Four-year repeated geoelectrical surveys for the monitoring of temperature and water content in the unsaturated zone

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Introduction

Resistivity monitoring was used to understand the change of subsurface hydrological environment by many researchers (KEAN et al., 1988; WHITE, 1988; FLOHLICH and PARKE, 1990; DAILY et al., 1992; OSIENSKY and DONALDSON, 1995; SLATER and SANDBERG, 2000). The changes of subsurface water, moisture and temperature can be certainly detected by an observation well. However, making the well is expensive and disturbs the subsurface hydrological environment. Moreover the well provides information on a localized change of hydrological environment, which does not necessarily represent the whole change. In contrast, geoelectrical methods like DC resistivity and EM methods are relatively low-cost and noninvasive techniques. In addition, 2-D or 3-D geoelectrical methods including resistivity tomography can provide 2-D or 3-D images of subsurface structure.

This paper describes a result of repeated geoelectrical surveys that were carried out for about four years together with the measurements of near-surface soil temperature and soil water content. The purpose of this study is to detect the change of hydrogeological environment in the unsaturated zone and to evaluate the effectiveness of resistivity monitoring for the subsurface temperature and water content changes.

Observation site

Long-term repeated geoelectrical (DC resistivity) surveys were carried out in the KR-1 groundwater observation site, North-Kanto, central Japan (Fig.1). In this site, the measurements of near-surface soil temperature and soil water content were conducted with the meteorological observation. Continuous GPS and SP observations and repeated gravity measurements were also carried out. Twenty-five electrodes were placed at 1 m intervals along a 24-m long line that crossed immediately near the soil moisture and temperature meters. The volumetric water contents were measured every 10 minutes at five depths from 0.6 to 3 m. The soil temperatures were measured at depths of 1, 3 and 10 m. Using dipole-dipole and Wenner electrode arrays, resistivity data had been collected nearly every month since 15 August 2006. From September 2006 to March 2007, two groundwater observation wells, KR-1 and KR-2, were made to depths of 350 m and 90 m, respectively and some experiments like a production test were done. Various noises accompanying these works affected the resistivity data. Therefore, this paper discusses the resistivity data acquired after 11 May 2007. The depth to water level in this site is about 60 m, indicating the repeated geoelectrical surveys monitored the resistivity changes in only the unsaturated zone.

Changes of resistivity structure

(1) Basic resistivity structure

In this study, a 2-D resistivity section was obtained for each measurement time using the 2-D inversion method described in UCHIDA (1993). This method is an iterative least-squares inversion with smoothness constraint, which uses the finite element method for a forward calculation. Fig. 2 shows the analysed resistivity section up to a depth of 10 m on 11 May 2007. The resistivity model is basically interpreted as homogeneous structure expect for near the surface. The low resistivity zone under near the electrode No. 10 is due to the steal casing of KR-2 well.

(2) Resistivity changes

Fig. 3 shows the analyzed resistivity sections on 24 August 2007, 22 November 2007, 19 February 2008, 23 May 2008, 31 May 2009, and 31 May 2010. A large change of resistivity is not seen in the figure. In order to detect the resistivity change in detail, we calculated the rate of resistivity of each measurement time by the following equation.

$R = \frac{\rho_2 - \rho_1}{\rho_1} \times 100$, where ρ_1 and ρ_2 are layer resistivities of two different time.

Fig. 4 shows 2-D images of the resistivity change at 24 August 2007, 22 November 2007, 19 February 2008, 23 May 2008, 31 May 2009, and 31 May 2010 relative to May 11 2007. The resistivity near the surface decreased over 20 % in wet summer season and increased over 60 % in winter season. The difference of the resistivities between May 2007 and May 2008 is relatively small. This means that the resistivity change near the surface is a cycle of one year, which is a seasonal change. In the past three years, the resistivity of shallower than 5m increased, while the resistivity of deeper than 5 m decreased gradually.

