Fundamental study on estimation of permeability at in-situ EDZ from pore air pressure response

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ABSTRACT: In this paper, we report the results of measuring the pore air pressure response at an isolated space in a rock block while pressure changes are given within a pressure range slightly less than atmospheric pressure. The transient decay method and the oscillation method were adopted to estimate the permeability in the laboratory. In transient decay method, the pressure outside of the rock block reduce from atmospheric pressure to 930 hPa, and the pore air pressure inside the block is monitored. On the other hand, the oscillation method applies a fixed amplitude and fixed frequency with a pressure of 900 to 950 hPa. After analyzing the recorded data, the estimated permeability values from two methods were compared with the permeability determined from measurements of flow rate through a sample under a constant pressure gradient.

Keywords: In-situ permeability test, Transient pulse test, Pore air pressure oscillation method, Intrinsic permeability, Excavation Damaged Zone (EDZ).

1 INTRODUCTION

The evaluation of permeability in an excavation damaged zone (EDZ) is very important in geological disposal of high-level radioactive waste. The permeability at a certain position in EDZ can also change over time due to late deformation and deterioration. There is a need for a methodology to measure permeability in situ, quickly and easily, including transient changes. We are studying a method of estimating permeability using atmospheric pressure fluctuations. A similar study has already been conducted by Jakubick & Franz (1993), but we are aiming for a simpler, long-term observation technique.

To achieve this, we are currently conducting long-term in-situ observations (Osada et al. 2019, 2021). However, it is still unclear how the pore air pressure in a rock mass responds to irregular changes such as atmospheric pressure fluctuations. The transient pulse (Brace et al. (1968)) and oscillation methods (Kranz et al. (1990), Fischer (1992) and Hasanov et al. (2019)) were originally developed to determine the permeability of rocks under high confining pressure, and it is necessary to examine whether these methods can be applied to small changes in air pressure, such as atmospheric pressure fluctuations.

In this study, we examined whether these methods can adequately evaluate permeability even for changes within the range of atmospheric pressure observed in the natural world.

2 METHODOLOGY AND SAMPLES TO BE USED

Triassic slate, which is called as Inai-ishi, was used as the sample. Physical properties are summarized in Table 1. The grain density is 2.765 g/cm^3 and the effective porosity is 0.56 % (Takakura 2018). It is a very tight and dark slate. Cylindrical specimens with a diameter of 49.5 mm and the height of 10 mm were used for the conventional permeability tests, and the 18 cm cubic block sample was used for transient pulse tests and oscillation tests.

In series of experiments described here, an integrated environmental sensor BME280 (Bosh Sensortec) manufactured by Switch Science Co., Ltd. was used to measure air pressure. This sensor can simultaneously measure air temperature and relative humidity. Measurement accuracy is temperature ±1℃, humidity ±3 %, and atmospheric pressure ±1hPa. We call this sensor the THP sensor in this paper.

In the block sample, a hole with a diameter of 20 mm and the depth of 100 mm was drilled at the center of the block. The block was dried at 110 °C for 24 hours and cooled in desiccator. Then, a THP sensor covered with a plastic capsule was placed in the hole of the rock block and was injected with silicon sealant to isolate the sensor. Once the silicon had hardened, the rock block was placed inside the vacuum box, and the sensor inside the rock block and the sensor for measuring the external pressure were connected to data logger (a microcomputer, Raspberry Pi is used for data logger).

The vacuum controller NVC-3000 made by Tokyo Science Machinery Co. was used to set a given pressure and pressure cycles.

Table 1. Physical properties of the sample.

Inai slate	unit	Value	remarks
Grain density	[g/cm^3]	2.765	
Wet density ρ	[g/cm^3]	2.763	Takakura (2018)
Porosity ϕ	[%]	0.56	Takakura (2018)
Water content	[%]	0.161	
Intrinsic permeability K	[m^2]	1.50×10^{-18}	

2.1 Conventional gas permeability test

To determine the intrinsic permeability of this slate sample, a conventional permeability test was conducted. A rock sample is set in a pressure vessel, sealed, and injected with nitrogen gas from the upstream side, which passes through the rock sample and flows out downstream. This downstream nitrogen gas is collected to measure the volume of gas flow.

