Electrical Resistivity Survey for Delineating Seawater Intrusion in a Coastal Aquifer

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Abstract The main purpose of this study is to propose electrical resistivity survey methods which can be adapted effectively in highly conductive regions including seawater intrusion region. To obtain high signal to noise ratios and to overcome the difficulty in setting up of remote electrodes, which should be located at least 20 times of the electrode separation index, in a two dimensional surface survey, we adapted an electrical resistivity survey using modified pole pole array, which is reformed from the convention pole pole array method. In order to evaluate the extent of seawater wedge and to estimate the resistivity variation with the tidal variation, we used electrical resistivity tomography using single well. We present two case histories for which above two methods were used at two different coastal aquifers in Korea, respectively, to delineate the extent of seawater intrusion with reasonable results over the coastal area. Although the subsurface condition is highly conductive near the coastal areas, the modified pole pole array method is proved to be effective in diminishing the interference of conductive layers comparing to a conventional pole pole array method. This array method would be useful for providing a more reliable information of a conductive aquifer despite the resolution is very low. When an observation well is established, borehole tomography using electrical resistivity can be carried out to enhance the resolution near the borehole. The result of the electrical resistivity tomography method using single well is well matched with the result of electrical resistivity logging, and shows the effect of tidal variations.

I. Introduction

Pollution of fresh groundwater due to seawater intrusion is common at coastal areas in Korea (Park et al., 2005; Sherif et al. 2006). Pollution of groundwater by seawater intrusion occurs when salt water displaces freshwater in an aquifer. Thus protection of the groundwater from the salt water encroachment has a great implication for sustainable agriculture especially in western coastal areas of Korea (Lee and Song, 2006). It was reported that effects of seawater mixing on the fresh groundwaters were observed even at about 6 km inland and over 21% of the shallow groundwaters were affected by the salinization process in the western coasts of the country (Park et al., 2002), which was largely attributed to intensive and extensive groundwater pumping in the areas.

One of the common methods for assessing seawater intrusion through an aquifer in coastal area is installation of observation wells. However, placements of monitoring wells become difficult without knowing the extent of seawater intrusion a priori (Song et al., 2006). To avoid excessive use of drilling to find the seawater wedge, surface geophysics such as electrical resistivity surveys or electromagnetic methods can be used. Electrical resistivity surveys introduce electrical current into the ground by means of metal electrodes to detect the electrical conductivity (EC) variation in subsurface formation. Since the difference between the ECs of freshwater and seawater is significant, electrical resistivity surveys are well suited for studying the relationship between the two in coastal aquifers.Since the coastal aquifer is composed of highly conductive formations, the electrode array method with high signal-to-noise ratios is necessary to diminish the rapid attenuation of current with depth which are called the masking effect. And, to enhance the resolution of a relatively deep conductive formation, an electrical resistivity survey method using borehole is necessary. The objective of this study is to present two case histories in which the surface electrical resistivity survey method and the electrical resistivity tomography method using single well were used at two small coastal aquifers in Korea to delineate the extent of seawater intrusion through an aquifer over the coastal areas, respectively

II. Methods and Materials

A. Characteristics of site A

The study area is located in a coastal region about 200 km south of Seoul, Korea and it is in contact with the West Sea to the west (Fig. 1). There exist some low relief mountains to the other three directions. Most areas in the middle of the study site are paddy fields. Thus some groundwater wells have been existed for agricultural irrigation. From geologic logging data obtained during the monitoring well construction, there generally exist three hydrogeologic layers (Song et al., 2006). The hydrogeological sequence of the study area is as follows: reclamation soil, a weathered layer, and bedrock. Among these

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hydrostratigraphic units, upper two are water-bearing units. The bedrock, considered impervious, consists of a cretaceous sedimentary rock, which is extruded by volcanic rock.