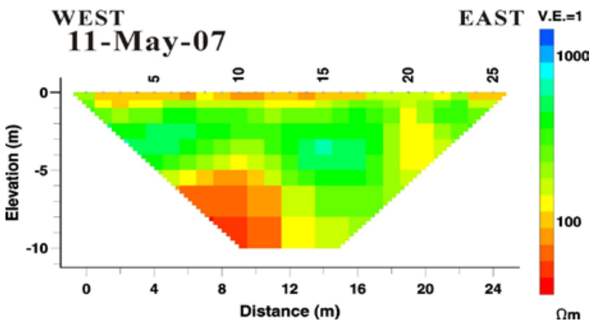

Fig.2: Analyzed 2-D resistivity section along the 24-m long survey line at 11 May 2007.

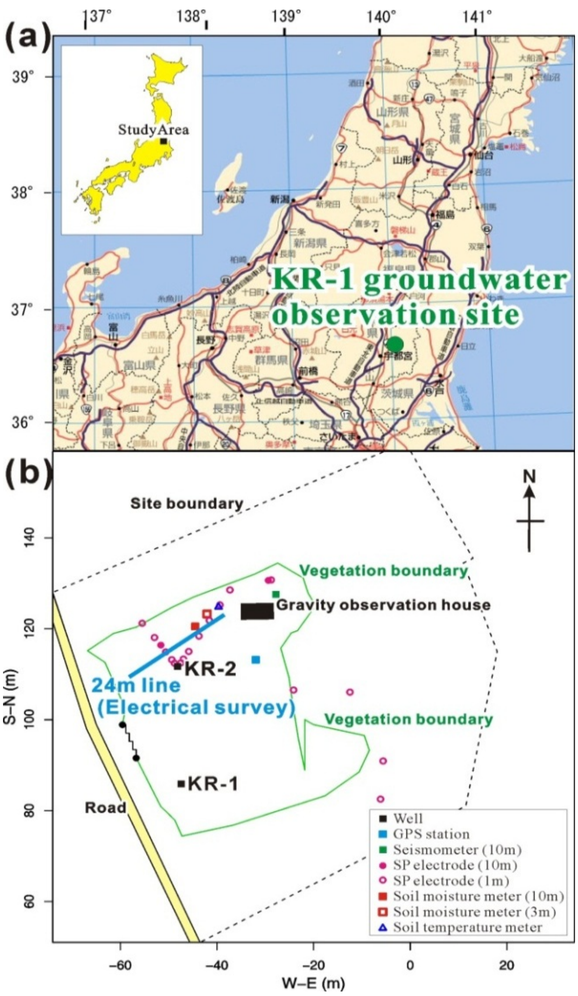

Fig. 1: Location map of the KR-1 groundwater observation site showing a repeated electrical survey line, observation wells and other observation points.