From the flow rate obtained, the intrinsic permeability was determined using the following equation (1).

$$K = \frac{2Q_g \mu p_a}{A} \cdot \frac{l}{{p_0}^2 - {p_1}^2} \tag{1}$$

where K [m^2] is intrinsic permeability, Q_g [m^3/s] is gas outflow under atmospheric pressure condition, μ [Pa s] is viscosity coefficient of fluid (=1.76×10^{-5} for Nitrogen gas), p_a [Pa] is atmospheric pressure (= 1013 [hPa]), A [m^2] is cross-sectional area, l [m] is length of sample, p_0 [Pa] is absolute pressure at inlet (= 5013 [hPa]), and p_1 is absolute pressure at outlet (= 1013 [hPa]).

The intrinsic permeability obtained here is taken as the true value, and the results of the other two permeability test methods are discussed.

2.2 *Transient pulse test*

Set the vacuum controller to 930 hPa in manual mode and measure the pressure inside the rock block until it converges to the external pressure. The data of temperature, humidity, and air pressure in the vacuum box and inside the block are recorded at one-second intervals. After the experiment, the next experiment is started as soon as the air pressure inside the rock block returns to atmospheric pressure. 10 experiments are performed.

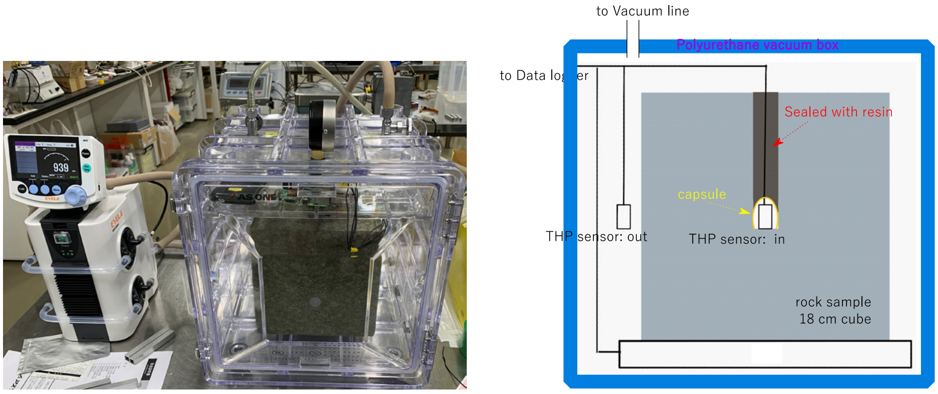

Figure 1. Experimental setup for transient pulse method and the oscillation method. Left: vacuum controller and the vacuum box installed the sample. Right: schematic drawing for sensor setup.

The time history curves obtained from the experiment are compared by solving equation (2), which is a three-dimensional extension of the governing equation of Brace et al. (1968) for the boundary conditions of the block sample using finite element method. The range of possible intrinsic permeabilities is estimated by varying the intrinsic permeability by several orders of magnitude.

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2} = \frac{\mu\beta}{K}\left[\frac{\beta_{eff} - \beta_S}{\beta} + \emptyset\left(1 - \frac{\beta_s}{\beta}\right)\right]\frac{\partial P}{\partial t} \tag{2}$$

where P[Pa] is air pressure, μ [Pa · s] is fluid viscosity (=1.83×10-5 for air), ϕ is porosity, β[1/Pa] is fluid compressibility, β_{eff} [1/Pa] is effective compressibility of the rock as measured for a jacketed sample, β_s [1/Pa] is compressibility of the minerals in the rock.

