Assessment of borehole resistivity tomography for subsurface CO$_2$ leakage: Lab-scale preliminary study

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Instructions

Global warming and extreme weather events are a hot issue in the world today. Carbon dioxide (CO$_2$), one of the greenhouse gases, has been nominated as the main culprit of this international concern (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 1997). The carbon capture and storage (CCS) technique is grabbing attention because the current energy paradigm that focuses on fossil fuel cannot be changed abruptly. However, CO$_2$ geological sequestration faces difficulties related to non-homogeneous underground conditions, poorly characterized interconnected geo-systems, and complex hydro-chemo-mechanical effects that involve reservoir rock and cap-rock mineralogy, saturating fluid, and injected fluid. Thus, it is considered as risky and uncertain, and there is the possibility of CO$_2$ leakage. For monitoring CO$_2$ storage sites, use of geophysical tomography methods has been studied (ARTS et al., 2000). CO$_2$ gas migration due to storage or leakage changes the resistivity of the medium, and it can be monitored through resistivity tomography (NAKATSUKA et al., 2010). If a resistivity survey can catch the complex phenomena caused by subsurface CO$_2$ leakage, it should be considered as a concrete option for monitoring CO$_2$ storage sites. In this study, we developed a unique laboratory facility for observing the evolution of subsurface CO$_2$ leakage. And we attached a resistivity measurement system based on borehole resistivity tomography. We attempted to get resistivity images when the phenomena related to CO$_2$ leakage were taking place in the tank. These images were compared with the time-lapsed photos and we analyze and discuss the applicability of the resistivity survey.

Experiments

The schematic diagram of the testing systems in this study is shown in Fig. 1. A very thin transparent tank (W x H x D=300 mm x 600 mm x 2 mm) was used for specimen preparation. Thickness was only 2 mm and it could be considered as a two dimensional model. The tank was filled with different sizes of glass-beads to form controlled layered stratigraphies; then the medium was saturated with water mixed with a universal pH indicator. The color changes to the yellow and red color families with decreasing pH values. To capture the evolution of gas invasion and diffusion, photos were taken at regular intervals. Flow paths, displacements, invading volume, pH and density contours of carbonated water were extracted by subsequent image analyses.

The measurement system for resistivity tomography was attached to the CO$_2$ gas migration monitoring system. Eleven electrodes were installed at the left and right boundaries of the tank. Two or more electrodes were installed at the top plate. The testing equipment for the resistivity survey was Syscal Pro from IRIS instruments. The survey method was a mixture of in-line and cross surveys. The connected CO_2 gas bubbles traversing the medium of the tank can be a barrier to measure reasonable potential between the left and right parts of the electrodes. The in-line survey will help this kind of problem. The array types were modified pole-dipole and dipole-dipole, which were specially designed for this lab test.

Various inversion schemes for resistivity tomography have been developed. A 3D inversion algorithm considering topography of a site and locations of electrodes has already been in general (Yi et al., 2001). Now a 4D inversion algorithm for the dynamic earth has been developed (Kim et al., 2009). Conventional inversion algorithms are not applicable for this study because the tank is perfectly isolated. A modified inversion scheme based on general 3D forward modeling was developed. It considered the shape of the container and the bottom line was put to earth to find solutions in forward modeling. Active constraint balancing was used to enhance the resolving power of least squares inversion (Yi et al., 2003). The main soil model for our resistivity survey monitoring is anticline structure, which is a typical type of structural/stratigraphical trapping for CO_2 geological sequestration (Fig. 1b-1). It is a three-layered model. Coarse glass-beads were used for the reservoir and upper layers. Fine glass-beads were used for the cap-rock. Red circles indicate trapped CO_2 gas inside pores.

