Effect of Dispersivity on Saltwater Intrusion and Removal Processes

Masahiro Takahashi[1] and Kazuro Momii[2]
[1]Research and Development Center, Nippon Koei Co.,ltd., Tsukuba, JAPAN
[2]Department of Environmental Sciences and Technology, Kagoshima University, Kagoshima, JAPAN

ABSTRACT

This study focuses on the behavior of residual saltwater trapped in the storage area upon installation of the cut-off wall based on the laboratory experiments and numerical simulation. The longitudinal and transverse dispersivities, α_L and α_T, respectively, are estimated using image analysis of pulse and continuous injection experiments with tracers, and numerical analyses. The saltwater intrusion and removal experiments are numerically reproduced by the SEAWAT numerical model with the estimated α_L and α_T. Sensitivity analyses carried out by varying the α_L and α_T values prove the effect on removal time of the residual saltwater. The transverse dispersivity, consequently, plays an important role in the dilution and removal of residual saltwater due to the groundwater flow along the mixing zone between the freshwater and saltwater.

INTRODUCTION

The report of the fifth IPCC predicts a rise in sea level by global warming by up to 82 cm in 2100, and, as a result, it is expected that the progress of the seawater intrusion is accelerated in the coastal areas. A deterioration of water quality by the saltwater intrusion and a decrease in pump discharge have a potential for the large impact on people's life and their productive activities because there are in general a lot of groundwater exploitations in the coastal areas. Therefore, that is the significant issue to overcome. Seven subsurface dams, which have a storage function for securing water resource and also suppressing the saltwater intrusion, have already been constructed in the Southwest Islands in Japan. In many of the traditional research on subsurface dam, the freshwater storage has been discussed, and the saltwater behavior at storage area enclosed by the cut-off wall has been hardly discussed (Luyun et al. 2009). It is considered that the quantitative evaluation of residual saltwater removal is extremely important for the saltwater management with the cut-off wall. In this study, the behavior of saltwater remained at storage area after installation of the cut-off wall is quantitatively investigated by laboratory experiments and numerical analyses for unconfined groundwater.

METHOD

Laboratory experiment and image analysis

Acrylic laboratory equipment is the size 100 cm×40 cm×1.5 cm. It has storage tanks where water is supplied in both ends of the device, and 1.2 mm diameter glass beads were filled in the device. A tracer colored with food dye or fluorescent dye was poured from injection hole and others of the equipment, and its dynamic state was taken images with a fixed digital camera in a darkroom. An imaging time interval was 0.5 to 30 minutes. Further details of the experimental setup can be found in Luyun et al. (2009).

First, after filling the device with pure water, provided a difference in water-level, generating a flow field of freshwater. After the flow became a steady state, the tracer was injected in pulsed or continuously from 6 mm diameter injection hole. Second, a flow of pure water was generated and stabilized after the experimental device was filled with pure water, and started the saltwater intrusion. After the saltwater intrusion had reached an equilibrium state, the cut-off wall of 28 cm height was inserted between the left saltwater tank and a permeability layer, and the saline water was excluded. The dynamic state of the saltwater at this time was saved in images. Two EC sensors were installed in the saltwater intrusion area, and EC changes at the time of invasion and exclusion were measured.

Images of each experiment were split into RGB values using the software of IMAGEJ (NIH). The concentration was determined using G value for fluorescent dye, and R/B value for food dye. In addition, a relationship between individual concentration and G, R/B values was determined by calibration test.

Numerical analysis

From the image of the results of the first experiment, positions of center nodes and spreads of longitudinal and transverse directions of the tracer were read with time. Their values were assigned to an estimation equation and an analytical solution, and the α_L and α_T values was calculated. To verify the experimental outcomes, the numerical analysis by MT3D was performed. Furthermore, a reproduction of the experiments were made by inputting the α_L and α_T values to SEAWAT.

RESULTS

Pulse and continuous injection experiments

The α_L and α_T were presumed using the estimation equation from the experimental outcomes of the pulse injection. As a result, the α_L values were within a range of 0.19 to 0.22 cm, and the α_T values a range of 0.011 to 0.007 cm. In the continuous injection test (Figure 1), the α_T value was estimated to be 0.007 cm, and became almost equivalent to the result of the pulse injection test. The ratio of α_L/α_T obtained by the pulse injection test was 20 to 27. The experimental results were verified by inputting the estimated α_L and α_T values to MT3D, and an image of the experiment was approximately reproduced.