2.3 *Oscillation test*

In the oscillation method, the pressure is first reduced from atmospheric pressure to 900 hPa, and then the response of the pressure inside the rock block is measured when a triangular wave with a fixed period is applied between 900 hPa and 950 hPa. The periods used ranged from 4 to 88 minutes. The relationship between the period and the amplitude ratio R and the phase shift δ under steady-state conditions are examined.

3 RESULTS

3.1 *Transient pulse test*

The results of the transient pulse test are shown in Figure.2. The air pressure inside the vacuum box (out) reaches its default setting value in 1.5 to 2 minutes. In contrast, the air pressure inside the rock block gradually reaches the same level as the outside pressure in 45 minutes to 1 hour. The same experiment was repeated 10 times on the same block sample, and the curves follow nearly identical paths, indicating a high degree of reproducibility.

In Figure 2, the numerical results are shown for three orders of variation of the intrinsic permeability. The experimental values are located between 1×10^{-18} and 1×10^{-17}, which is close to the 3×10^{-18} line. The estimated intrinsic permeability obtained in this way is of the same order as the results of the conventional permeability test shown earlier. In addition, Figure 3 shows the pressure distribution inside the rock block as indicated by the numerical analysis. The pressure varies from the outside to the inside, and this relationship is not linear with position, indicating the effect of the compressibility of air.

In the usual transient pulse method, the cross sections of the upstream and downstream specimens are assumed to be the same. Therefore, the method of Brace et al. (1968) cannot be applied directly to the present experimental conditions, and a numerical analysis as described above must be used. It should be noted that if one wants to know the order of intrinsic permeability, one can substitute the surface area of the rock block for the upstream cross-sectional area under the present conditions.

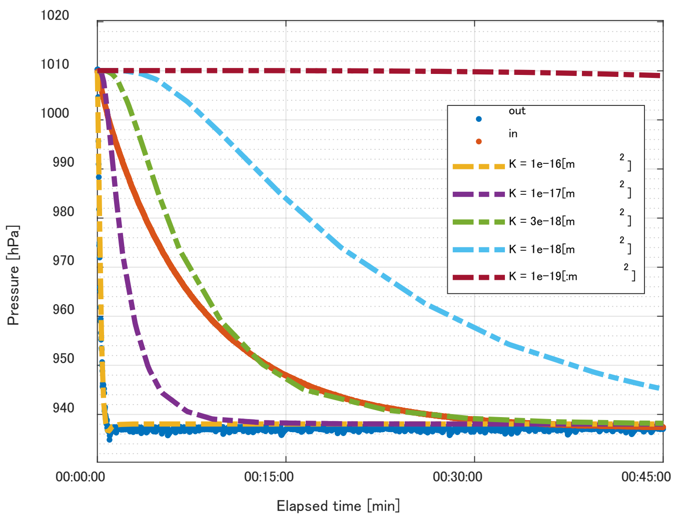

Figure 2. Result of transient pulse test with numerical simulation for various intrinsic permeabilities.

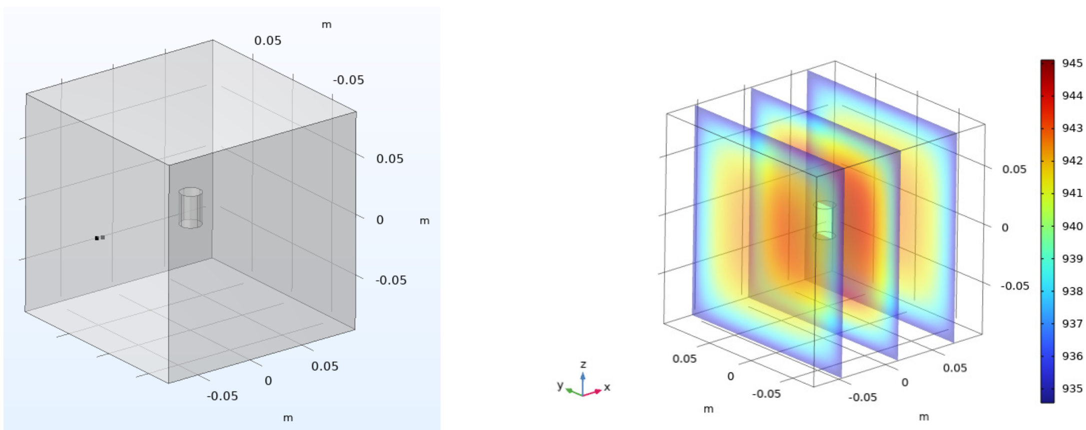

Figure 3. Pressure distribution inside the block. Left: model to be constructed. Right: after 105 seconds.

