

Title	Application of Electrical Resistivity Imaging for Measuring Water Content Distribution on Hillslopes
Author(s)	Yamakawa, Yosuke; Masaoka, Naoya; Kosugi, Ken ' ichirou; Tada, Yasuyuki; Mizuyama, Takahisa
Citation	Journal of Disaster Research (2013), 8(1): 81-89
Issue Date	2013-02
URL	http://hdl.handle.net/2433/173622
Right	(C) 2013 Fuji Technology Press Co., Ltd.
Type	Journal Article
Textversion	author

Survey Report: Dr8-1-5768; 2013/1/25

Application of Electrical Resistivity Imaging for Measuring Water Content Distribution on Hillslopes

Yosuke Yamakawa*, Naoya Masaoka**, Ken'ichirou Kosugi**,
Yasuyuki Tada***, and Takahisa Mizuyama**

*Educational Unit for Adaptation to Extreme Weather Conditions (GCOE-ARS Unit),
Center for the Promotion of Interdisciplinary Education and Research (C-PIER),
Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
E-mail: yosuke82@kais.kyoto-u.ac.jp

**Laboratory of Erosion Control, Department of Forest Science,
Graduate School of Agriculture, Kyoto University
Oiwake-Cho, Kitashiraka, Sakyo-ku, Kyoto 606-8502, Japan

***Laboratory of Hillslope Conservation, Department of Soil and Water Conservation,
Forestry and Forest Products Research Institute
1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan

[Received December 3, 2012; accepted January 5, 2013]

Electrical resistivity imaging (ERI) as a method for effectively evaluating soil water content distribution on natural hillslopes was validated by combining ERI technique with the invasive measurement of volumetric water content (θ) using a combined penetrometer-moisture probe (CPMP) on a hillslope in a head-water catchment underlain by weathered granite porphyry. There was a reasonable correlation ($R^2=0.54$) between θ and electrical resistivity (ρ). The correlation between θ and ρ measured on two natural hillslopes in a head-water catchment underlain by weathered granite in our previous studies was also analyzed, and there was some reasonable correlation ($R^2=0.33$ to 0.53) between θ and ρ within each slope, indicating the potential of ERI for quantitatively evaluating moisture conditions within soil layers of natural hillslopes based on field-scale calibrations with invasive methods. These θ - ρ datasets were roughly consistent with a common fitted functional model (Archie's equation) ($R^2=0.37$), indicating the possibility of quantitatively evaluating θ of soil layer on natural hillslopes using ERI without directly measuring θ using any invasive method, although results still showed the importance of combining invasive methods with ERI and obtaining site-specified θ - ρ correlation models for providing a more accurate spatial distribution of θ within the soil mantle. Inconsistencies between θ and ρ within datasets may be significantly attributable to not only limitations on spatial resolution of ERI technique related to the issue of representative volumes of the technique and inversion analysis to obtain ρ profiles but also the assumption that soil properties and pore-water resistivity of the entire slope are homogeneous. Using a CPMP as invasive method, detecting heterogeneous θ distribution more accurately than ERI technique, together with ERI is one of the most reasonable ways of effectively quantifying soil water content distribution on natural hillslopes.

Keywords: ERI (electrical resistivity imaging), soil water content, shallow landslide, Archie's equation, CPMP (combined penetrometer-moisture probe)

1. Introduction

Japan in the Asian monsoon zone is frequently stricken by landslide disasters due to heavy rainfall, causing heavy damage to human lives and property each year. The greater part of landslide disasters involves shallow landslides (slope failures) that are caused by surface soil layers of hillslopes destabilized by rainfall. In this context, it should be considered a pressing social need to establish effective methods for predicting the occurrence – place and timing – of landslides and to define the basic mechanism of landslides. But the mechanism by which some slopes preferentially collapse within a watershed is still poorly understood.

Shallow landslides are caused by interactions between soil structures of slope surface layers and the behavior of rain water. Recent studies on hillslope soil moisture indicate that the heterogeneous behavior of ground water like pipe flows in soil layers and bedrock groundwater seeping into the soil mantle could be the dominant cause for shallow landslides [1-4]. It will provide a clue to the definition of mechanisms of shallow slides to accurately grasp data on the spatially heterogeneous groundwater flowing of hillslopes.

Water flow in hillslope soil layers are grasped effectively with buried moisture probes. Their measuring range and spatial resolution are defined, however, by the number of sensors, cost and labor for installing sensors, which provides a great barrier when grasping water-flow processes in detail in more extended areas of hillslopes. It remains one of the important issues to be addressed to establish methods to effectively grasp data on water movement in the ground. A combined penetrometer-moisture probe

(CPMP), developed by Kosugi et al. (2004) [5] and Yamakawa et al. (2007) [6], has a soil moisture probe at the tip of the soil penetrometer. The CPMP is a highly maneuverable technique and could provide simultaneous measurements of the penetration resistance and water content of soil layers. In fact, Yamakawa et al. (2010) [7] and Masaoka et al. (2010) [8] actually succeeded in grasping in detail the distribution of ground water level in soil layers as well as the moisture distribution of complex soil structures by applying the CPMP to natural hillslopes, demonstrating the usefulness of the developed technique. It should be noted, however, that what we can obtain from the CPMP is no more than spot data and that it will require a much larger amount of labor to carry out the same measurements in more extended areas.

