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Detecting groundwater flowing on a mountain slope using electrical resistivity imaging

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1. INTRODUCTION

For accurate evaluation of groundwater movement in forested mountain slopes, a dense system of moisture sensors and observation wells is needed because groundwater has been found to have high spatial heterogeneity in both the soil mantle and bedrock. However, such intensive observations may be unfeasible, especially in bedrock where drilling, installing, and monitoring a sufficiently dense network are costly and labor intensive. Electrical resistivity imaging (ERI) is a non-invasive and spatially integrated multi-electrode method that maps distributions of electrical conductivity and offers an important advantage compared to local-scale measurements. In order to validate the reliability of ERI in evaluating moisture distributions in an entire natural slope including the soil mantle and bedrock, we compared ERI surveys with hydrometric observations obtained by combined penetrometer-moisture probe (CPMP; Kosugi et al., 2009, [1]) and tensiometers on a natural hillslope.

2. METHOD

At 57 points in a footslope area, with grid interval of about 1 to 2 m, vertical profiles of volumetric water content (θ) were measured using the CPMP under no-rainfall condition (from 7 to 11 Aug. 2007) and 1 or 3 tensiometers were installed at each point within the soil layer to monitor water pressure head (from 28 May to 18 Nov. 2008). Electrical resistivity (ER) data were acquired with 0.5 m electrode spacing along a longitudinal line and four transverse lines passing through the hydrometric observation points under no-rainfall condition (on 10 Nov. and 8 Dec. 2009).

3. RESULT AND DISCUSSION

The relationship between θ and electrical resistivity (ρ) measured at the same points and depth showed that ρ is inversely related to θ (Fig. 1). Archie's equation (Archie, 1942 [2]) relates the ρ of soil or rock to the ρ of pore water (ρ_w), effective porosity (ϕ), θ of a medium with the following equation on core scale:

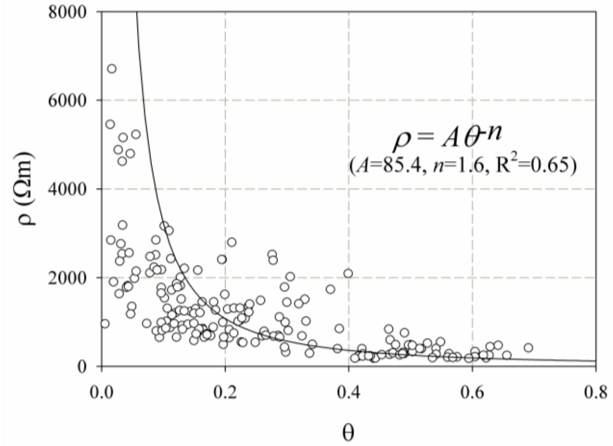

Fig.1 The relationship between volumetric water content (θ), measured with the CPMP, and electric resistivity (ρ) at each point along four transverse lines.

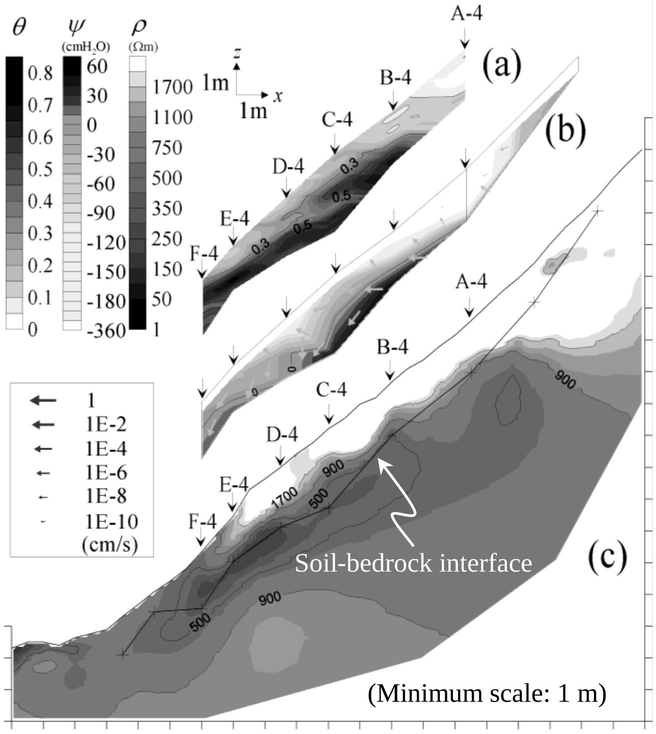

Fig.2 Spatial distributions of (a) volumetric water content (θ), (b) pressure head (ψ), and (c) electrical resistivity (ρ) under the no-rainfall condtion.

$$\rho = a\phi^{n-m}\theta^{-n}\rho_w \quad \text{………………………..…} \ (1)$$

where *a*, *m*, and *n* are empirical constants with positive values, all of which depend on soil and rock characteristics. On the assumption that soil properties and pore-water resistivity of the entire slope are homogeneous and $a\phi^{n-m}\rho_w$ could be replaced with a constant, *A*, the functional θ-ρ curve was obtained by fitting Eq. (1) to all of the measured θ-ρ plots by the least-square method, where *A* and *n* were optimized to be 85.4 and 1.6, respectively. The θ-ρ datasets are generally consistent with this fitted curve (Fig. 1). This result indicates that θ distribution in soil layer of the natural hillslope is correctly depicted on the ER image, demonstrating that the two-dimensional θ distribution can be quantified using ERI if parameter *A* and *n* is properly estimated. In detail, however, the fitted and estimated θ-ρ curves do not perfectly describe the observed θ-ρ plots (Fig. 1). These inconsistencies might be significantly attributable to the difference of the spatial resolution between CPMP and ERI and applying constant values of *A* and *n* to all of the measured θ-ρ plots.

In a longitudinal cross-section of the observed slope (Fig. 2), large water flux vectors toward the downslope direction were observed within the subsurface soil layer in the lower section (points C-4 through F-4) and relatively large horizontal and upward fluxes within the subsurface soil layer in the middle section (around B-4) occurred, where the saturated zone was detected, under the no-rainfall condition (Fig. 2a and 2b). In contrast, pressure head (ψ) showed that the quite dry conditions in the region upstream from A-4. These results indicated that the saturated zone around B-4 was probably not developed by lateral flow from the upstream region but by exfiltration of bedrock groundwater, resulting remarkable lateral flow within the subsurface soil layer in the lower section. In the ER profile along this longitudinal cross-section, shallow bedrock layer and the regions just above soil-bedrock interface indicated low ρ < 500-1000 Ωm implying the existence of saturated regions, while the soil layer and shallow bedrock of the region upstream from A-4 indicated high ρ > 2000 Ωm (Fig. 2c). These results of ERI significantly support the estimated hydrological processes based on pressure head measurements described above. Thus, ERI method could be useful to evaluate groundwater flowing on a natural hillslope including bedrock layers, which may be more difficult to achieve, if using invasive methods such as buried moisture sensors.

References:

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[2] G.E. Archie, “The electrical resistivity log as an aid in determining some reservoir characteristics,” Trans. Am. Inst. Mining Metallurgical Eng., Vol. 146, pp. 54–61, 1942.