Evaluation of Groundwater Permeation in Fractures around Rock Cavern using Ground Penetrating Radar

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Abstract

The groundwater condition in fractures around the rock cavern is important for groundwater management in geological disposal of radioactive waste and underground oil / LPG storage project with water containment system or for planning of effective measures for seepage of mountain tunnel. The GPR (Ground Penetrating Radar) method is unique technique to survey the water condition in fractures around the rock cavern, indirectly, and with no disturbance of original ground water condition. The authors conducted the GPR survey from the surface of the concrete placed on the granitic rock with fractures. In the survey, the difference of water condition behind the lining concrete caused the change in the reflected waveforms and the intense of spectrum due to the results of spectrum analysis of reflected waveforms. The results indicated that the water condition in the rock could be evaluated using the information of reflected waves of GPR survey.

Keywords: ground penetrating radar, ground water, fractured rock, spectrum analysis

1. Introduction

Fractures developing around rock caverns during the excavation results in issues related not only to the mechanical stability of rock caverns, but also to the groundwater paths. Specifically, in terms of the safety assessment of geological disposal of radioactive waste, the groundwater management of rock caverns for oil/LPG storage using hydraulic containment system, or planning of countermeasures for water seepage of tunnels, etc., it is important to have a thorough understanding of the groundwater conditions around rock caverns. However, in survey using boreholes, there is a possibility of disturbing the original hydrological conditions during a survey, and there are also limits to areal evaluations.

Therefore, the authors have been developing a non-destructive method that uses GPR (Ground Penetrating Radar) to make areal evaluations of groundwater conditions in fractures around rock caverns (Masumoto and Kurihara, 2013). So far, in preliminary experiments using model ground, GRP has been applied to measure changes in reflected waveforms and reflection intensity, and the results indicate that it is possible to evaluate the saturation conditions of water into fractures and the infiltration conditions of saline water (Masumoto and Kurihara, 2014).

In the present study, tests were conducted to verify the survey method using GPR. In these tests, radar measurements were conducted from the upper surfaces of concrete that had been placed on the rock with fractures, assuming a survey from the interior of underground lined rock caverns. From the results of measurements of changes in reflected waveforms and their spectral analysis during permeation of fresh (tap) water and saline water into the rock, it was concluded that the survey method using GPR could be used to evaluate the groundwater permeations in the rock of concrete backfaces. This paper is a report on those results.

2. Methodology of the Verification Test using GPR

As a verification test assuming a survey around rock caverns, the granitic rock was cropped out using the rock splitter and concrete about 30cm thick were placed on the surface of rock. Before placement of concrete, the fracture distribution was observed on the surface of the test area. After water injection holes were drilled from the surface of concrete, water contents of fractures in the rock, and along the boundary between the rock and the concrete, were changed using water injection holes, and radar measurements were taken from the surface of the