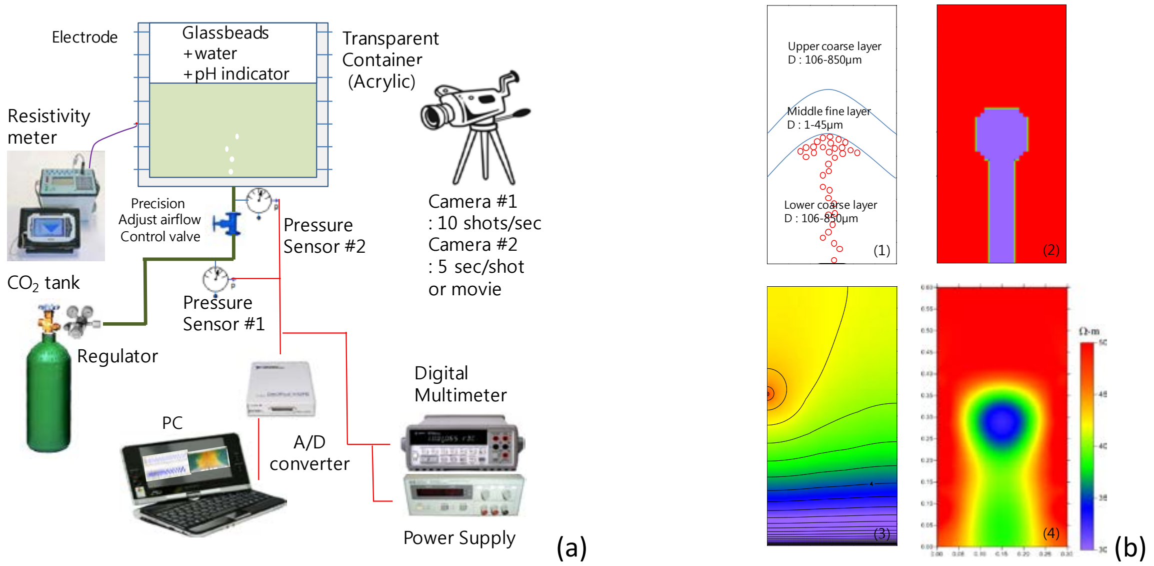

Fig. 1: Schematic diagram of the testing systems for monitoring CO2 gas migration (a) and verification of the inversion procedure for resistivity tomography through numerical modeling (b): Depressurized CO2 gas was injected into a transparent thin gap container though a needle. Bubble pressure was monitored with a pressure sensor attached near the injection point. Pictures were taken for recording and image processing. (1) soil model for the feasibility test of resistivity tomography and expected form of trapped CO2 gas bubble inside the medium, (2) simple model for numerical verification, (3) a typical potential contour during mono-pole current, (4) inversion result using numerical data.

The proposed inversion scheme was verified using numerical data. Fig. 1b-2 is a simplified resistivity model for the main soil model shown in Fig 1b-1. The resistivity of the anomaly caused by CO_2 dissolved water was 30 Ωm while the resistivity of the background medium was 50 Ohm-m. The size of model was 300 mm x 600 mm x 2 mm and the interval of the imaginary electrode was 50 mm. This is same dimensions as the experimental setup. The size of the elements was 1 mm x 1 mm x 0.5 mm and the number of nodes were 904,505 (301x601x5). Fig. 1b-3 shows an example of the potential contour when a current was injected through an imaginary monopole electrode at 0.35 m of the left boundary. The bottom line was put to earth while the other boundaries were considered as having the Neumann condition. Thus, the potential was zero at the bottom line. Using all twenty-two electrodes, in-line, cross, reverse-cross surveys were performed though dipole-dipole electrode arrays. Inversion was done using a total of 216 measurement data items. The constructed image of resistivity is shown in Fig. 1b-4. The block size for the inversion was 5 mm x 5 mm and total number of blocks was 450. Due to the smoothness constraint, it appears that the boundary of the anomaly has expanded, but it shows well the low resistivity anomaly at the center of the model. Furthermore, the resistivity value is similar to the original value of the model. Thus, it appears that the proposed inversion scheme for resistivity survey works well for this kind of lab-scale study.