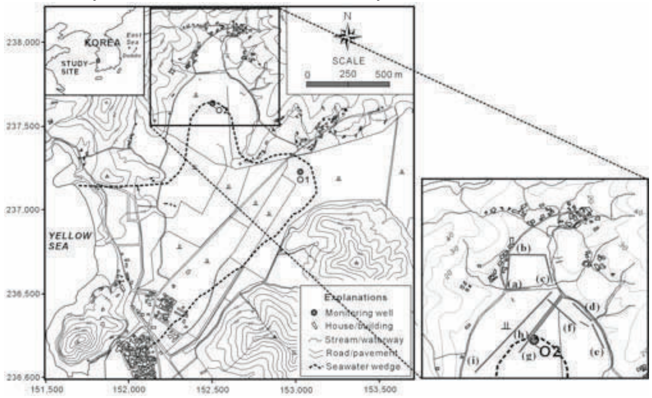

Fig. 1 Location map of the site A showing locations of electrical resistivity survey linesFinal Stage

A. Characteristics of site B

The study area is located in Haenam-gun, on the southwestern coastal area of Korea (Fig. 2). The topography is generally flat in the central part where agricultural activities are concentrated. Several tens of pumping wells exist for agricultural and industrial use and two observation wells O-1 and O-2 are installed to monitor groundwater levels and specific conductivities of groundwater with time. The hydrogeological sequence of the study area is as follows: reclaimed soil, weathered layer, and bedrock. Among these hydrostratigraphic units, upper two are water-bearing units like site A.

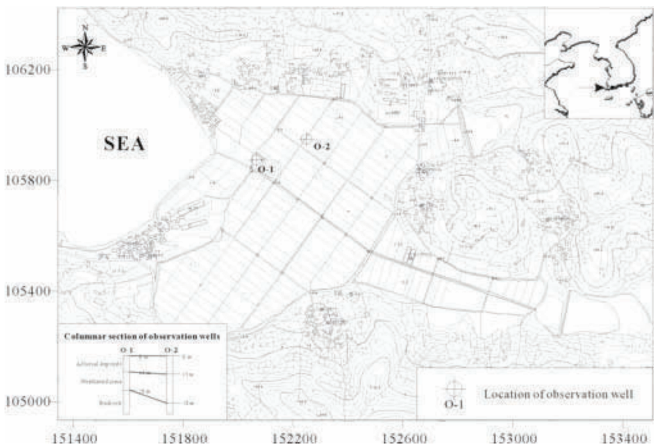

Fig. 2 Location map of the site B showing locations of electrical resistivity survey linesFigures

B. 2 D resistivity survey using modified pole pole array

Conventional electrode array methods in two-dimensional electrical resistivity survey are pole-pole, pole-dipole, dipole-dipole, Wenner and Schlumberger. Among these, the dipole-dipole array method is commonly used in Korea since the resistivity of bedrock is relatively high ranging over several thousands of ohm-m.

In general, the measured potential in field indicates the summation of electrical responses and noises. The signal-to-noise ratio of measured data is decreased as the measured potential is decreased because electrical noises are relatively increased assuming the constant of electrical noises. Therefore, the signal-to-noise ratio of measured data can be smaller as both conductivity of ground and separation index increase due to decreasing measured potential. Because the conventional electrode array method can distort the measured potential in case of pole-pole and pole-dipole using remote electrodes, Kim et al. (2001) proposed a modified electrode array method in which remote electrodes were located at both ends of survey line. Fig. 3 shows the schematic view of the conventional and modified electrode array for pole-pole array.

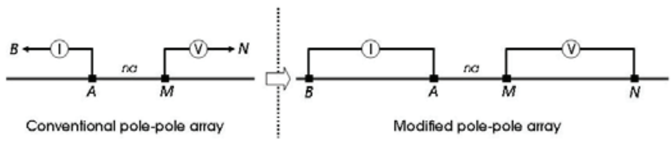

Fig. 3 Schematic comparison diagram of surface electrical resistivity survey between conventional and modified pole-pole array.

