Evaluation of permeability of intact rock under confining pressure condition using a constant-head permeability tester

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Abstract. This study first developed an original constant-head permeability tester for rocks, which can represent the pressure environment that is deep underground (approximately 1,000 m) and directly measure runoff volume using an electronic balance. Second, this study measured the permeability of three intact rocks (Inada granite, Toyooka basalt, and Shakudani tuff) under confining pressure conditions using the constant-head permeability tester. The test was performed at 22±1°C in a temperature-controlled room. As result, we found that the hydraulic conductivity of Inada granite, which was measured using this device, is quite similar to that reported by Kato et al. [1]. In addition, the observed decline in permeability due to the confining pressure is consistent with the observations of Kato et al. [1]. Therefore, the permeability measurement system used in this study is established and reliable. In this full paper, an evaluation of the permeability of three intact rocks under confining pressure conditions using a constant-head permeability tester is presented along with the experimental data.

Keywords: Constant-Head Permeability Test, Confining Pressure, Intact Rock.

1 Introduction

It is very important to understand the permeability of rocks especially in engineering projects that require the underground utilization of bedrock, such as geologic disposal of high- and low-level radioactive wastes, liquefied petroleum/natural gas stockpiling, and carbon dioxide capture and storage. The network of fractures in a rock mass plays an important role because it provides a pathway for fluid flow in the rock. In order to ensure the ultra-long-term safety of geological disposal barrier systems, which have been attracting particular attention in recent years, it is extremely important to accurately determine the permeability of natural barrier materials (rock mass) under various conditions. In general, constant-head, falling-head, transient pulse, flow pump, pore pressure oscillation, and other methods are used to evaluate the permeability of rocks in the laboratory, and many researchers (e.g., [1]-[5]) have investigated the permeability of rock masses and rock materials using these methods. In particular, for rocks with low permeability, there are many examples of evaluating permeability using the transient pulse method proposed by Brace et al. [6]. On the other hand, there is an example of rock permeability evaluation using the constant-head method, which is regarded as a classical method, however, this method is often applied to rocks with a relatively high permeability with a hydraulic conductivity of about 10^{-5} m/s or more, and the constant water level method is not suitable for low-permeability rocks represented by intact rocks, and it is rarely implemented at present. In addition, since the constant-head method mainly uses a measuring cylinder to measure the runoff volume, the measurement error tends to be large. However, the constant-head method has the following three advantages over the transient pulse method. (1) Stable measurement results of...
runoff volume can be obtained, (2) If there is a leak from a pipe or sleeve, it can be easily detected, and (3) The measurement method is simple and does not require special know-how.

First, this study developed an original constant-head permeability tester for rocks. This tester can freely adjust the confining pressure and hydraulic pressure (hydraulic gradient) (i.e., this tester can represent the pressure environment deep underground (approximately 1,000 m)), and can directly measure the runoff volume using an electronic balance. This tester can measure the hydraulic conductivity more accurately than the conventional constant-head method that measures the runoff volume using a measuring cylinder. The above is the advantages/novelty of this tester over the conventional constant-head permeability tester. Second, the hydraulic conductivity of the intact Inada granite specimen was measured using this tester, and the usefulness of the developed tester was confirmed by comparing the permeability measurement results with those of a previous study that used a more established technique [1]. Finally, this study measured the permeability of two intact rocks (Toyooka basalt and Shakudani tuff) under confining pressure conditions using a constant-head permeability tester, and we observed how the hydraulic conductivity changes as the confining pressure increases.

2 Constant-Head Permeability Test Method

The intact rock specimens used in this study were Inada granite, Toyooka basalt, and Shakudani tuff (Fig. 1), and all specimens had a diameter of 50 mm and a length of 40 mm. The properties of these rock samples are listed in Table 1.

![Fig. 1. Intact rock specimens (A: Inada granite, B: Toyooka basalt, and C: Shakudani tuff).](image)

| Rock samples   | Dry density (g/cm³) | Effective porosity (%) | P-wave velocity (km/s) |
|----------------|---------------------|------------------------|------------------------|
| Inada granite  | 2.61                | 0.79%                  | 4.37                  |
| Toyooka basalt | 2.71                | 6.59%                  | 3.44                  |
| Shakudani tuff | 1.98                | 26.9%                  | 3.14                  |

* Average of 3 specimens.

