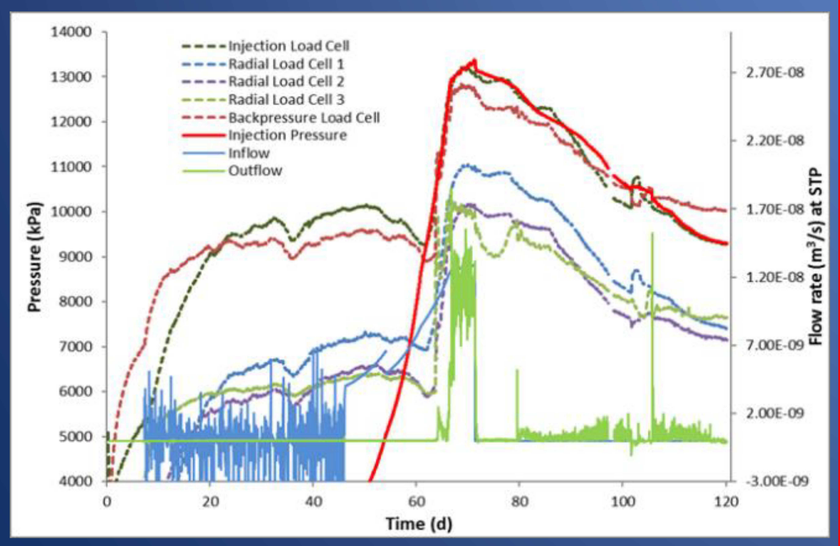
Introduction

Bentonite has been proposed as a buffer/barrier material for nuclear waste disposal. Gas generation from metal corrosion and its potential impact on material structural integrity are an important concern in long-term waste isolation. To investigate the underlying mechanism for gas migration in a buffer material, gas injection experiments on bentonite Mx80-D were conducted at the British Geological Survey. The experimental data show that gas migration in a water-saturated compacted clay material exhibits rich nonlinear dynamic behaviors as the injection gas pressure varies: from a constant flow to a periodic flow and eventually to a chaotic behavior.