Fig. 4 shows normalized potential variations of modified electrode arrays in the homogeneous half-space. Because the normalized potential decreases drastically with a higher electrode separation index, a modified electrode array method with the relatively low normalized potential is necessary. Although the result of the modified pole-pole array method is not shown due to the variable values with the location of potential and current electrodes, this method can be indicated the highest value of normalized potential over separation index

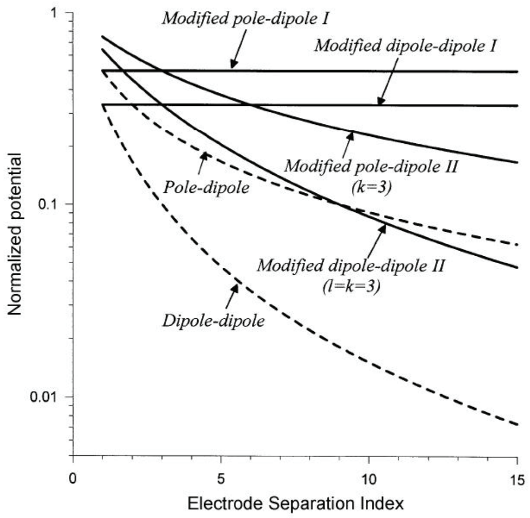

Fig. 4 Normalized potential variations of modified electrode arrays in the homogeneous half-space. (Kim et al., 2001).

In order to obtain high signal-to-noise ratios to diminish the interference of conductive layer and to overcome geographical problems in setting up remote electrodes, we conducted a 2-D resistivity survey using a modified pole-pole array in a small watershed at west coast of Korea.

C. Electrical resistivity tomography using single well

Increasing demand on high resolution imaging of subsurface formations makes borehole geophysics using electrical resistivity method is necessary. Like seismic tomography, one pair of current electrodes is located at borehole and the other pair of potential electrodes is moved in a borehole or along ground surface. Because unlike seismic tomography the resolution is decreased drastically as the distance between electrodes increases, an inline survey, which places both current and potential poles in the same borehole, is necessary (Fig. 5)

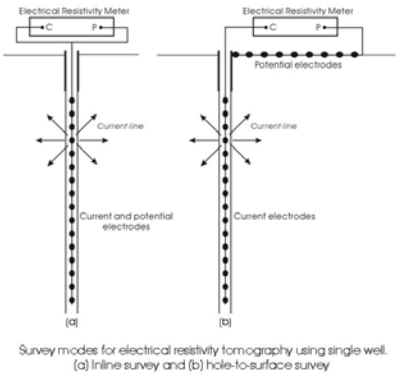

Fig. 5 Survey modes for electrical resistivity tomography using single well.

Because most boreholes have steel casings to prevent the collapse of borehole interval in upper unconsolidated layer in Korea, the resistivity data near steel casing is not sufficient. Moreover, the resolution is decreased drastically in case of the distance between the borehole bottom and the end of surface electrode is too large (Fig. 6).

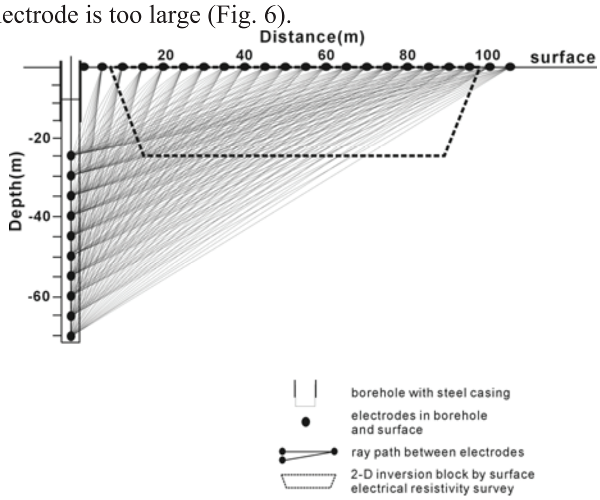

Fig. 6 Ray path of electrical resistivity tomography using single well and 2-D inversion block by surface electrical resistivity survey

In order to evaluate the extent of a seawater wedge near the borehole, to estimate the resistivity variation with the tidal effect and to enhance the resolution of resistivity near the borehole, we carried out electrical resistivity tomography using single well in a coastal aquifer located at the southwest coast of Korea.