3.2 *Oscillation test*

Figure 4. (Left) shows the measurement results when the periods were 4 and 8 minutes. The horizontal axis of the figure shows the number of cycles obtained by dividing the elapsed time by the period. The normalized air pressure (out) in the vacuum box almost overlaps, and the amplitude

of the air pressure is almost constant. On the other hand, the air pressure (in) inside the rock block gradually decreases and approaches a convergence value of 930 hPa, as in the transient pulse test, indicating that it reaches a steady state around cycle 15. The amplitude of the air pressure (in) is clearly smaller than that of the air pressure (out). Comparing the steady-state amplitudes for the 4-minute and 8-minute cycles, the amplitude for the 8-minute cycle is slightly larger.

Figure 4. (Right) shows the relationship between the steady-state amplitude ratio R and phase shift δ and the period. The results show that the phase shift and amplitude attenuation are strongly affected by the period, and that the phase shift and amplitude attenuation become smaller as the period increases.

The numerical simulation for the oscillation test is still under consideration. Instead, the intrinsic permeability was estimated from the amplitude ratio R and phase shift δ obtained from the tests by assuming the cross-sectional area to be the surface area of the rock block like the transient pulse test. The estimated value is 2.23×10^{-18} $[m^2]$, and close to the intrinsic permeability of this slate sample.

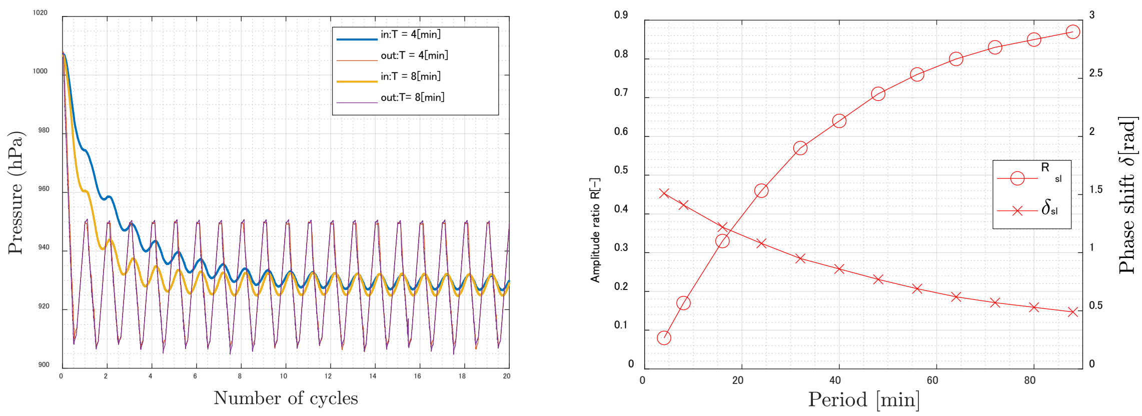

Figure 4. Result of oscillation tests. Left: air pressure behaviors. Right: the relations between amplitude ratio, phase shift and period.

4 SUMMARY

This study examines the applicability of the transient pulse method and the oscillation method, which were developed to estimate the seepage characteristics of rocks under high confining pressure, to estimate the seepage characteristics in the excavation damaged zone formed around the tunnel wall. By combining various laboratory tests with 3D FEM, it is shown that these two methods can be applied to small changes in atmospheric pressure such as atmospheric pressure fluctuations.

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