Application of the Transient Pulse Method to Measure Clay Permeability*1

Masaji Kato1, Yoshitaka Nara2,*,2, Yuki Okazaki3, Masanori Kohno3, Toshinori Sato4, Tsutomu Sato1 and Manabu Takahashi5

1Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan
2Graduate School of Engineering, Kyoto University, Kyoto 615-8540, Japan
3Graduate School of Engineering, Tottori University, Tottori 680-8552, Japan
4Japan Atomic Energy Agency, Horonobe-cho, Hokkaido 098-3224, Japan
5National Institute of Advanced Industrial Sciences and Technology, Tsukuba 305-8567, Japan

To ensure the safe geological disposal of radioactive waste, it is important to determine the permeability (hydraulic conductivity) of clays. The transient pulse method is suitable for low-permeability materials because it requires a relatively short time to determine their permeability. Upstream pore pressure typically increases in the measurement conducted via the transient pulse method. However, this procedure cannot be used to determine the permeability of clays due to the increase in pore pressure. Therefore, the transient pulse method has never been applied to determine clay permeability. In this study, we applied the transient pulse method to a clay sample obtained in the Mizunami Underground Research Laboratory to determine its permeability while decreasing the downstream pore pressure. We found that this method was also appropriate for conducting measurements on granite. The hydraulic conductivity of the clay measured by the proposed method was higher by a factor of 10 compared to the conventional constant head method, indicating that hydraulic conductivity can be determined using the transient pulse method with reasonably small error. The measurement time of the transient pulse method was much shorter than that of the falling head method. We concluded that the transient pulse method is appropriate for determining clay permeability.

Keywords: clay, granite, hydraulic conductivity, permeability test, transient pulse method

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1. Introduction

The geological disposal of radioactive waste involves using a rock mass as a natural barrier. A low-permeability rock mass containing fractures filled with materials such as clays can provide a suitable disposal environment. To understand the characteristics of these natural barriers, measurements of the hydraulic conductivity of rocks and clays are essential.

Laboratory hydraulic conductivity measurement approaches include the constant head method,1 the falling head method,2 the constant flow method (formerly the flow pump method),3,4 and the transient pulse method.5,6 The transient pulse method is effective for the measurement of a material with low permeability (hydraulic conductivity: 10−14 to 10−8 m/s).12 In this method, a hydraulic head pulse (or pore pressure pulse) is applied to the upstream side of the specimen, which is covered by a jacket made of a soft material, such as rubber, and set in a pressure vessel. The difference between the upstream and downstream pore pressure then decreases over time.

The transient pulse method has been widely used to measure the hydraulic conductivity of low-permeability rocks.7-11,13,14 However, it is difficult to apply this method to clays, despite their low permeability. For clays, permeability measurement and consolidation tests require the control of water flow by placing the clay in a high-rigidity container under a confining pressure. In contrast, a soft material, such as rubber, is used as the jacket during permeability measurements of rocks. If a clay sample is covered by a soft jacket and placed in a permeability measurement system designed for rocks, then pore pressure increases with increased confining pressure under undrained conditions. When a confining pressure is applied under drained conditions, clay pore pressure increases due to the low permeability of the clay, causing a delay in water flow despite simultaneous clay deformation. This process leads to further deformation of the clay. If the effective pressure is large, the jacket also becomes significantly deformed, and the pore fluid can flow out to the confining pressure medium. Therefore, a transient pulse permeability test for clay will inevitably lead to an effective pressure that approaches 0. In addition, if we increase the upstream pore pressure during such a test, the pore pressure may become higher than the confining pressure, because the pore pressure was initially very similar to the confining pressure. The pore fluid would then flow out to the confining pressure medium, preventing completion of the permeability test.

However, it is meaningful to apply the transient pulse method in clay permeability measurement, because hydraulic conductivity can be determined within a short measurement period. If the measurement period is shortened, the temperature change in the surrounding environment during the permeability test decreases15 and measurement can be conducted with high accuracy. However, the transient pulse method has not yet been applied for the determination of hydraulic conductivity in clays.

In this study, we applied the transient pulse method to determine the hydraulic conductivity of a clay sample and compared the effectiveness of the method between clay and rock samples.