III. RESULTS AND DISCUSSION

A. Application of modified pole pole array in a coastal area

Groundwater chemistry data from 15 groundwater monitoring wells in the study area indicates that the boundary between freshwater and seawater wedge is located near O2 monitoring well (see Fig. 1) (Song et al., 2006). We conducted 9 lines of two-dimensional electrical resistivity survey using the modified pole-pole array near the boundary of seawater wedge with 5 m (number (a) to (g)) and 10 m spacings (number (h) and (i)) (see Fig. 1). Among them, both (g) and (h) lines, which were located near the boundary between seawater and freshwater, show that the region with less than 5 ohm-m of resistivity correspond to that of seawater wedge and the boundary is well matched with the inferred boundary line proposed by Song et al. (2006) (Fig. 7).

A 3-D fence diagram of resistivity shows the boundary between seawater wedge and relatively fresh bedrock (Fig. 8). The ranges of resistivities are over several hundreds of ohm-m in the north part of the study area near mountains, and the horizontal variations of resistivities are dominant.

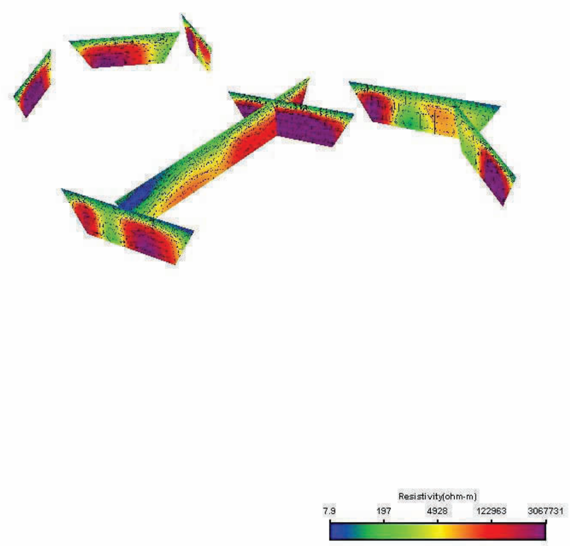

Fig. 8 3-D fence diagram of resistivity shows the boundary between seawater wedge and relatively fresh bedrock in a small watershed.

This boundary of seawater wedge from 3-D fence diagram is corresponding to the estimation of the seawater intrusion results from vertical electrical soundings at 30 points and groundwater chemistry data that the highly conductive zone was mainly distributed in near coastal area, which indicated substantial influence of seawater intrusion.

distributions at high tide is high comparing to those of at low tide and the tidal effect at this well is delayed about 12 hours.

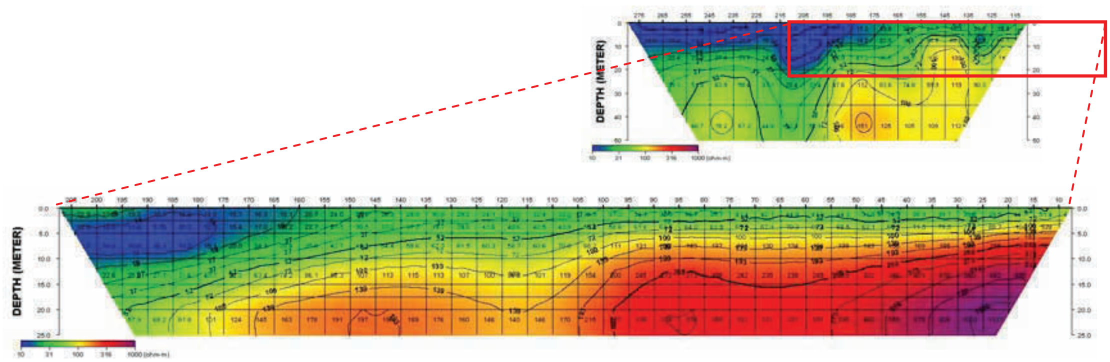

Fig. 7 2-D inversion results showing the boundary between seawater wedge and relatively fresh bedrock

B. Application of borehole tomography in a coastal aquifer

We carried out electrical resistivity tomography using one observation well O-2 (Fig. 2) with 25 m long steel casing at upper layer. According to electrical conductivity logging result, this observation well do not show notable variation by

seawater intrusion, but seawater wedge moves toward inland from the coastal line by vertical electrical sounding and hydrogeological results (Song, 2006).