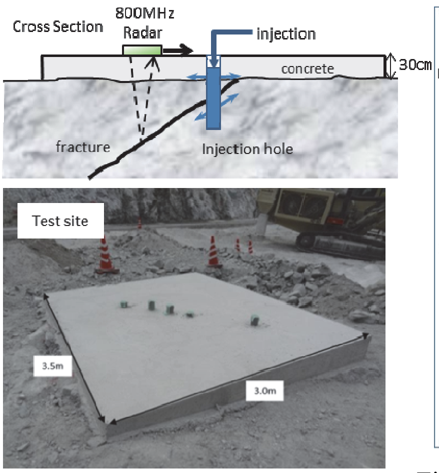


Fig. 1 Schematic diagram of the test

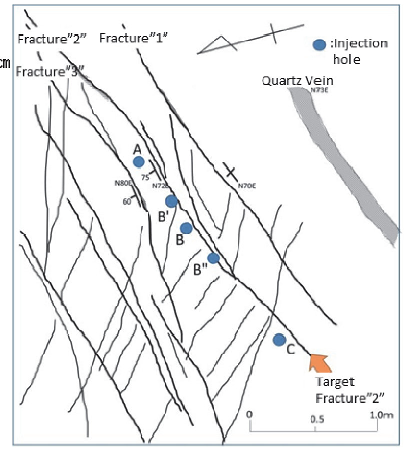


Fig. 2 Fracture distribution of test site

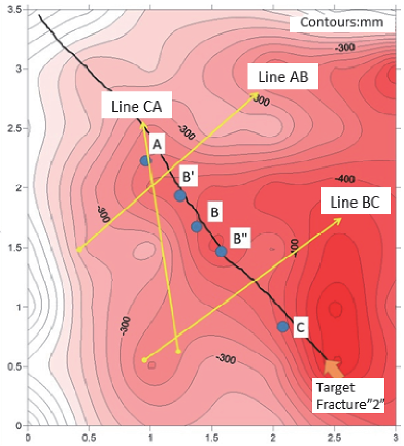


Fig. 3 Profile measuring lines and concrete thickness distribution

concrete under different water contents in the rock of concrete backfaces. Fig. 1 shows a schematic diagram of the test and a photo of the testing site. In order to measure changes in reflected waveforms during permeation of groundwater into fractures in the rock, Fracture"2" was selected as the target for water injection from three fractures ("1" to "3") with a relatively continuous NE strike, which were identified from the results of geological survey. Then 5 water injection holes of 1m in depth were drilled to intersect with Fracture"2" (Fig. 2). Fracture"2" is 75 degrees dip toward the north and has openings in places, some of which are soft sections of a few centimeters in width. Fractures"1" and "3" include a white vein, and they dip toward the north at angles of 90 degrees and 60 degrees, respectively. Concrete was placed horizontally within a 3.0m by 3.5m area on the rock with these fractures. Because the rock surface was uneven, there was a difference in concrete thickness of maximum 45cm, minimum 10cm, as shown in the contours of Fig. 3. The groundwater in the water injection hole was not observed, therefore, the groundwater level was at least 1m below the rock surface.

In the verification tests, an 800MHz pulse radar was used to take profile measurements with three 2m-long measuring lines as shown in Fig. 3. Measurements were conducted under three different conditions: (1) original condition, (2) condition under which all water injection holes were completely filled with fresh water, and (3) condition under which the water in all injection holes was replaced with saline water (electrical conductivity 1.7S/m). At replacing with saline water, saline water was injected after all injection holes were dried up using storage pump. For the profile measurements, stacking were performed about 200 times at each receiver/transmitter location, and measurements were taken at a 2.5cm interval. The procedure of the verification tests is shown in Fig.4.

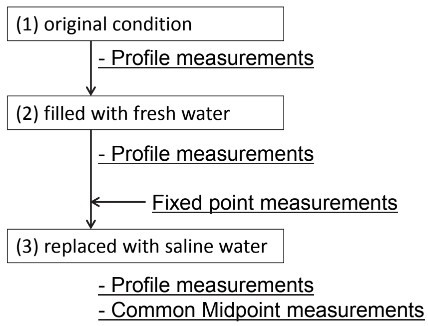


Fig. 4 Procedure of verification test

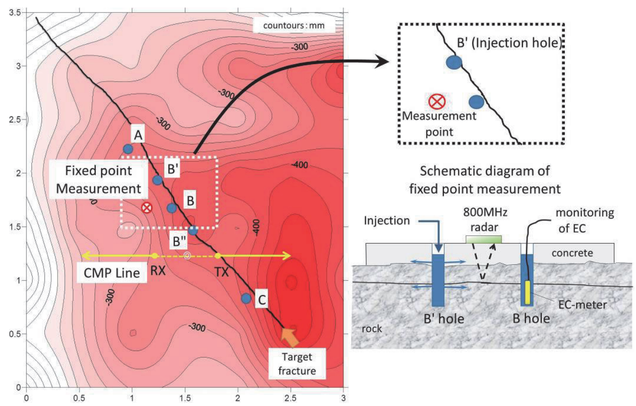


Fig. 5 CMP measurement lines and measurement point during injection

In addition to the above tests,

1) CMP (Common Midpoint) measurements were carried out to evaluate the thickness of the concrete, and

2) Fixed point measurements were taken at one point in order to monitor changes in reflected waveforms during the injection of saline water into the injection holes.