Electrical resistivity imaging (ERI), a physical exploration method for grasping electrical resistivity distribution in soil from the ground surface, could be a more effective method for grasping moisture distribution for more extended areas of soil than the techniques providing spot data like as the CPMP or the buried moisture probe, so that ERI has been applied recently very enthusiastically in an increasing number of fields [9-12]. ERI, a method for indirect measurement from the ground surface, cannot, however, be completely free of limitations in terms of quantitative evaluation (calibration) of water content in soil and spatial resolutions. In addition, any difficulty in applying a direct measuring technique to extended areas of soil layers on hillslopes prevents us from verifying the reliability of ERI on natural hillslopes, which still remains a big issue to be solved. In fact, very few studies which compared in-situ electrical resistivity distributions and spatial distributions of water content have been conducted. Such studies include that by Yamakawa et al. (2010) [7], in which they measured soil volumetric water content (θ) with a CPMP and electrical resistivity (ρ) with ERI on natural hillslope in forest catchment areas (Kiryu Hydrological Test Catchments) underlain by granite to compare both types of measurement along the same measurement lines. On another slope in the same catchment, Yamakawa et al. (2012) [12] measured the pressure head of water (ψ) in soil layers with tensiometers to obtain θ and compared θ with ρ on the same points. These measurements present a largely reasonable correlation between ρ and θ , which suggests that soil moisture distribution in soil layers of natural hillslopes could be effectively measured by measuring electrical resistivity with ERI. The correlation between θ and ρ , however, was not completely consistent with Archie's equation [13] fitted by the least-squares method. The reasons for inconsistency probably are difference in scales of measurement objects (extent of influence) between ERI and CPMPs or tensiometers (pore pressure meters); difficulty in explaining all θ - ρ plots with a uniform parameter set in view of soil properties with spatial distribution; or the smoothing of spatial distribution of ρ that were estimated by inversion analysis.

In order to accurately grasp the hydrological structure of hillslopes with ERI, we should continue verification

studies based on a comparison of data for soil water content and electrical resistivity obtained by direct in-situ measurement methods on hillslopes and we should also develop efficient direct measuring methods in combination with ERI.

In this study, we have measured, in detail, for comparison along the same measurement lines, penetration resistance and θ with the CPMP and ρ with ERI on a slope in a hill catchment with different topographical and geological conditions from those of our previous studies [7, 12]. We have also compared the measurement results with the θ - ρ correlation data in the previous studies [7, 12] and have integrated the both data for analysis. The primary objective of this study is to validate the potential (applicability and limitations) of ERI to provide soil water content distribution in natural slopes for many different geological and soil conditions by comparing invasive methods. Additionally, we discussed the availabilities of combination with ERI as a noninvasive method and the CPMP as an invasive method for a quantitative as well as high spatial resolution evaluation of soil water content distribution in natural slopes.

2. Experimental and Observation Methods

2.1. Combined Penetrometer-Moisture Probe (CPMP)

Figure 1 shows the CPMP, a penetrometer with a 20-mm-diameter 60-degree tip cone, a 2-kg falling weight, and a soil moisture sensor right above the tip cone. The moisture sensor adopts time-domain reflectometry (TDR) [14] and the probe consists of two stainless steel wires coiled along grooves in acrylic pipe. Relative dielectric constant (κ) of peripheral media of the probe is derived from the observed velocities of electromagnetic waves propagated through probe wires and then converted to volumetric water content (θ). (For details on the structure of the CPMP, details of the measuring system, and conversion from κ to θ , refer to Yamakawa et al. (2007) [6] and Kosugi et al. (2009) [15].)

2.2. ERI

In ERI, electric current is passed into soil to measure the potential responses and seek the distribution of electrical resistivity (ρ) [16]. Since ρ -values represent compound reflections of various physical properties in soil, Archie (1942) [13], for example, proposes the following equation to explain ρ :

$$\rho = a\varphi^{-m}S^{-n}\rho_w \dots \dots \dots (1)$$

where φ denotes porosity, S the saturation degree, and ρ_w , the electrical resistivity of pore water; a , m , n are constants determined by geological and soil conditions and reflect differences in porosity, pore structure, clay content, clay properties, contained minerals and weathering degrees of soil materials [17]. Laboratory experiments

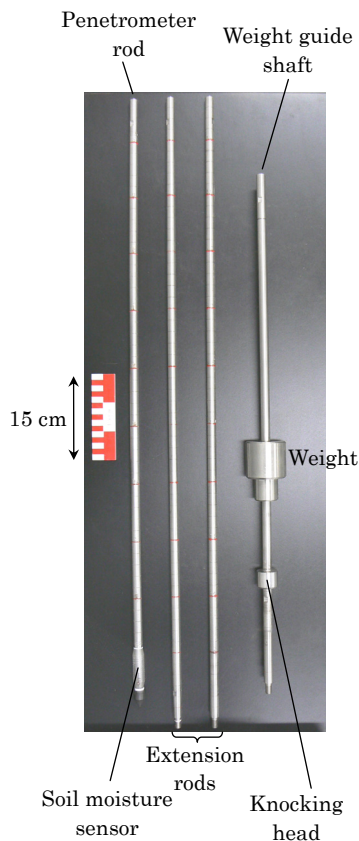


Fig. 1. General view of CPMP.

with core sample scales report that a , m , n are generally 0.5-2.5, 1.3-2.5 and around 2.0, respectively [17-19].

2.3. Observation Sites and Measurement Content

The observation slope is situated in the head water catchment area of Hirusani within the jurisdiction of the Hodaka Sedimentation Observatory of Kyoto University in Gifu Prefecture (36°15'N, 137°35'E). Fig. 2 shows topography around the observation slope. The observation slope is positioned at the foot of the valley wall; the average gradient of the slope is 40°; soil properties of the base material are granite porphyry; main components of soil layers are brown forest soil. On the observation slope, Masaoka et al. (2010) [8] conducted penetration tests with the CPMP and detailed moisture observation through the pressure water head observation network, using high-density tensiometers (pore pressure meters). (In Fig. 2, a tensiometer for depths 1-3 is installed in soil layers at each point marked with a plus (+).) General moisture conditions in soil layers at the observation site (marked with a plus (+) in Fig. 2)) are as follows: it is moister downstream; on measurement lines downstream from measurement line C, soil layers are found to be constantly saturated zones at a majority of measurement points. For measurement line B, constantly saturated zones are only observed at the fourth measurement point from the left bank (a point where measurement line V in the longitudinal direction and measurement line B in the topographical