Fig. 9 shows that the joint inversion result from electrical resistivity tomography using single well and surface resistivity survey agreed well with the result of electrical resistivity logging with the fractured zone located between 25 and 60 m. Moreover, low resistivity region with less than 10 ohm-m connected to that of seawater wedge (Song, 2006). To verify the effect of tidal variations, we carried out this survey at high and low tides, respectively (Fig. 10).

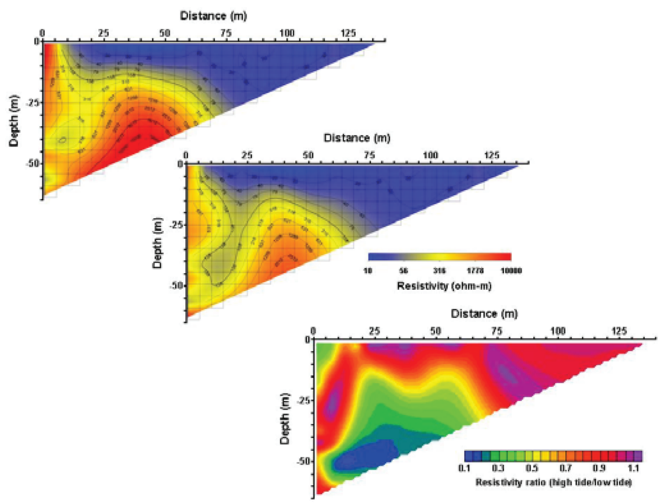

Fig. 10 Ratio of resistivity variations between high tide and low tide.

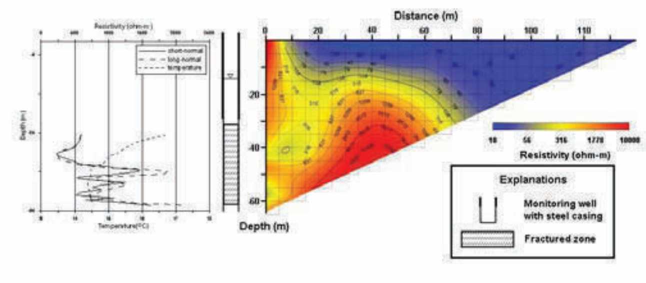

Fig. 9 Joint inversion result of electrical resistivity tomography using single well and surface resistivity survey compared to electrical resistivity logging.

Although the wedge with relatively low resistivity intruded to the fractured region at high and low tides, the difference between the two is too small. Fig. 10(c) shows that the region of high-to-low tide ratios with more than 1.0 corresponds to the intruded pathway and indicates that the resistivity

IV. CONCLUSIONS

We showed that surface electrical resistivity survey and electrical resistivity tomography using single well could provide reasonable results of the subsurface condition in coastal areas with two different case histories. To enlarge the signal-to-noise ratios and to overcome the difficulty in installing remote electrodes, we conducted the modified pole-pole array method. This modified method is proved to be powerful with increasing separation index because this array has the highest value of normalized potential to the potential of pole-pole array. According to two-dimensional inversion results, the boundary between seawater wedge and relatively fresh bedrock can be identified clearly comparing to the result of groundwater chemistry by Song et al. (2006).

In order to obtain the high resolution resistivity distribution near the borehole, we carried out electrical resistivity tomography using single well and surface resistivity survey and compared to electrical resistivity logging. According to joint inversion result with surface survey and borehole resistivity tomography, relatively low resistivity region corresponds to the direction of seawater wedge and the result of electrical resistivity tomography method using single well are well matched with the result of electrical resistivity logging. Moreover, the ratio of resistivity variations between high and low tide shows the pathway of seawater wedge as well as time delay with tidal variations. Finally, both surface survey and borehole tomography survey were found to be quite effective for investigation of seawater intrusion region

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