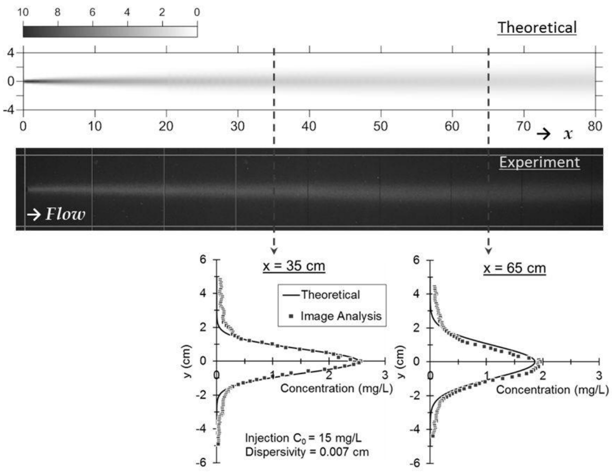

Figure 1. Result of continuous injection test.

Results of saltwater intrusion and removal experiments

Figure 2 shows the changes in the salt concentrations measured by two electrical conductivity probes EC1 and EC2 and the image analysis for the laboratory experiments of the saltwater intrusion and removal processes. Concentration estimated from EC1 reached the saltwater concentration in a minute or two, and in case of EC2, concentration increased from six minutes and arrived at the max salt concentration in about 12 minutes. As with the EC probes, the concentrations of EC1 obtained by the image analysis reached the saltwater concentration in approximately one minute, at EC2, rose from five minutes to slightly faster than the measured values, leading to the salt concentration in about 15 minutes.

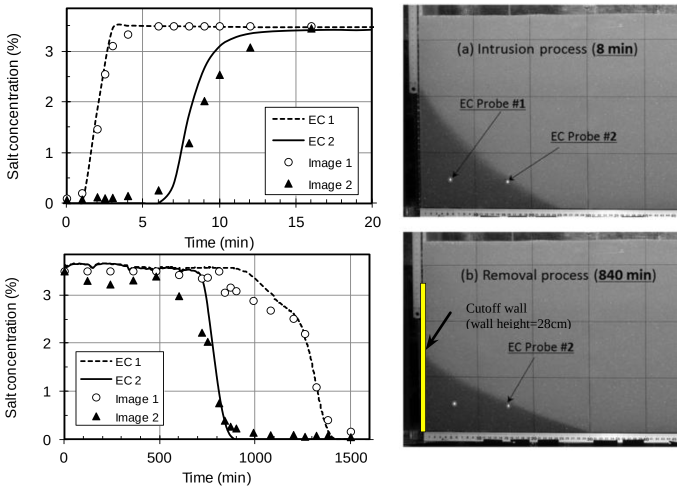

Figure 2. Changes in salt concentration by experiments.

In the removal process, the concentration began to change from approximately 700 minutes at EC2 after inserting the cut-off wall, and it altered to freshwater substantially in 900 minutes. On the other hand, the concentration began to decrease from 900 minutes and it became freshwater in 1400 minutes at EC1. The concentration change at EC1 with time has two gradients. The first gradient is smaller than the second one, and the similar trend was also observed in the image analysis.

Numerical analysis

As a result of conducting a reproduction analysis of the saltwater intrusion and the removal experiments by SEAWAT, the experimental outcome has been almost reproduced (Figure 3). Taking a more detailed look at it, the time-dependent change of the concentrations at EC1 and EC2 indicated the approximately the same tendency as that of EC sensor also in the analysis result. However, the concentration gradient in the invasion process was slightly looser than the EC measurements, and resulted in similar to the image analysis. In the removal process, the concentration change has two gradients at EC1 was reproduced, except that the gradient was also gradual than the EC measurements.

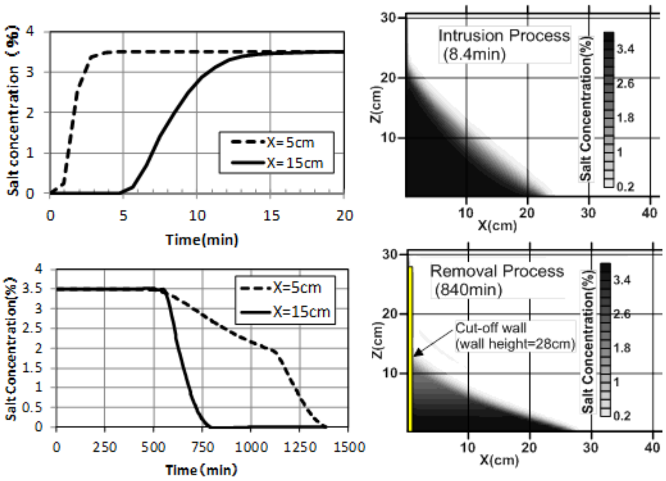

Figure 3. Changes in salt concentration with time by numerical simulation.