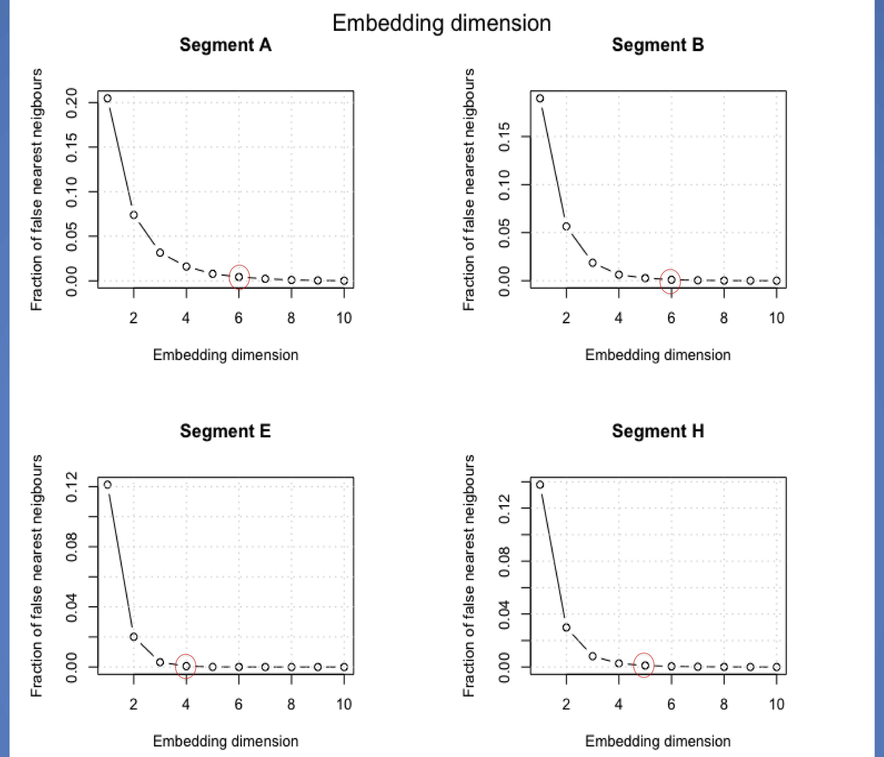




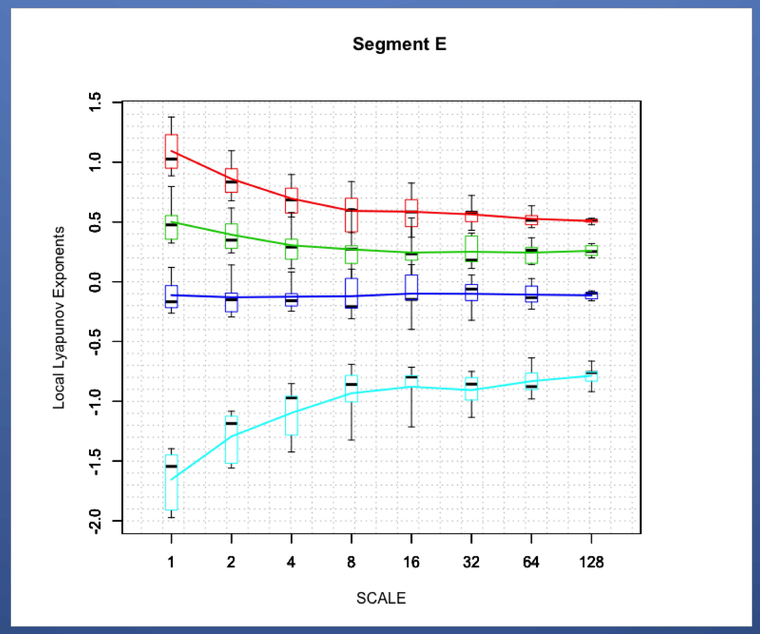
Experimental setup and measurements of gas inflow and outflow rates in water-saturated compacted bentonite Mx80-D.

Time Series Analysis

Evaluation of the Global Embedding Dimension (GED=4-6) indicates phenomena of low-dimensional chaos with both deterministic and small stochastic components. Global Embedding Dimension was calculated using the False Nearest Neighbors Method

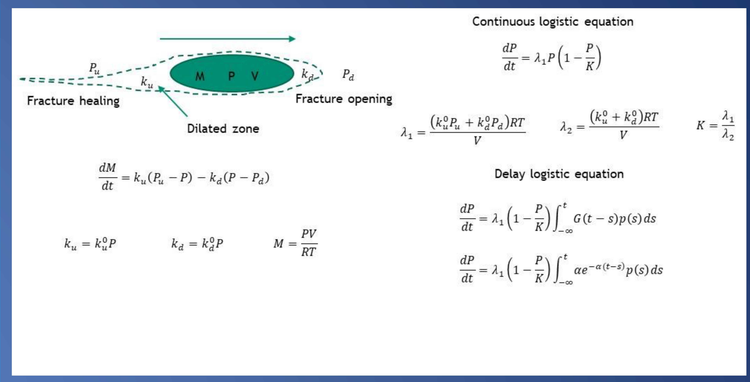


Spectrum of Lyapunov Exponents of gas outflow indicates a combination of deterministic and stochastic chaotic components. The sum of positive and negative Lyapunov exponents is positive, indicating that the attractors are not converging, likely due to the presence of the stochastic component.



Physical Model

Bubble migration under a pressure gradient



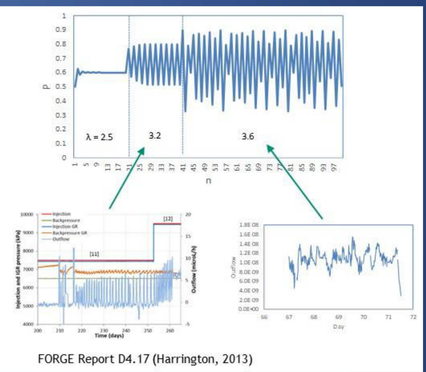
Logistic equation and chaotic behavior

$$\frac{dP}{dt} = \lambda_1 p\left(1 - \frac{P}{K}\right)$$

$$P_{n+1} = P_n + \lambda_1 P_n\left(1 - \frac{P}{K}\right)\Delta t$$

$$\lambda = 1 + \lambda_1 \Delta t$$

$$p_{n+1} = \lambda p_n (1 - p_n)$$



Summary

To test if the flow rate variation is truly chaotic, we have performed a time series analysis for gas inflow and outflow measurements. It is found the embedded dimension for the gas migration phenomenon ranges from 3 to 4. In the embedded space the flow rate seems to possess an internal structure (a chaotic attractor), i.e., not completely random (white noise), indicating a deterministic chaotic behavior. To explain this dynamic behavior, we have developed a chaotic model based on the concept of delay logistic model. In this model, we show that, given a low permeability of the material, the dominant mechanism for gas migration is first to nucleate a bubble and then push the bubble through the clay matrix through dilation and fracturing. In the wake of bubble movement, matrix compression and fracture healing may also take place. The chaotic model thus provides a new perspective for modeling gas migration in low-permeability materials.

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