With the CMP measuring lines shown in Fig. 5, a 50 to 500MHz continuous wave radar was used to take measurements at a 10cm interval while expanding the offset distance from 60cm to 200cm. At the position shown in Fig. 5, an 800MHz pulse radar was used to take fixed point measurements to continuously monitor the permeating process of injected saline water from the B' hole to the B hole. The electromagnetic reflected waveforms were measured at 1-minute intervals after saline water injection. It should be noted that an electrical conductivity meter was set at the bottom of the B hole in order to measure break-through process of the saline water resulting from changes in electrical conductivity.

3. Test Results

3.1 Results of CMP measurements

Fig. 6 shows the results of CMP measurements. The reflected waveform was detected later than the direct wave that was at the velocity of light C = 3.0e+8m/sec. The travel time where the direct wave was intersected with the offset distance of 0 cm was set as 0 in two-way travel time. When this reflected waveform was approximated to the theoretical hyperbola curve, it could be calculated that the reflection boundary was at a depth of 29cm, and the propagation velocity of the electromagnetic wave to the reflection surface was 1.2e+8m/sec. The depth of the reflection boundary appeared to be slightly shallower than the 36cm thickness of the concrete in the center of the CMP measuring line. The calculated velocity of 1.2e+8m/sec corresponded to a dielectric constant of 6.3, which roughly coincided with the dielectric constant of 4 to 10 of the concrete in a dry condition (Sato et al., 2001). The result that the common reflection boundary of the CMP measurements was at a position slightly shallower than the boundary between the concrete and the rock, indicates that the saline water that permeated into the boundary infiltrated into the interior of the concrete, forming a saturated capillary zone in the concrete, and that waves reflected from the upper surface of the saturated capillary zone may have been captured by the CPM measurements. In addition, from the propagation velocity obtained in these CMP measurements, the waves reflected from the saline water that had permeated into the boundary between the concrete and the rock was appeared at around 5ns in the two-way travel time at the profile measurements.

3.2 Results of the fixed point measurements

Fig. 7 shows the changes of the electrical conductivity in the B hole after injection of saline water into the B' hole. At 7 minutes after the commencement of injection, the saline water broke through to the B hole, and 35 minutes later the electrical conductivity in the B hole has reached 1.7S/m, the electrical conductivity of the injected