In the analysis of the exclusion experiment, in order to make a smooth insertion of the cut-off wall and to reinforce intensity, the porous acrylic board about 3 mm in thick was inserted between the cut-off wall and the glass beads. Since this must be considered to reproduce the measured values in the analysis, the reproduction analysis was performed by applying a high permeability to the left mesh corresponding to the porous acrylic plate. Then, the α_L/α_T was varied to 10, 27 and 100, and the change of the salt concentration was predicted (Figure 4). The high permeability of the left-end mesh is not taken into account in the predictive analysis. Figure 4 shows that no significant differences are found in the concentration change from saltwater to freshwater at the location of EC2 in the invasion process even if the α_T is changed. On the other hand, the difference of removal time was as large as about 1000 minutes in the removal process. It was recognized that the width of mixing zone became thick as the α_T increased and concentrations was diluted on the whole.

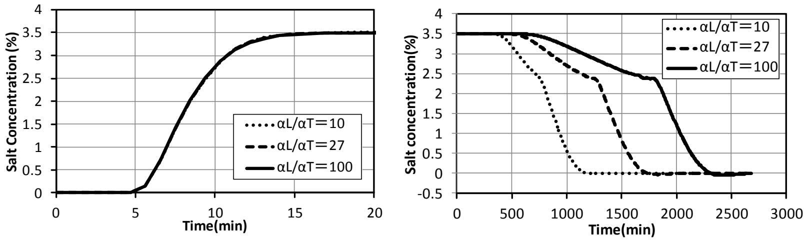

Figure 4. Changes in concentration with time for the ratio of α_L/α_T=10, 27, and 100.

DISCUSSION AND CONCLUSIONS

Although the difference in the α_T value does not affect the invasion time in the saltwater intrusion process, the removal time becomes short as the α_T value increases in the removal process. In the removal process, saltwater is excluded along the groundwater flowing through the mixing zone between the freshwater and saltwater, and the concentration changes in an orthogonal direction to the groundwater flow along the mixing zone. The spread range of concentration change is evaluated in the α_T. Thus, the transverse dispersivity has a profound effect on the concentration change in the exclusion process.

When the ratio of α_L/α_T was altered, the simulated intrusion and removal processes indicated that the ratio of α_L/α_T contributes significantly to the retreating process because it took about 1.3 times removal time in case of α_L/α_T = 27 compared with α_L/α_T = 10. In the removal process, steep and gentle gradients can be seen in the concentration curves. Not all the saltwater flowing along the mixing zone moves upward and is removed, but a part of it moves downward and forms a circulating flow (Figure 5). This causes that the concentration in the upper part of the wedge is reduced gradually. It is considered that this generates the gentle slope in the concentration curve with respect to time shown in the experiment (Figure 3) and the analysis (Figure 4). The subsequent steep slope is interpreted as the exclusion by the flow along the mixing zone.

The numerical and image analyses of the experiments are effective to evaluate the ratio of α_L/α_T. The experimental results show that the evaluated ratio of α_L/α_T was larger than the general ratio of 10, indicating 20 or more. As a result, analysis of the saltwater removal process using the general ratio is found to predict a result that the complete removal will finish in a shorter time than reality. Therefore, it is considered that a comprehension of the α_L/α_T is required to develop more precise predictions.

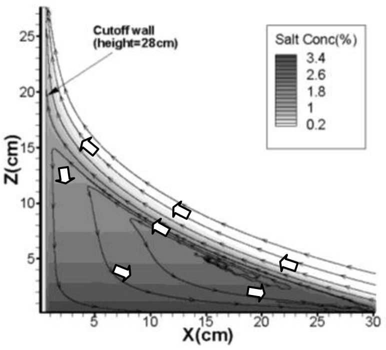

Figure 5. Streamlines and concentration distribution in removal process.

REFERENCE

Luyun Jr. R., K. Momii, and K. Nakagawa. 2009. Laboratory-scale saltwater behavior due to cutoff wall. Journal of Hydrology 377: 227-236.