Results and discussion

Fig. 2 shows the representative time-lapse images taken by a digital camera for the simulation of CO_2 injection. Fig. 2a is for the sea bottom mountain model. The path of CO_2 gas migration is easily observed. The color of the pore water near the conduit is changed due to acidification because CO_2 is dissolved and makes carbonated water. Pore-water is pH sensitive because the universal pH indicator is mixed. It changes color with different pH values. In this way, the path of the CO_2 gas is clearly detected. The direction of gas migration is upward due to buoyancy. When medium is not homogenous, injected CO_2 tries to find an easier way to migrate, so the direction of gas migration can be horizontal and sometimes downward. This model was non-homogeneous due to segregation of the glass-beads when the specimen was prepared. Therefore, the path of the CO_2 gas was not simple and it changed with time. The bottom graph of Fig. 2a shows the time history of the bubble pressure inside. When the gas migrated, the pressure of the gas bubbles changed. There is a drop point [2] in the graph which means the gas bubble broke through the medium of glass-beads. After that, there were repeated fluctuations of pressure due to continuous gas migration.

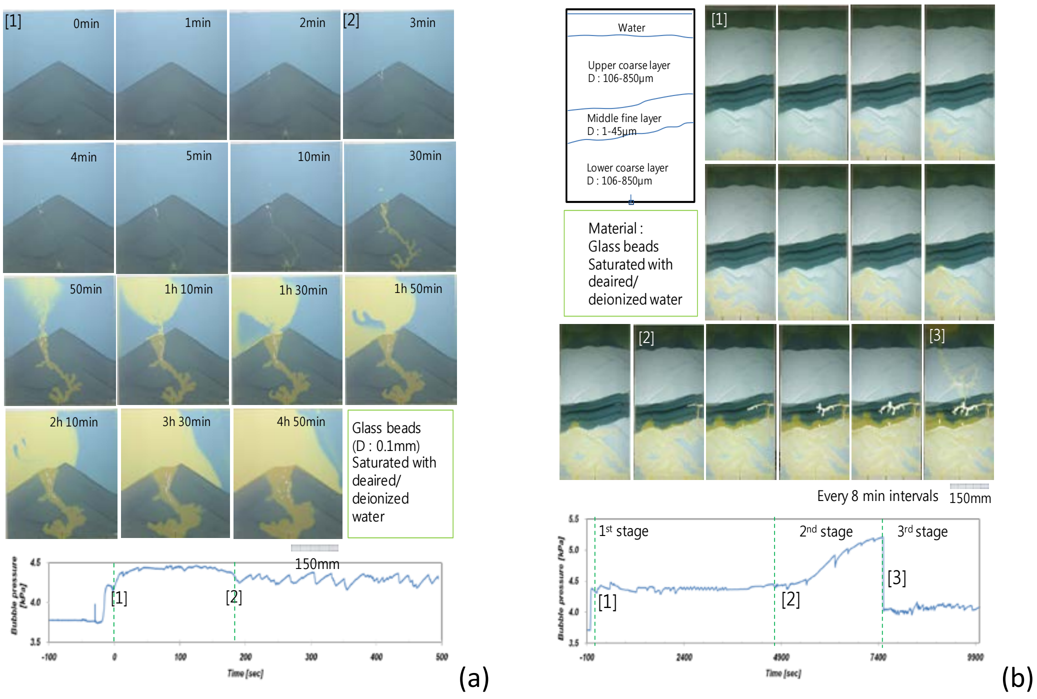

Fig. 2: The results of CO_2 gas injection test (time-lapse digital images and time history of gas bubble pressure): (a) a sea bottom mountain model, (b) a layered glassbead-water mixture system having a find middle layer.