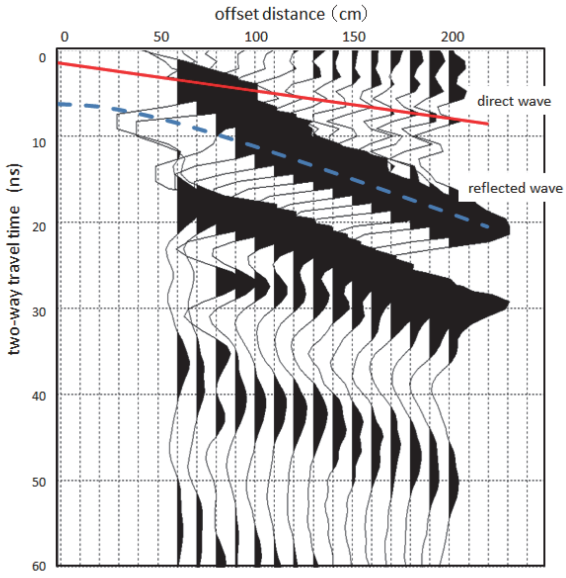


Fig. 6 Results of CMP measurements

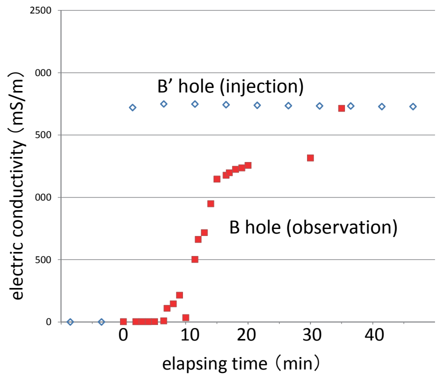


Fig. 7 Change of EC after injection of saline water

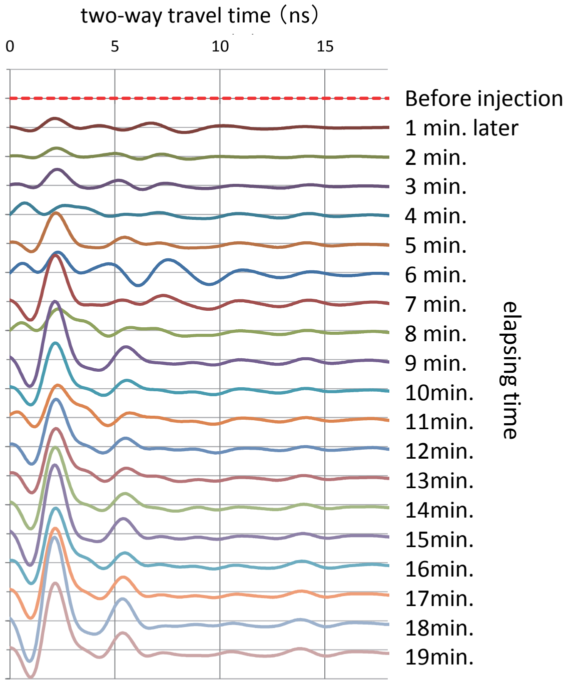


Fig. 8 Results of fixed point measurements
(Difference of amplitude from standard waveform)

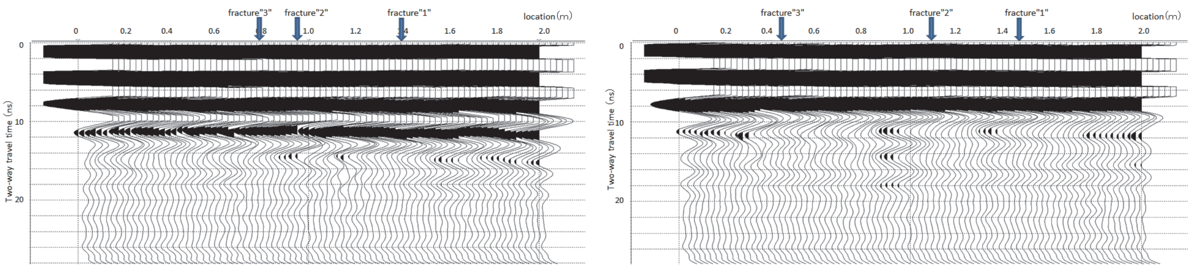
saline water.

Fig. 8 shows the measurement results of the reflected waves at the fixed point of this permeation process. The figure shows the results of calculating the differences in amplitude values of the waveform after the elapsing time from the standard waveform, which was the waveform just before the injection of saline water. From 5 minutes after injection, the differential amplitude of the direct waves at the 2 to 3ns two-way travel time began to increase, and the differential amplitude at the 5 to 6ns two-way travel time also increased. Because it appears from the CMP measurements that the reflected waves resulting from the permeation of the saline water into the boundary between the concrete and the rock could be observed at around 5ns, the increase in the differential amplitude indicates an increase in the reflection intensity due to the permeation of saline water into the boundary. From these results, it could be concluded that the main permeation depth was the boundary between the concrete and the rock. In addition, the commencement of the increase in differential amplitude from about 5 minutes, before the break through into the B hole at 7 minutes, indicates that the saline water arrived directly under the position of the fixed point measurements after about 5 minutes had elapsed. Therefore, it was found that the permeation velocity of the saline could be estimated by changes in the reflected waveform.