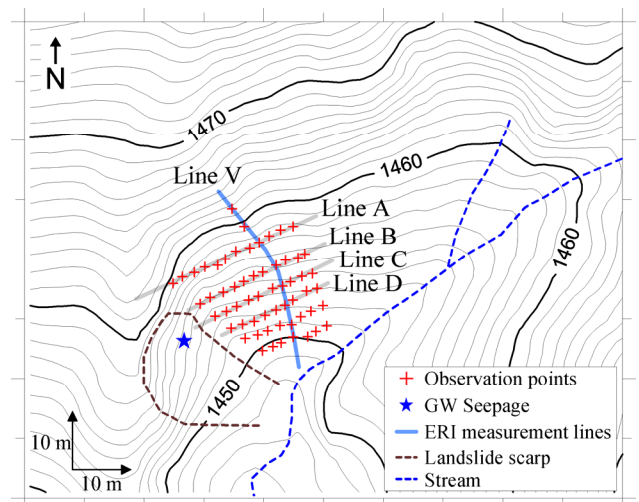


Fig. 2. Topography around observation slope.

direction intersect) (point B-4) and the fifth measurement point (point B-5). On measurement line A, constantly saturated zones are not observed at any measurement points. At points B-4 and B-5, tensiometers installed at the depth of the interface between the soil layer and bedrock locally record peaks in the rise of the pressure water head about two days after the end of rainfall at the observation site, which seems to suggest some existence of bedrock groundwater seeping into the soil mantle.

In this study, we have compared electrical resistivity (ρ) measured with ERI on measurement line V with volumetric water content (θ) measured with the CPMP at points A-4, B-4, C-4, D-4 (points where measurement lines A, B, C, D and measurement line V intersect with each other).

For penetration tests with the CPMP, we have determined soil layers with penetration resistance (N_c) of more than 100 to be bedrock, based on studies by Yamakawa et al. (2010) [7] and Masaoka et al. (2010) [8]. The measurement interval in the depth direction for θ at test points is 0.5-10 cm according to the penetration depth. Immediately after tests, we have inserted a vinyl chloride pipe into holes made for the CPMP to make a makeshift soil layer well at each measurement point and have measured depths of ground water levels in holes.

For measurement of electrical resistivity, we have conducted measurement on measurement line V (in Fig. 2) with electrical resistivity imaging system E60CN Multielectrode Resistivity System (Geopen Shanghai Ltd., China): the electrode interval is 0.5 m; electrode configurations are dipole-dipole. The measured apparent resistivity data were processed to generate 2-D resistivity models of the subsurface area using inversion analysis software E-Tomo version 4 (DIA Consultants Company, Tokyo, Japan).

Penetration tests with the CPMP were conducted from August 7 to 11, 2007 and resistivity was measured on November 10, 2009, while rainfall three days, seven days and 14 days prior to measurement were: 0 mm, 31 mm

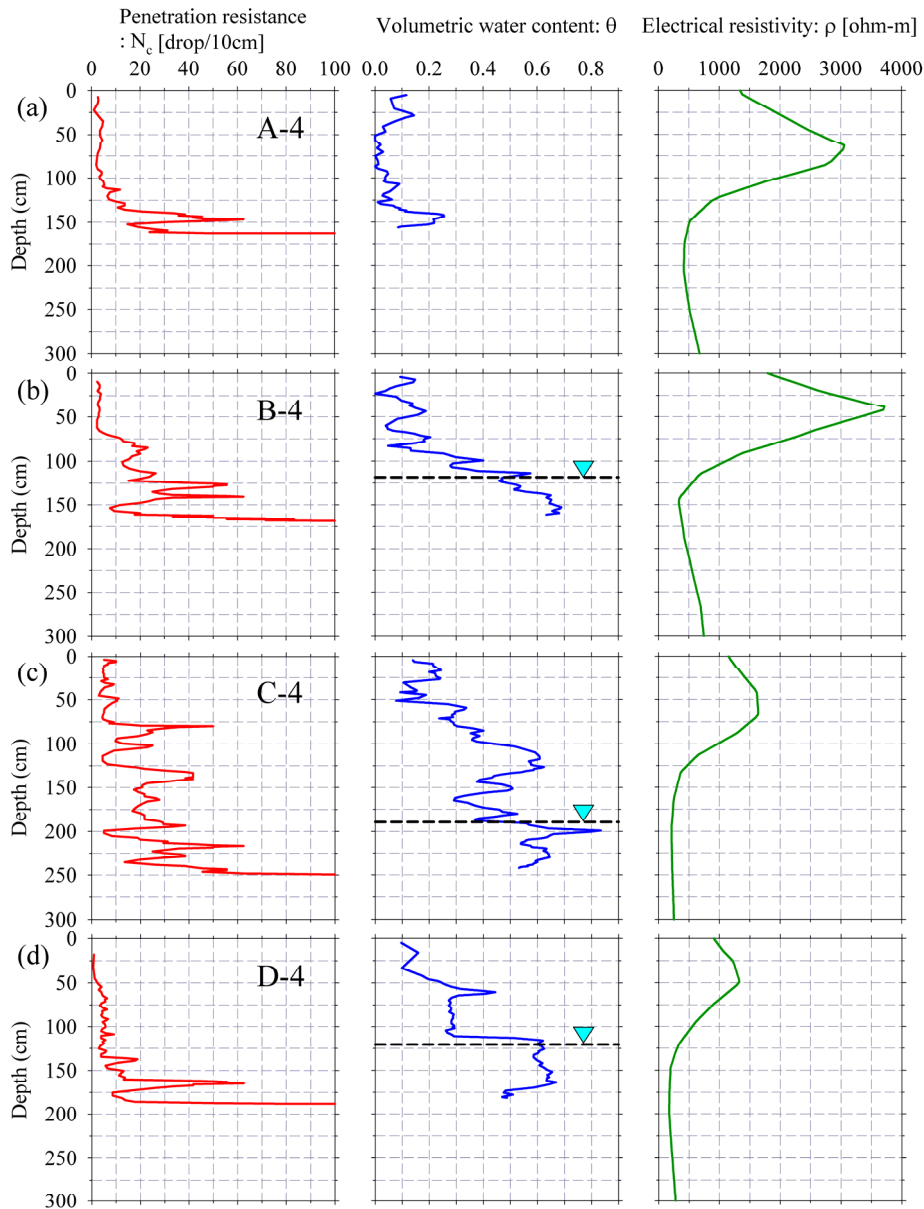


Fig. 3. Soil penetration resistance, volumetric water content, ground water level (vertex of inverted triangle), vertical distribution of electrical resistivity; (a) Point A-4, (b) Point B-4, (c) Point C-4, (d) Point D-4.