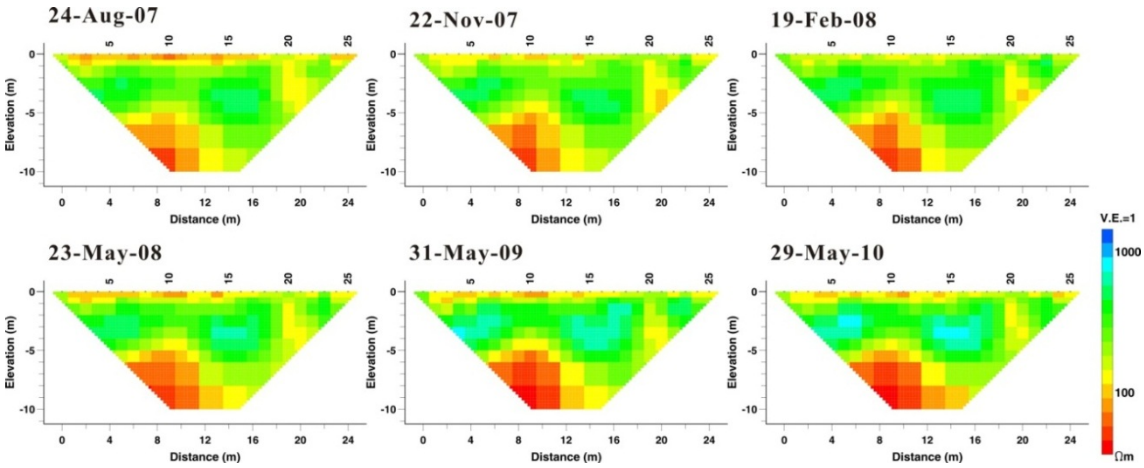

Fig.3: Analyzed 2-D resistivity sections along the survey line on 24 August 2007, 22 November 2007, 19 February 2008, 23 May 2008, 31 May 2009, and 31 May 2010.

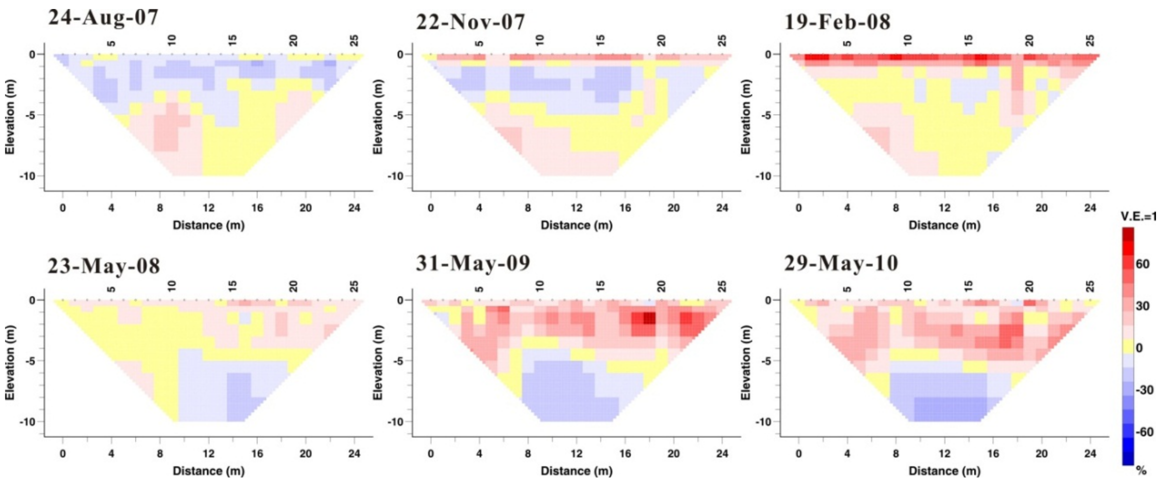

Fig. 4: 2-D images of the resistivity change at 24 August 2007, 22 November 2007, 19 February 2008, 23 May 2008, 31 May 2009, and 31 May 2010 relative to 11 May 2007.

(3) Comparison of resistivity with soil temperature

Fig. 5 shows the changes of soil temperature at depths of 1, 3 and 10 m with daily mean air temperature and the changes of resistivity analyzed from the repeated geoelectrical data at some depths near the soil temperature meter from 1 May 2007 to 19 February 2011. The soil temperature changes at depths of 1 and 3 m lag about 1 and 3.5 months behind the air temperature change, respectively. The change at a depth of 10 m is not observed. The analyzed resistivity change is the largest at the surface and decreases with depth. The resistivity and temperature are inversely related at the depths of 1 m and 3 m, indicating that the seasonal change of resistivity near the surface is mainly due to the change of temperature. Except for the depth of 8 - 10 m, the resistivities have trends which increased gradually.