3.3 Results of the verification tests

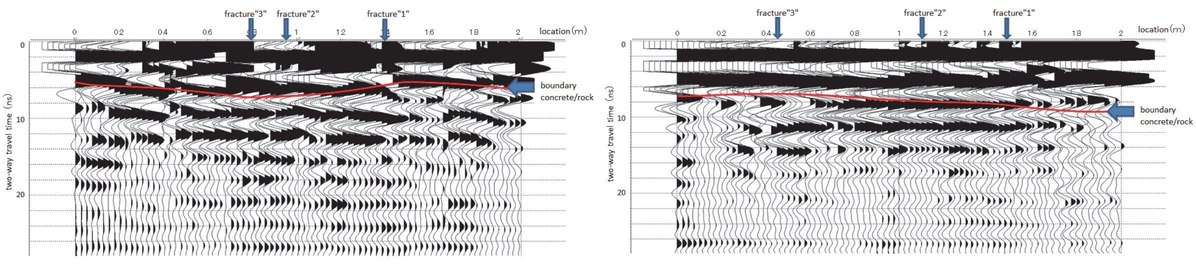
a) Evaluation by differential profile

The profile measurements were carried out along three measurement lines under each condition. Fig. 9 shows the results of the profile measurements at measuring lines AB and BC at replacement with saline water. The reflection from the boundary between the concrete and the rock, as estimated from the CMP measurement results, should have been observed near 5ns in the two-way travel time, but the amplitude of the direct waves was too large for this reflection to be confirmed. In addition, there was no clear reflection from the fractures. Therefore, the profile under conditions of injection of fresh water was set as the standard profile, and the differential profile was calculated under the saline water replacement conditions. Fig. 10 shows the profile results obtained after differential processing. In this figure, a waveform of the large differential amplitude is seen at around 5 to 6ns, and it could be determined that this was reflection from the boundary between the concrete and the rock. The appearance of changes in the amplitude due to the differential processing indicates that the injected saline water permeated along this boundary. At the same time, reflected waves can be seen around the location corresponding to Fractures"2" to "3", even at a depth below the boundary. This indicates that the injected saline water permeated into the fractures through the boundary and/or the fracture network.



(a) Measuring Line AB (b) Measuring Line BC

Fig. 9 Results of profile measurements at replacement with saline water



(a) Measuring Line AB (b) Measuring Line BC

Fig. 10 Profile results after differential processing

b) Evaluation by spectral analysis

Regarding the reflected electromagnetic waves, the reflection coefficient R of media 1 and 2 can be approximated as follows when the conductivity is low:

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \qquad (1)$$

where ε_1, ε_2 : dielectric constants (F/m) of medium 1 and medium 2, respectively.

On the other hand, when the conductivity is high, the reflection coefficient of the normal incidence is expressed as a function of angular frequency of the electromagnetic wave, magnetic permeability (H/m) and conductivity (S/m) of medium 1 and medium 2. Here, the influence on reflection of differences in conductivity cannot be ignored. For example, when a high-conductivity medium which contains saline water is the reflection boundary, it indicates that the high-frequency component of the reflected wave is decreasing (Onishi et al., 2004). From this theory, it can be estimated that the amplitude of reflected waves in the area where saline water permeates greatly attenuates in the high-frequency bands. Therefore, spectral analysis was applied to confirm the area where the dominant frequency decreased, and to evaluate the saline water permeation.

Fig. 11 shows the results of spectral analysis conducted in the 4ns to 20ns range for the waves after injection with fresh water and after its replacement with saline water for each measuring line, and the dominant frequencies that were derived for each reflected waveform. Due to the specification of the pulse radar used in the test, the dominant frequency for each waveform was shown to be around 300MHz, and the area where the frequency decreased after saline water replacement was confirmed. A noticeable decrease was detected at the A hole, but such a large decrease was not found at the location around Fracture 2. From these results, the decrease in frequency was the effect of reflection not from the fracture, but from the concrete and rock boundary. Fig. 12 shows the location where the frequency decreased along the measuring lines. In this figure, the areas with thick concrete, that is, the places with a low rock surface, corresponded to the areas of frequency decrease, and it can be concluded that the saline water injected from the injection hole permeated by passing through the trough of the rock surface.