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*2Corresponding author, E-mail: nara.yoshitaka.2n@kyoto-u.ac.jp
2. Experimental Procedure

2.1 Experimental outline

We used the permeability measurement system shown in Fig. 1 to test the proposed method. This system permitted the application of the transient pulse method under strictly controlled temperatures.\(^\text{15)}\)

The transient pulse method was introduced by Brace et al.\(^\text{7)}\) for the purpose of granite permeability measurement under high confining pressure and high pore pressure. This method is well known for the evaluation of hydraulic conductivity in low-permeability rocks over a short period. Brace et al.\(^\text{7)}\) introduced the approximate solution to evaluate hydraulic conductivity, as follows:

\[
\frac{h_u - h_d}{H} = \exp \left\{ -\frac{KAt}{l} \left( \frac{1}{S_u} + \frac{1}{S_d} \right) \right\} \tag{1}
\]

where \(H\) (m) is the water head pulse (initial difference between the upstream and downstream water heads), \(h_u\) (m) and \(h_d\) (m) are the upstream and downstream water heads, respectively, at an elapsed time \(t\) (s) after applying the water head pulse, \(l\) (m) is the length of the specimen, \(A\) (m\(^2\)) is the cross-sectional area of the specimen, \(S_u\) (m\(^3\)) is the compressional storage of the upstream reservoir, \(S_d\) (m\(^3\)) is the compressional storage of the downstream reservoir, and \(K\) (m/s) is the hydraulic conductivity. \(K\) is then evaluated from the temporal change of the water head difference (differential head).

2.2 Samples

We used granite and clay samples in this study.

Toki granite is a coarse- to medium-grained biotite granite with a mean grain size of 3–4 mm. The Toki granite sample was obtained from the 08MI14 borehole at the Mizunami Underground Research Laboratory, Mizunami, Japan. This borehole was excavated in a direction normal to the ventilation shaft at the Mizunami Underground Research Laboratory for various geoscience studies, at a depth of 200 m below ground level. The granite sample was prepared for the permeability measurement from the intact part of the rock sample, and cut into a cylinder with a diameter of 50 mm and length of 25 mm. The porosity of the granite sample was 0.8%. A scanning electron photomicrograph of the Toki granite is shown in Fig. 2.

The clay sample used in this study was obtained from the side wall of the tunnel 200 m below ground level at the Mizunami Underground Research Laboratory. The void ratio and porosity of the clay sample were 2.6 and 72%, respectively. A scanning electron photomicrograph of the clay sample is shown in Fig. 3, and an X-ray diffraction pattern of the clay sample is shown in Fig. 4. The clay sample consisted mainly of mica clay minerals; its particle size distribution is shown in Fig. 5. The clay sample was not self-supporting due to its low rigidity.

Both granite and clay samples were saturated with distilled water by vacuum degassing in a desiccator, and then maintained in distilled water under vacuum conditions until they were placed in the pressure vessel of the permeability measurement system.

Because the clay sample was not self-supporting, it was kept in a high-rigidity container during the permeability measurement. To avoid any influence from differences in the

![Fig. 1 Schematic illustration of permeability test system. RT: resistance thermometer, Bar: barometer, PT: pressure transducer, DPT: differential pressure transducer.](image)

![Fig. 2 Scanning electron microscope (SEM) photomicrograph of the granite sample. Height: 0.096 mm; length: 0.128 mm.](image)

![Fig. 3 SEM photomicrograph of the clay sample. Height: 0.096 mm; length: 0.128 mm.](image)
experimental apparatus, we used the same rubber jacket for both the clay and granite samples. The shape of both samples within the rubber jacket was therefore the same. The sample was then set in the pressure vessel of the permeability measurement system (Fig. 1). We verified that the flow rate was 0, and applied water to the sample under a constant pore pressure after degassing the permeability measurement system. Thus, we were able to ignore any influence of suction on the experimental results.

Granite has high rigidity, low porosity, low storability, and low permeability, whereas clays possess low rigidity, high porosity, high storability, and low permeability. The value of Skempton’s $B$ coefficient for granite is $0.55 - 0.85$, and that of clay is $0.99$. In this study, due to the rigidity of the storage tanks, pipes, and valves of the permeability measurement system, we could not determine the value of Skempton’s $B$ coefficient.