The test was performed at 22±1°C in a temperature-controlled room. The constant-head permeability testing system is shown in Fig. 2.
The testing system consisted of an air-compressor, pressure water tank, pressure regulator, confining and water pressure gauges, water pipe, permeability cylindrical mold (stainless steel), paper filters, rubber O-ring, heat-shrinkable tube, and electronic balance. The pipe and cylinder were made of stainless steel (SUS304). An electronic balance (resolution 0.1 mg) was used to measure the amount of water discharge while considering evaporation. The runoff volume was measured at 1 min intervals, and the data were transmitted from the balance to a personal computer. Each specimen was saturated using a water-filled decompression container. A constant confining pressure was applied to the side surface of the specimen through a heat-shrinkable tube (polyolefin). Distilled water was passed through the specimen at constant water pressure using an air compressor and pressurized water tank. However, the water pressure was set to a value (0.45 MPa) smaller than the confining pressure in order to prevent water leakage from the gap between the side surface of the specimen and the heat-shrinkable tube. Measurements were taken for ≥24 h after the first confirmation of water runoff. The runoff volume measured by the analytical balance decreased momentarily due to evaporation; however, this decrease was added to the runoff volume at the data organization stage, and the evaporation volume was also taken into consideration. The hydraulic conductivity \( k = QL/hAt \); \( Q \): runoff volume, \( L \): height of the rock specimen, \( h \): difference in water level, \( A \): cross-sectional area of the rock specimen, \( t \): measurement time) of the specimens was calculated using Darcy's law. \( h \) was calculated based on the pressure in the pressure water tank (at water pressure 0.45 MPa, where \( h \) is 4591.8 cm).

3 Results and Discussion

3.1 Permeability of intact Inada granite rock under confining pressure conditions using a constant-head permeability tester

The results of the constant-head permeability test of intact Inada rock specimens under confining pressure (1-12 MPa) are shown in Fig. 3.
Fig. 3. Results of constant-head permeability test for Inada granite specimen. A: relationship between time and runoff volume (Specimen 1), B: relationship between confining pressure and measured runoff volume interval time (Specimen 1-3).

Fig. 3A shows the time change of the runoff volume during the 24 h measurement time. Since the slope of the runoff volume is almost linear at any confining pressure, it can be confirmed that the hydraulic conductivity does not change with the passage of time during the test. It can be seen that the slope of the runoff volume decreases as the confining pressure increases. Since the amount of runoff volume that falls on the measuring cup on the electronic balance is almost the same, a small slope means that the interval time corresponding to the amount of runoff volume that falls on the measuring cup is long. As can be seen from Fig. 3B, this interval time increases exponentially as the confining pressure increases.

Fig. 4 shows the hydraulic conductivity of three types of rock specimens at each confining pressure (1-12 MPa). The hydraulic conductivity (red marker) of Inada granite under confining pressures of 1 to 12 MPa ranged from 2.9\times 10^{-11} to 1.8\times 10^{-12} m/s. It was observed that the hydraulic conductivity tended to decrease as the confining pressure increased. This tendency is similar to what has been reported previously [1], [7]. This is likely because micro-fractures inside the specimen (in the case of granite, the grain boundaries of mineral particles such as quartz, plagioclase, biotite, and others) closed as the confining pressure increased [8]. Fig. 4 also shows the hydraulic conductivity (confining pressure 2-10 MPa) [1] of the Inada granite specimen measured by the transient pulse method. Comparing the results of the current study to those reported previously [1] demonstrates that the tendency of the hydraulic conductivity to decrease as the confining pressure increases is similar, and that the hydraulic conductivity values are almost the same. The maximum difference in hydraulic conductivity was 8.0\times 10^{-12} m/s (confining pressure 2 MPa). Therefore, using the constant-head permeability tester developed in this study, it is possible to evaluate the hydraulic conductivity of low-permeability rocks represented by intact rocks, and the results are similar to those of the established and highly reliable transient pulse method.
3.2 Hydraulic conductivity of various intact rock specimens

In the case of Toyooka basalt (hydraulic conductivity \( k = 1.7 \times 10^{-11} \) to \( 8.9 \times 10^{-13} \) m/s, triangle marker), the permeability tended to decrease as the confining pressure increased, as in the case of Inada granite. In contrast, the hydraulic conductivity of Shakudani tuff (\( k = 1.0 \times 10^{-10} \) to \( 8.7 \times 10^{-11} \) m/s, diamond marker) did not change significantly with increasing confining pressure. This is likely because the porosity of Shakudani tuff is as large as 26.9% (Table 1), which means that a confining pressure of 1 to 12 MPa would have little effect on porosity closure. In other words, a confining pressure in the range of 1 to 12 MPa was not enough to close the large porosity. Zhang et al. [8] reported that higher aspect ratios of cracks and voids in rocks require higher pressure to mechanically close them. The results of this experiment demonstrate a similar tendency. As described above, in this study, the hydraulic conductivity of each of the three types of intact rock specimens was measured using a constant-head permeability tester that was developed independently. We were able to confirm the changes in hydraulic conductivity as the confining pressure increased.

4 Conclusion

In this study, various intact rock samples were subjected to permeability testing using an original constant-head permeability tester that we developed. In addition to the tests performed in this study, it is also necessary to carry out permeability tests using this tester on rock materials with macro-fractures and to compare the results with those of many other previous research studies. In the future, we plan to collect and accumulate experimental data and examine the usefulness of this device in detail. Furthermore, we believe that the results of this research can contribute to evaluation of the permeability of natural barriers (rock mass) in geological disposal, which has become an important issue in recent years.

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