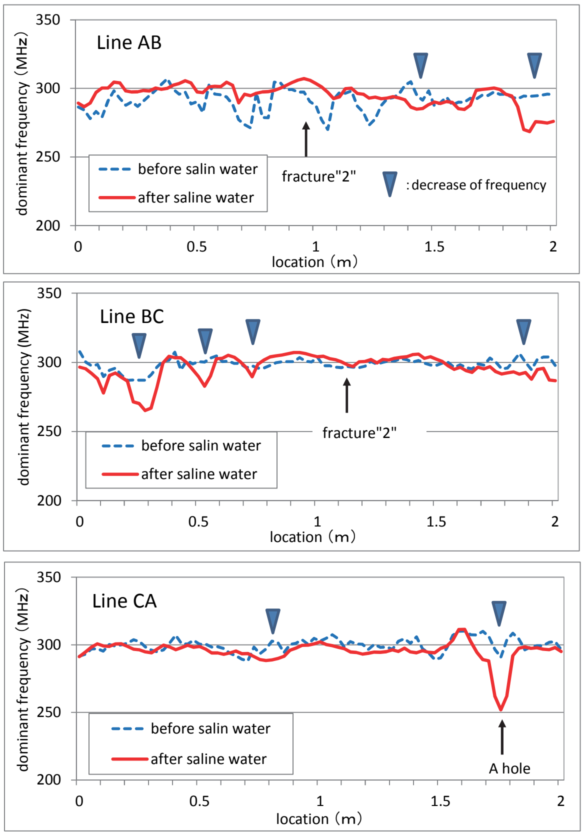


Fig. 11 Results of spectral analysis

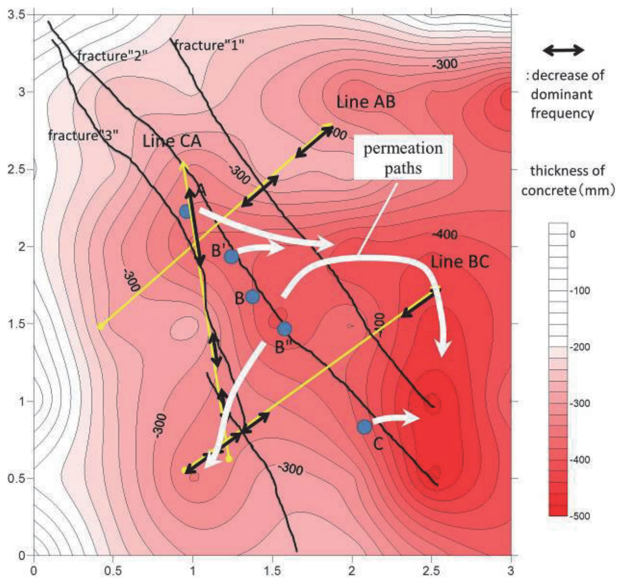


Fig. 12 Location of decrease of dominant frequency and permeation paths

4. Conclusions

This study was conducted as a groundwater survey in fractures around rock caverns to investigate the practicality of methods for using GPR to evaluate groundwater permeation in the rock of lining backfaces. As a verification test, fresh (tap) water and saline water were permeated into fractured granite, and concrete of about 30cm thick was placed on the granite, then 800MHz pulse radar was used to take profile measurements from the concrete surface at a 2.5cm interval. Furthermore, CMP measurements were also carried out, and fixed point measurements were taken during the injection of the saline water. As a result, it could be indicated to estimate the permeation velocity and permeation paths of saline water in fractures and concrete backfaces, in a non-destructive way, based on spectral analysis and changes in the reflected waveforms of GPR.

This method, such as differential profiles and spectral analysis, may make it possible to conduct non-destructive monitoring of changes in saturated and non-saturated conditions of groundwater, and of permeation behavior as a tracer of liquids having different conductivities. In the next step, the authors plan to apply this method to monitor the submerge process of unsaturated zones around rock caverns, to measure the break-through process in tracer tests 2-dimensionally, and to monitor the permeation of grouting materials in grouting work.

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