In the three-layered model containing a fine layer, other interesting phenomena related to gas migration were observed as shown in Fig. 2b. There were three stages. In the first stage, CO_2 gas migrated into interconnected pores displacing pore-water in the bottom layer. There was no big pressure build-up. There are just small pressure fluctuations during the gas migration. Otherwise, in the second stage, high pressurized gas made cracks in the fine middle layer to advance. The bubbles pressure increased continuously and dropped a little repeatedly when the gas advanced into the fine layer making cracks. When the gas broke through into the second fine layer, the bubble pressure dropped abruptly at point [3] in the bottom graph of Fig. 2b. After that, the CO_2 gas migrated freely through the percolated path that was the third stage. When the bubble pressure is larger than the air entry value of the medium and smaller than confining pressure, it migrates into the interconnected pores. On other hand, when the bubble pressure is smaller than the air entry value of the medium and larger than the confining pressure, it migrated by open mode discontinuity.

Fig. 3 shows representative photos of the test in which CO_2 gas was injected into the tank containing only water. The initial color was in the blue family. The color changed into the yellow and red color families around the path of the bubble rising. Furthermore, the area of carbonated water expanded or enlarged from diffusion and convection. During the CO_2 gas injection, a resistivity tomography survey was performed periodically. However, those resistivity images do not well agree with the photos. It may be that there are artifacts due to erroneous measurement procedure and inversion scheme. An additional experiment is being done to modify the results of the resistivity survey. Another application test using the main soil model of Fig. 1b-1 is also being done. The feasibility of the resistivity tomography survey for complex phenomena related to CO_2 leakage will be discussed later.

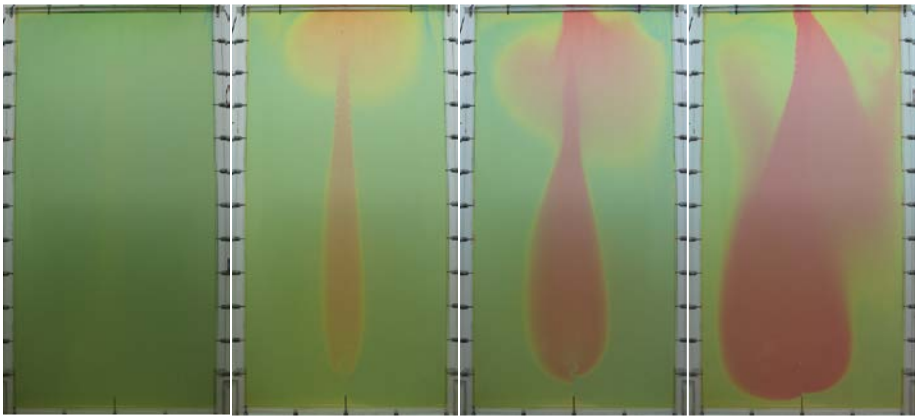

Fig. 3: Representative photos for CO_2 gas injection and application of resistivity tomography survey.

Conclusion

A unique laboratory facility for observing the evolution of subsurface CO_2 leakage was developed. A resistivity measurement system based on borehole resistivity tomography was included. A universal pH indicator especially helped the movement of carbonated water to be monitored effectively. The nature of CO_2 gas migration, the effect of fine-grained layers such as the cap-rock, water acidification near conduits and subsequent diffusion and the convection of carbonated water were observed. This study was a first step to understanding the salient characteristics of subsurface CO_2 leakage and an assessment of the applicability of borehole-based resistivity tomography. The path of CO_2 gas migration in the medium of a tank is easily observed. The color of water near the path of the CO_2 changes from acidification because CO_2 is dissolved and makes carbonated water. Carbonated water tends to move downward because carbonated water is denser than the surrounding water. Carbonated water with a lower pH has a relatively larger density. An inversion scheme was developed based on 3-D forward modeling that considers the shape of the container. Through numerical modeling, the proposed inversion scheme was verified. Nevertheless, to use the scheme with real experimental data, a refined testing procedure and modification of the proposed inversion scheme are necessary and will be pursed.

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