and 40 mm on August 7, 2007 and 0 mm, 7 mm and 37 mm on November 10, 2009. Steady-state θ distribution in soil layers with no rainfall seem almost the same at the time of the above-mentioned measurement. No rainfall was observed during measurement periods.

3. Results and Discussions

3.1. Measurements of Soil Moisture Spatial Distribution with CPMP

Figure 3 shows vertical profiles of penetration resistance and volumetric water content measured by the CPMP at points A-4, B-4, C-4, D-4. At point A-4 (Fig. 3(a)), a relatively soft, uniform soil structure was detected down to a depth of about 135 cm with pene-

tration resistance (N_c) less than 5-10 drops/10 cm. The soil layer is 163 cm thick. With volumetric water content (θ) of 0.2 or less down to a depth of about 140 cm, the soil layer is found to be relatively dry; specifically, θ at depths between 40 and 100 cm is 0.05 or less; θ right above bedrock is 0.25 or slightly more than that at the surface layer. We directly measured ground water level via makeshift wells, immediately after measurement with the CPMP, and observed that there was no water table in the soil at point A-4. At point B-4 (Fig. 3(b)), with N_c of 40-60 drops/10 cm at a depth between 125 and 140 cm, locally high values were detected; at 150 cm in depth right above the interface between the soil layer and bedrock, a soft soil layer with N_c of 40-60 drops/10 cm was detected; the soil layer is 168 cm thick. θ increased with depth and direct measurement detected a ground water table 118 cm

below the ground surface. At point C-4 (**Fig. 3(c)**), with N_c heavily varied in a range of 10-50 drops/10 cm at a depth of 75 cm or more, a very heterogeneous soil structure was detected; the soil layer is 249 cm thick. Vertical distribution of θ indicates a heterogeneous moisture distribution with a peak value of 0.6 at a depth of 110-130 cm, where N_c is 5-10 drops/10 cm, locally low. In view of a study by Yamakawa et al. (2010) [7] in which they found that in unsaturated areas above the ground water surface, θ in silt layers with lots of fine-grained fractions is higher than in neighboring sandy layers, a soil layer at a depth of 110-130 cm at point C-4 probably involves soil properties with lots of fine-grained fractions with higher θ than in neighboring layers. A ground water table at point C-4 is detected at a depth of 189 cm. At point D-4 (**Fig. 3(d)**), vertical distribution of penetration resistance (N_c) indicates that there is a relatively soft, uniform soil structure with N_c of 5-10 drops/10 cm or less in the surface layer at a depth of about 130 cm, as at point A-4. The soil layer is 188 cm thick. Although vertical distribution of θ shows a tendency to increase in proportion to depth, it shows an almost constant value of 0.3 at a depth of 70-10 cm and a rapid rise at the ground water table at a depth of 121 cm where direct measurement was taken, or a stepwise profile. At points B-4, C-4 and D-4, a comparison between ground water level directly measured via the observation wells and the vertical distribution of θ measured with the CPMP shows that a depth with θ of 0.6 or more corresponds roughly to the ground water level. At points C-4 and D-4, however, θ decreases at a depth below the ground water surface. This seems to suggest that soil properties at the ground water table may be different from those at a depth below the ground water table or that ground water may be in a perched condition.

As mentioned above, it can be seen from measurement with the CPMP, broadly speaking, that soil layers of observation slopes are more moist lower down and that they have very complex, heterogeneous structures in terms of soil layer thickness, soil layer structure (N_c values) and vertical profiles of θ .

3.2. Comparison of Measurement Results for Soil Volumetric Water Content and Resistivity

Figure 3 also shows the vertical distribution of resistivity (ρ) at points A-4, B-4, C-4 and D-4 out of the two-dimensional resistivity distribution measured on measurement line V on the observation slope in the Hirudani catchment area. We check for correspondence between θ measured with the CPMP and vertical profiles of ρ at these respective points. At point A-4 (**Fig. 3(a)**), ρ is in the range of 500-3,000 ohm-m at a depth of 0-160 cm in the soil layer; ρ - θ profiles of the soil layer show reasonably good correspondence: ρ in the area of intermediate depth (40-100 cm) of a very dry soil layer with θ of 0.05 or less is 2,000-3,000 ohm-m, while ρ in the surface layer or at a depths of 100 cm or more is 2,000 ohm-m or less. ρ in a slightly moist area with θ of 0.1-0.25 is 500-1,000 ohm-m. At point B-4 (**Fig. 3(b)**), ρ in unsatu-

rated soil areas at the depth of the ground water table or shallower is 1,000-3,700 ohm-m. ρ in areas with high θ at the depth of the ground water table or deeper is 300-1,000 ohm-m. ρ , however, does not follow in conformity with complex changes in θ in areas between the surface layer and ground water table. At point C-4 (**Fig. 3(c)**), ρ in unsaturated soil areas is 1,600 ohm-m or less, which is corresponded to the observation results that θ at the depth of the ground water table or shallower is generally higher than at points A-4 and B-4 upstream. ρ at a depth of 100 cm or more where θ shows a rapid rise to 0.5-0.6 is 1,000 ohm-m or less and is extremely low at 250 ohm-m at a depth of 150 cm or more. The ρ profile, however, does neither correspond to a peak value of θ of about 0.6 at a depth of 110-130 cm nor the ground water table at a depth of 190 cm. At point D-4 (**Fig. 3(d)**), ρ in unsaturated soil areas is 1,300 ohm-m or less, which is corresponded to the observation results that θ in unsaturated soil areas is higher than that upstream on the slope as at point C-4. ρ at the depth of the ground water table or deeper is 400 ohm-m or less.