Conducting measurements using the transient pulse method is possible when a confining pressure is applied to the sample. When the pressure applied to the clay sample increased, the pore pressure increased simultaneously due to the low rigidity of the clay sample, which led to large deformation. Therefore, all measurements for the clay sample were conducted at an effective pressure approaching zero. The confining pressure applied to the clay sample was in the range 0.6–4.1 MPa, which would represent overconsolidation of the clay at a depth of 200 m below ground level.

3. Results

Figure 6 shows the temporal changes in the differential head normalized by the maximum value for Toki granite obtained using the transient pulse method under 1 MPa effective pressure. Figures 6(a) and (b) show the temporal change obtained by increasing the upstream pore pressure (i.e., by applying the pressure pulse upstream) and decreasing the downstream pore pressure. To reach 85% and 99% decreases in the differential head took approximately 40 and 110 minutes, respectively. From these changes, we determined the hydraulic conductivity using the approximate solution by Brace et al., shown in eq. (1); this solution produced the dotted curves in Fig. 6. The resulting hydraulic conductivity values were $4.32 \times 10^{-12}$ m/s for increasing upstream pore pressure and $3.77 \times 10^{-12}$ m/s for decreasing downstream pore pressure, respectively. These values agree well with each other; therefore, the hydraulic conductivity of granite was successfully determined using the transient pulse method, by increasing upstream pore pressure and decreasing downstream pore pressure.

As described above, it is impossible to conduct a transient pulse permeability test for clay by increasing the upstream pore pressure. We therefore conducted the test for the clay sample by decreasing the downstream pore pressure.

Figure 7 shows the temporal change in the differential head normalized by the maximum value for the clay sample. It took approximately 42 minutes to reach an 85% decrease in the differential head. Using the approximate solution of Brace et al., the hydraulic conductivity was determined to be $2.05 \times 10^{-11}$ m/s. Figure 8 shows hydraulic conductivity values for the clay sample determined under different confining pressures. Since the effective pressure was constant...
for all measurements, the influence of confining pressure on the hydraulic conductivity of the clay sample was very low. Therefore, the hydraulic conductivity of clay was successfully determined using the transient pulse permeability test over a short period.

4. Discussion

Using granite samples, we successfully evaluated hydraulic conductivity using the transient pulse permeability test by increasing the upstream pore pressure and decreasing the downstream pore pressure. Therefore, we were able to evaluate the hydraulic conductivity of clay using the transient pulse permeability test by decreasing the downstream pore pressure.

It is essential to obtain the temporal change (decay curve) in the differential head using the transient pulse method. For a material with high permeability, it is impossible to obtain the decay curve of the differential head, because the difference in the water head decreases rapidly despite the difference in pore pressure applied upstream and downstream. It is therefore impossible to conduct permeability measurements using the transient pulse method for such materials.

We were able to obtain the decay curve of the differential head (Fig. 7) and could therefore evaluate the hydraulic conductivity of the clay sample. However, there was a greater difference between the decay curve obtained by measurement and the approximate curve obtained from the solution of Brace et al.\(^7\) for the clay sample than for granite (Fig. 6). This greater difference was likely caused by the lower rigidity, higher porosity, and higher storability of the clay sample. The solution of Brace et al.\(^7\) was obtained by assuming that the compressional storage of the sample was much smaller than that of the apparatus. This assumption may have caused the difference between the experimentally obtained decay curve and the approximated curve. However, if the data on the approximated curve include both sides of the intersection point between the experimental decay curve and the approximate curve, we can evaluate an appropriate value of hydraulic conductivity, despite the included error. This error can be determined from data analysis of the error bars shown in Fig. 8. Additionally, since the transient pulse method has never been used to determine the hydraulic conductivity of clay, we decided to use a conventional experimental method and compare the result to that from the transient pulse method. We therefore applied the falling head method\(^2\)-\(^4\) to determine the hydraulic conductivity of the clay sample.

In the falling head method, the hydraulic conductivity is calculated by the following equation:

\[
K = \frac{al}{At} \ln \frac{H_u - h_d}{h_u - h_d}
\]

where \(a\) (m\(^2\)) is the cross-sectional area of the standpipe, \(H_u\) (m) is the initial value of the upstream water head, and \(h_u\) (m) and \(h_d\) (m) are the upstream and downstream water heads at an elapsed time \(t\) (s), respectively.