(4) Comparison of resistivity with water content

Because the resistivity change is greatly influenced by the temperature change, we compensated for temperature variations using the equation suggested by HAYLEY et al. (2007).

$$\rho_{STD} = \left[\frac{m(T-25)+1}{m(T_{STD}-25)+1}\right]\cdot \rho ,$$

where T_{STD} is a standard reference temperature and ρ_{STD} is the temperature-corrected resistivity. T and ρ are the in situ temperature and resistivity, respectively, and m is a temperature correction coefficient and is generally around 0.02 (HAYLEY et al., 2007). Fig.6 shows the changes of volumetric water content at depths of 0.6m and 2.4 m and the changes of temperature-corrected resistivity at depths of 0-1 m and 2-3 m. In this case, the value of m was chosen to be 0.02 and T_{STD} was 15.5 °C that was average soil temperature. It became clear that the changes of temperature-corrected resistivity are inversely proportional to the changes of the volumetric water content. This means that the resistivity monitoring method may be effective for detecting the change of water content in the unsaturated zone if temperature compensating is made.

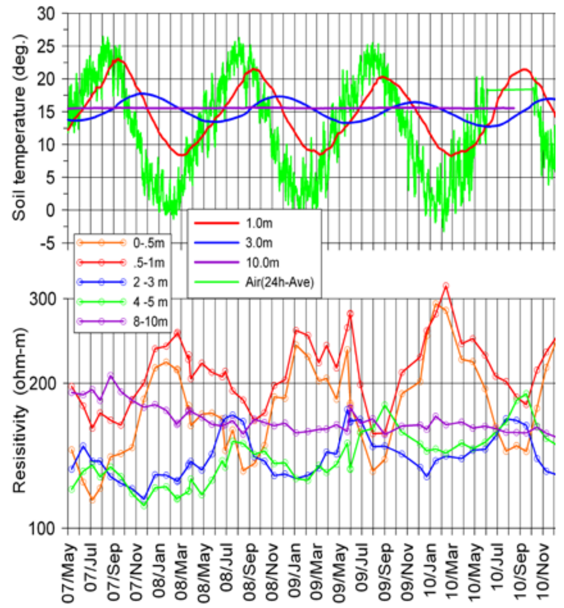

Fig.5: Changes of soil temperature at depths of 1, 3, 10 m with daily mean air temperature (upper graph), and changes of analyzed resistivity at five depths up to 10 m near the soil temperature meter (lower graph) since 1 May 2007.

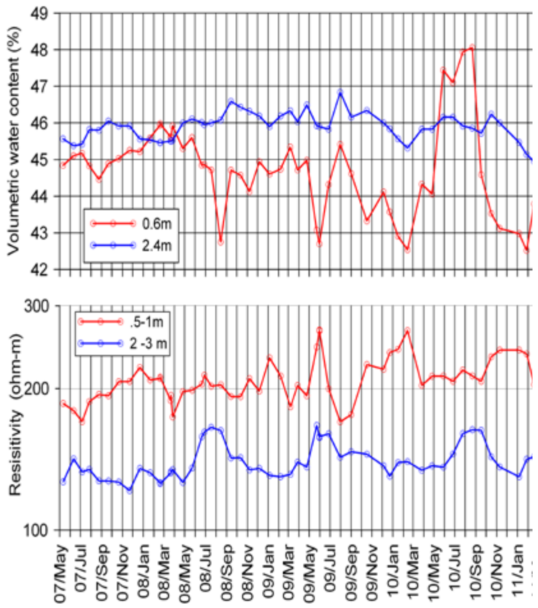

Fig.6: Changes of volumetric water content at depths of 0.6m and 2.4 m (upper graph), and changes of temperature-corrected resistivities at depths of 0.5-1 m and 2-3 m (lower graph) since 1 May 2007.

Conclusions

Repeated geoelectrical surveys were carried out in the KR-1 groundwater observation site for four years. Analyzed 2-D resistivity sections show the seasonal resistivity change is recognized near the surface. The resistivity change is the largest at the surface and decreases with depth. It seems that the long cycle change of resistivity was most influenced by the change of soil temperature. The changes of temperature-corrected resistivity are inversely proportional to the changes of the volumetric water content. These facts indicate that the geoelectrical method can be used for subsurface temperature monitoring, and may be effective for detecting the change of water content in the unsaturated zone if temperature compensating is made.

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