As mentioned above, broadly speaking (for more than about 1-m scale), θ directly measured with the CPMP and vertical profiles of ρ correspond well with each other at least qualitatively, but the complex, heterogeneous vertical distribution of θ in a complex soil layer structure (for less than about 50-cm scale) does not correspond completely to its ρ profile. Such non-correspondence still seems attributable to the following aspects related to the limitations in spatial resolutions of ERI method: apart from the effects of differences in measurement time, the difference in scales of measurement objects (extent of influence) between the electrical resistivity imaging method and direct spot measurement (the CPMP in this study) and the smoothing of spatial distribution of ρ that were estimated using inversion analysis, as indicated in previous studies (e.g., Yamakawa et al., 2010 [7]; Yamakawa et al., 2012 [12]; Schwartz et al., 2008 [20]). Accordingly, at points with complex soil structures involving heterogeneous moisture distribution, we need to complement spatial resolution of the electrical resistive imaging method with the high-density direct measurement of moisture.

We next consider the quantitative correlation between θ and ρ of soil in situ. We have actually checked the correlation between θ and ρ of soil layers at a depth interval of 5 cm at points A-4, B-4, C-4 and D-4 (**Fig. 4**). As a result, we have confirmed that there is basically an inverse correlation between θ and ρ at the same points. Archie's model (Eq. (1)) is rewritten as follows by substituting S for $S = \theta/\rho$:

$$\rho = a\phi^{n-m}\theta^{-n}\rho_w \dots \dots \dots (2)$$

Assuming that soil properties and the electrical resistivity of pore water are uniform over the entire slope, Eq. (2) is rewritten as follows by substituting the term $a\phi^{n-m}\rho_w$ for constant A:

$$\rho = A\theta^{-n} \dots \dots \dots (3)$$

Approximate curves (Archie's model) are obtained by

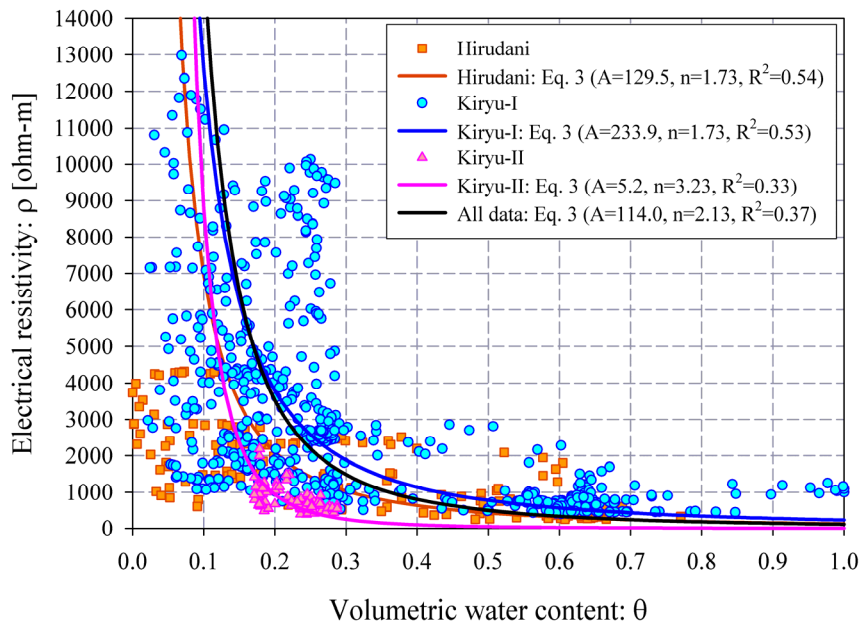


Fig. 4. Correlations between volumetric water content and electrical resistivity.

fitting Eq. (3) using the least squares method for minimum residual error of θ for plotted θ - ρ data when n and A are 1.73 and 129.5, respectively, and determination coefficient (R^2) is 0.54. These results demonstrate that spatial distribution of θ in soil layers of slopes as a measurement object could be quantitatively obtained from the measurement of ρ with the electrical resistivity imaging method. In this case, however, it should be duly noted that parameters (n , A) specific to slopes need to be obtained accurately. Although this normally requires the in-situ measurement of θ of soil layers, the proposed method combining electrical resistivity imaging and the CPMP proves to be a method effective in efficiently achieving the above-mentioned objective.

Note, furthermore, that strictly, all of plotted θ - ρ data cannot be fully explained (varied plots) by any common model that is defined by a certain parameter set (n , A). This seems attributable to limitations in the spatial resolution of the electrical resistivity imaging method as well as to the spatial distribution of soil properties, so all plotted θ - ρ data cannot be fully explained by any uniform model.

3.3. Comparison of Soil Volumetric Water Content – Electrical Resistivity Correlations on Different Slopes and Catchment Areas

Data on θ - ρ of soil layers on adjacent slopes in Kiryu Hydrological Test Catchment areas underlain by granite bedrock, which were obtained by Yamakawa et al. (2010) [7] (Kiryu Catchment I) and Yamakawa et al. (2012) [12] (Kiryu Catchment II), are added to Fig. 4. Data for Kiryu Catchment I is extracted at a depth interval of 5 cm from vertical profiles of θ and ρ that were measured with the CPMP and ERI on the same measurement lines the same way as tests conducted in Hirudani Catch-

ment areas. Data for Kiryu Catchment II, however, represents θ converted from pressure water head (ψ) as measured with tensiometers installed in soil layers and ρ at corresponding measurement points; in converting ψ to θ , we assumed that moisture characteristic curves (namely, ψ - ρ correlations) are uniform in soil layers and have applied a uniform moisture characteristic curve to all measurement points, so data should be used for reference only in this study.