A photograph of the apparatus for the falling head permeability test is shown in Fig. 9. The shape of the standpipe is a circle with a diameter of 54 mm, and the length \(l\) of the sample was 8 mm. Figure 10 shows the temporal change in the differential head during the transient pulse permeability test on the clay sample.

Fig. 7 Temporal change in the differential head during the transient pulse permeability test on the clay sample.

Fig. 8 Relationship between hydraulic conductivity and confining pressure for the clay sample.

Fig. 9 Photograph of apparatus used for the falling head test.
change in the differential head. The hydraulic conductivity of the clay sample was determined to be $5.18 \times 10^{-10}$ m/s. This value is one order higher than that found by the transient pulse permeability test. This higher value may be due to the outflow of clay particles into the distilled water used in the experiment. However, this value is appropriate, because the difference from the value obtained by the transient pulse permeability test was around one order of magnitude. It took approximately 1 month to determine the hydraulic conductivity using the falling head test, and only approximately 1 hour using the transient pulse permeability test. The transient pulse permeability test is therefore obviously a more convenient method to conduct measurements under precisely controlled experimental conditions.

Hydraulic conductivity is dependent on the boundary conditions of the sample, particularly the stress condition. The displacement boundary condition has little influence on the experimental result under steady-state flow, but has a significant effect under non-steady-state flow due to the deformation of pores. If a difference in the apparatus causes such a difference in boundary conditions, then permeability measurement results will be affected. Therefore, hydraulic conductivities obtained by different experimental methods may have been obtained under different boundary conditions. We must ensure that the boundary conditions are appropriate for the measurement. In this study, the transient pulse permeability tests on the clay sample were conducted using the same apparatus at an effective pressure approaching 0. The falling head permeability test on the clay sample was also conducted under an effective pressure of 0. Deformation of the clay sample is possible during the transient pulse permeability test due to the use of a rubber jacket to set the sample. However, because the sample was set in a rigid container, there was little deformation in the clay sample during the falling head permeability test. This condition can simulate clays existing in rock fractures.

For the geological disposal of radioactive wastes, clays (especially bentonite) are used as the buffer material. Clay permeability measurements are therefore important. Rocks often include macroscopic fractures that are filled with clays. Mitchell and Faulkner\(^8\) suggested that the permeability of a rock can decrease if its fractures are filled with fine-grained particles such as clays. According to Nara \textit{et al.},\(^9\,20\) and Pérez-Flores \textit{et al.},\(^21\) the permeability of dense rocks such as igneous rocks is significantly affected by fine-grained rock fracture fillings. If the rock includes an open macroscopic fracture, its permeability is high. In contrast, the macroscopic fracture is filled with fine-grained particles, and permeability decreases. In addition, the permeability of fine-grained fillings in the fracture strongly influences the permeability of the rock.\(^19\) In the area around faults in a rock mass, permeability increases with an increase of the damaged zone immediately after faulting, providing flow paths for fluids and materials. However, these flow paths can be suppressed.\(^23\) Consequently, to understand the confining ability of a rock mass, it is essential to evaluate the permeability of fracture-filling materials such as clays. The application of the transient pulse method in clay permeability measurements is appropriate as long as the measurements are completed within a short period.

### 5. Conclusion

In this study, we evaluated the hydraulic conductivity of granite and clay using the transient pulse permeability test. Using a granite sample, we demonstrated that hydraulic conductivity can be determined using the transient pulse method by increasing upstream pore pressure and decreasing downstream pore pressure. We evaluated the hydraulic conductivity of a clay sample using the transient pulse method with decreasing downstream pore pressure, and compared it with that evaluated using the falling head method. Because the difference was approximately only one order of magnitude, we conclude that hydraulic conductivity can be successfully evaluated using the transient pulse permeability test.

Since permeability measurements can be completed within a short period, the transient pulse method is convenient. For low-permeability materials such as clays, the transient pulse method can be conducted by decreasing downstream pore pressure. We therefore conclude that the transient pulse method is appropriate for clay permeability measurements, and will be very useful in determining conditions for the safe geological disposal of radioactive waste.

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### REFERENCES