Figure 4 shows plotted data on θ and ρ of three slopes in two catchment areas with different soil properties. Although plotted data in each group vary largely, there is no great deviation among the three groups of plotted data. In other words, broadly speaking, plotted data groups for the three slopes could be reasonably approximated with Archie's model defined by a uniform parameter set. This seems to suggest that a common Archie's model could be applied to quantitatively evaluate θ in soil layers of slopes from ρ of soil even for different catchment areas with different geological and soil conditions. A common Archie's model (Eq. (3)) obtained by integrating plotted data groups for the three slopes is found to have the following values for n , A and R^2 : $n = 1.73$; $A = 233.9$; $R^2 = 0.53$.

A comparison of catchment areas and of slopes shows that for plotted data for Kiryu Catchment I, there are especially greater variations in the region of $\theta \leq 0.3$ than those for the Hirudani Catchment and, nevertheless, that plotted data on θ - ρ are found to be in reasonably good inverse correlation in general. Parametric fitting of Archie's model (Eq. (3)) produced the following values for n , A and R^2 : $n = 1.73$; $A = 233.9$; $R^2 = 0.53$. Plotted data on θ - ρ for Kiryu Catchment II, which is less varied than those for the other two slopes, also present a generally good inverse correlation: n and A are 3.23 and 5.2 respectively and R^2 , 0.33. A comparison between the Hirudani Catchment

and Kiryu Catchment I reveals apparently similar correlation patterns of θ - ρ with $n = 1.73$ for both catchments. Specifically, ρ for Hirudani Catchment areas is generally lower than that for Kiryu Catchment I. In the region of $\theta \leq 0.3$ in particular, ρ of 10,000 ohm-m or more was measured at several points in Kiryu Catchment I, while it is 4,500 ohm-m or less in Hirudani Catchment areas. This seems attributable to a difference in geological and soil conditions between the two catchments. Although observation slopes in the Kiryu Catchment and Hirudani Catchment areas are both classified into forest brown soil, observation of the soil profile at the site reveals that Kiryu Catchment areas are mainly made of decomposed granite soil with weathered granite as a basic material and that the surface layer of the slope in particular, leached away by rainfall, has less fine-grained fractions such as clay and silt than Hirudani Catchment areas with granite porphyry as a basic material. Generally, clayey or silty soil has higher values of θ than sandy soil in unsaturated conditions, which is clearly explained by soil moisture characteristic curves [21]. Additionally electrical resistivities of clayey soil could be less than those estimated from Archie's model due to some electrochemical effects of clay minerals [22]. Then, both or either of these aspects could be the reason that ρ for Hirudani Catchment areas is generally lower than that for Kiryu Catchment I. ρ values for Kiryu Catchment II in the range of 500 ohm-m to 2,000 ohm-m are lower than those for Kiryu Catchment I but they are still within the range of variations for Kiryu Catchment I.

As mentioned above, for each observation slope with distinctive inverse correlations of θ - ρ , it was proven that the spatial moisture distribution of slope soil layers can qualitatively be grasped from ρ measurement data alone. In order to quantitatively seek more accurate distribution of θ from the distribution of ρ , however, we may still need to draw up calibration curves of θ - ρ for each slope or catchment area through direct measurement of θ .

4. Conclusion

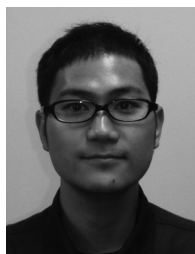
In order to verify the in-situ applicability of electrical resistivity imaging (ERI) as a soil moisture measurement method for hillslopes, we have measured, on the same measurement lines on natural hillslopes, electrical resistivity (ρ) with ERI and soil volumetric water content (θ) with a combined penetrometer-moisture probe (CPMP) and have compared both types of measurement data. We have also analyzed data on θ - ρ for other catchment areas in previous studies to check for correlations of θ - ρ as obtained for plural slopes (two catchments, three slopes in total) with different geological and soil conditions. Data on θ - ρ for each slope present generally good inverse correlations ($R^2 = 0.34$ - 0.54), proving the effectiveness of ERI as a soil moisture measurement method for hillslopes. Groups of θ - ρ data for the three slopes are not so much varied among each other (integration of θ - ρ data for the three slopes produces $R^2 = 0.37$), which

indicates the applicability of a common θ - ρ correlation model (Archie's model) for certain geological and soil conditions. Since, strictly speaking, any θ - ρ correlation model (Archie's model) tends to differ with different geological and soil conditions, we need to acquire a separate θ - ρ correlation model for each slope in order to quantitatively evaluate, with high accuracy, θ distribution in soil layers of slopes with ERI. Variations in plotted data on θ - ρ or limitations in the accuracy of θ measurement with ERI seem attributable to differences in measurement scale between ERI and the direct spot measurement method; electrical resistivity distribution smoothed by inversion analysis; spatial distribution of soil types. In addition to much higher-accuracy quantitative evaluations of θ distribution for the entire slope, simultaneous application of the CPMP to complement limitations in spatial resolution of ERI was found to be still an effective technique. As future work for more understanding of the availabilities and limitations of ERI, it would be important to accumulate more verifications based on a comparison of data for soil water content and electrical resistivity obtained by direct in-situ measurement methods on hillslopes for many different geological and soil conditions. On the other hand, it would be also needed to closely investigate the influences of the spatial distribution of soil type within a slope soil layer on the obtained electrical resistivity profile.

References:

- [1] D. R. Montgomery, W. E. Dietrich, R. Torres, S. P. Anderson, J. T. Heffner, and K. Loague, "Hydrologic response of a steep, unchanneled valley to natural and applied rainfall," *Water Resources Research*, Vol.33, No.1, pp. 91-109, doi:10.1029/96WR02985, 1997.
- [2] T. Uchida, K. Kosugi, and T. Mizuyama, "Effects of pipe flow and bedrock groundwater on runoff generation in a steep headwater catchment in Ashiu, central Japan," *Water Resources Research*, Vol.38, No.7, pp. 1119-1133, doi:10.1029/2001WR000261, 2002.
- [3] T. Uchida, Y. Asano, N. Ohte, and T. Mizuyama, "Seepage area and rate of bedrock groundwater discharge at a granitic unchanneled hillslope," *Water Resources Research*, Vol.39, No.1, doi:10.1029/2002WR001298, 2003.
- [4] S. Katsura, K. Kosugi, N. Yamamoto, and T. Mizuyama, "Saturated and unsaturated hydraulic conductivities and water retention characteristics of weathered granitic bedrock," *Vadose Zone Journal*, Vol.5, No.1, pp. 35-47, doi:10.2136/vzj2005.0040, 2005.
- [5] K. Kosugi, D. Tsutsumi, T. Mizuyama, and S. Hasegawa, "Combined penetrometer-moisture probe for measuring water content distribution in hillslope," *Journal of the Japan Society of Erosion Control Engineering*, Vol.57, No.3, pp. 3-13, 2004 (in Japanese, with English abstract).
- [6] Y. Yamakawa, K. Kosugi, W. Liang, and T. Mizuyama, "Improvements of the combined penetrometer-moisture probe (CPMP)," *Journal of the Japan Society of Erosion Control Engineering*, Vol.60, No.3, pp. 34-39, 2007 (in Japanese, with English abstract).
- [7] Y. Yamakawa, K. Kosugi, N. Masaoka, Y. Tada, and T. Mizuyama, "Use of a combined penetrometer-moisture probe together with geophysical methods to survey hydrological properties of a natural slope," *Vadose Zone Journal*, Vol.9, No.3, pp. 768-779, doi:10.2136/vzj2010.0012, 2010.
- [8] N. Masaoka, K. Kosugi, Y. Yamakawa, T. Mizuyama, and D. Tsutsumi, "Application of a combined penetrometer-moisture probe for investigating heterogeneous hydrological properties of a footslope area," *Vadose Zone Journal*, Vol.11, No.2, doi:10.2136/vzj2011.0064, 2012.
- [9] D. Michot, Y. Benderitter, A. Dorigny, B. Nicoulaud, D. King, and A. Tabbagh, "Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography," *Water Resources Research*, Vol.39, No.5, pp. 1138-1158, doi:10.1029/2002WR001581, 2003.
- [10] L. Schrott and O. Sass, "Application of field geophysics in geomorphology: Advances and limitations exemplified by case studies," *Geomorphology*, Vol.93, Nos.1-2, pp. 55-73, doi:10.1016/j.geomorph.2006.12.024, 2008.

- [11] G. Cassiani, A. Godio, S. Stocco, A. Villa, R. Deiana, P. Frattini, and M. Rossi, "Monitoring the hydrologic behaviour of a mountain slope via time-lapse electrical resistivity tomography," *Near Surface Geophysics*, Vol.7, Nos.5-6, pp. 475-486, 2009.
- [12] Y. Yamakawa, K. Kosugi, S. Katsura, N. Masaoka, and T. Mizuyama, "Spatial and temporal monitoring of water content in weathered granitic bedrock using electrical resistivity imaging," *Vadose Zone Journal*, Vol.11, No.1, doi:10.2136/vzj2011.0029, 2012.
- [13] G. E. Archie, "The electrical resistivity log as an aid in determining some reservoir characteristics," *Transactions of the American Institute of Mining and Metallurgical Engineers*, Vol.146, pp. 54-61, 1942.
- [14] G. C. Topp, J. L. Davis, and A. P. Annan, "Electromagnetic determination of soil water content: Measurements in coaxial transmission lines," *Water Resources Research*, Vol.16, No.3, pp. 574-582, doi: 10.1029/WR016i003p00574, 1980.
- [15] K. Kosugi, Y. Yamakawa, N. Masaoka, and T. Mizuyama, "A combined penetrometer-moisture probe for surveying soil properties of natural hillslopes," *Vadose Zone Journal*, Vol.8, No.1, pp. 52-63, doi: 10.2136/vzj2008.0033, 2009.
- [16] A. Samouëlian, I. Cousin, A. Tabbagh, A. Bruand, and G. Richard, "Electrical resistivity survey in soil science: A review," *Soil and Tillage Research*, Vol.83, No.2, pp. 173-193, 2005.
- [17] D. B. Watson, W. E. Doll, T. J. Gamey, J. R. Sheehan, and Philip M. Jardine, "Plume and lithologic profiling with surface resistivity and seismic tomography," *Ground Water*, Vol.43, No.2, pp. 169-177, 2005.
- [18] C. F. Pearson, P. M. Halleck, P. L. McGuire, R. Hermes, and M. Mathews, "Natural gas hydrate deposits: A review of in situ properties," *The Journal of Physical Chemistry*, Vol.87, No.21, pp. 4180-4185, doi:10.1021/j100244a041, 1983.
- [19] O. Fasesan, F. Awolusi, and L. R. Heinze, "Analysis of errors in historical use of Archie's parameters," *Journal of Canadian Petroleum Technology*, Vol.46, No.6, pp. 57-61, 2007.
- [20] B. F. Schwartz and M. E. Schreiber, "Quantifying potential recharge in mantled sinkholes using ERT," *Ground Water*, Vol.47, No.3, pp. 370-381, 2009.
- [21] A. J. William and H. Robert (Eds.), "Soil Physics (6th Edition)," Wiley, 2004.
- [22] H. W. Patnode and M. R. J. Wyllie, "The presence of conductive solids in reservoir rocks as a factor in electric log interpretation," *Transactions of the American Institute of Mining and Metallurgical Engineers*, Vol.189, pp. 47-52, 1950.



Name:
Yosuke Yamakawa

Affiliation:
Program-Specific Assistant Professor, Educational Unit for Adaptation to Extreme Weather Conditions (GCOE-ARS Unit), Center for the Promotion of Interdisciplinary Education and Research (C-PIER), Kyoto University

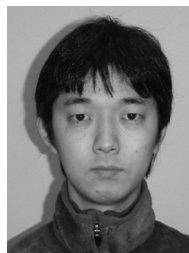
Address:
Oiwake-Cho, Kitashiraka, Sakyo-ku, Kyoto 606-8502, Japan

Brief Career:
2011-2012 Research Fellow, Graduate School of Agriculture, Kyoto University
2012- Center for the Promotion of Interdisciplinary Education and Research (C-PIER), Kyoto University

- Selected Publications:**
- "Combined geophysical methods for detecting soil thickness distribution on a weathered granitic hillslope," *Geomorphology*, Vols.145-146, pp. 56-69, 2012.
 - "Spatial and temporal monitoring of water content in a weathered granitic hillslope using electrical resistivity imaging," *Vadose Zone Journal*, Vol.11, No.1, 2012.
 - "Use of a Combined Penetrometer-Moisture Probe together with Geophysical Methods to Survey Hydrological Properties of a Natural Slope," *Vadose Zone Journal*, Vol.9, No.3, pp. 768-779, 2010.

Academic Societies & Scientific Organizations:

- Japan Society of Erosion Control Engineering (JSECE)
- The Japanese Forest Society (JFS)
- American Geophysical Union (AGU)



Name:
Naoya Masaoka

Affiliation:
JSPS Postdoctoral Research Fellow, Laboratory of Erosion Control, Division of Forest Science, Graduate School of Agriculture, Kyoto University

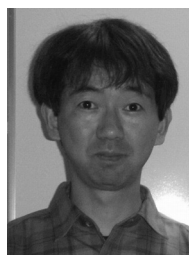
Address:
Oiwake-Cho, Kitashiraka, Sakyo-ku, Kyoto 606-8502, Japan

Brief Career:
2012- JSPS Postdoctoral Research Fellow, Graduate School of Agriculture, Kyoto University

- Selected Publications:**
- "Intensive measurements of soil pore water pressure for analyzing heterogeneous hydrological processes on a hillslope," *International Journal of Erosion Control Engineering*, Vol.3, No.1, pp. 53-58, 2010.
 - "Application of a combined penetrometer-moisture probe for investigating heterogeneous hydrological properties of a foot slope area," *Vadose Zone Journal*, Vol.11, doi:10.2136/vzj2011.0064, 2012.

Academic Societies & Scientific Organizations:

- Japan Society of Erosion Control Engineering (JSECE)
- The Japanese Forest Society (JFS)
- American Geophysical Union (AGU)



Name:
Ken'ichirou Kosugi

Affiliation:
Graduate School of Agriculture, Kyoto University

Address:
Oiwake-Cho, Kitashiraka, Sakyo-ku, Kyoto 606-8502, Japan

Brief Career:
1994-2008 Assistant, Graduate School of Agriculture, Kyoto University
2008- Associate Prof., Graduate School of Agriculture, Kyoto University

- Selected Publications:**
- "A localized bedrock aquifer distribution explains discharge from a headwater catchment" *Water Resources Research*, Vol.47, W07530, doi:10.1029/2010WR009884, 2011.
 - "A combined penetrometer-moisture probe for surveying soil properties of natural hillslopes" *Vadose Zone J.*, Vol.8, pp. 52-63, doi:10.2136/vzj2008.0033, 2009.
 - "Anomalous behavior of soil mantle groundwater demonstrates the major effects of bedrock groundwater on surface hydrological processes" *Water Resour. Res.*, Vol.44, W01407, doi:10.1029/2006WR005859, 2008.

Academic Societies & Scientific Organizations:

- Japan Society of Erosion Control Engineering (JSECE)
- American Geophysical Union (AGU)
- Soil Science Society of America



Name:
Yasuyuki Tada

Affiliation:
Senior Researcher, Laboratory of Hillslope Conservation, Department of Soil and Water Conservation, Forestry and Forest Products Research Institute

Address:

1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan

Brief Career:

2004-2005 Research Fellow, Disaster Prevention Research Institute, Kyoto University

2005- Forestry and Forest Products Research Institute

Selected Publications:

- "Characteristics and differences of flood disaster through all times in kinki area, Japan," Jour. of Erosion Control Eng., Vol.65, No.5, pp. 58-64, 2013.
- "Relation between collapse position and water path position in slopes," Jour. of Erosion Control Eng. Vol.60, No.4, pp. 3-11, 2007.
- "Examination of the influence of soil pipes on slope failure," Jour. of Erosion Control Eng., Vol.55, No.3, pp. 12-20, 2002.

Academic Societies & Scientific Organizations:

- The Japanese Forest Society (JFS)
 - Japan Society of Erosion Control Engineering (JSECE)
-



Name:
Takahisa Mizuyama

Affiliation:
Professor, Laboratory of Erosion Control, Division of Forest Science, Graduate School of Agriculture, Kyoto University

Address:

Oiwake-Cho, Kitashiraka, Sakyo-ku, Kyoto 606-8502, Japan

Brief Career:

1977-1990 Sabo Division, Public Works Research Institute, Ministry of Construction

1981-1982 Visiting Researcher, Colorado State University

1990- Department of Agriculture, Kyoto University

Selected Publications:

- "Prediction of floods caused by landslide dam collapse," Jour. of Disaster Research, Vol.5, No.3, pp. 288-295, 2010.
- "Structural countermeasures for debris flow disasters," International Jour. of Erosion Control Eng., Vol.1, No.2, pp. 38-43, 2008.
- "Measurement of bedload with the use of hydrophone in mountain torrents," IAHS Publ.283, pp. 222-227, 2003.

Academic Societies & Scientific Organizations:

- Japan Society of Erosion Control Engineering (JSECE)
 - Japan Society for Civil Engineers (JSCE)
 - International Association for Hydro-Environment Engineering and Research (IAHR)
 - International Association of Hydrological Sciences (IAHS)
-