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ON THE SPATIAL HETEROGENEITY OF SOIL PERMEABILITY IN A MOUNTAIOUS FOREST AREA

by

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SYNOPSIS

In the field of hillslope hydrology it is very important to understand the spatial characteristics of the soil so as to make accurate lumping representations in modeling. In order to clarify the spatial characteristics of soil permeability in mountainous slope, experiments were made on soil samples taken from the field. In the experiments, 96 undisturbed 10 cm long samples were taken from 35 locations. The spatial variations of parameters of unsaturated permeability $K=K_s(\psi_{cr}/\psi)^\eta$ and void ratio *n* were examined.

Results show the coefficient of variability of K_s and *n* are small but large for the unsaturated characteristics ψ_{cr} and η. The corelogram analysis shows the soil characteristics are independent when they are taken more than one meter apart.

INTRODUCTION

The understanding of soil water movement in a hillslope is important not only in the sense it is a fundamental process of elemental unit of runoff but also it controls the basinwide environmental condition through the mass transport with the soil water. Various studies on soil water movements have been, therefore, carried out for the past few decades both in test basins and in laboratories. The sub-surface flow behavior is usually simulated by Richard's equation that is based on the unsaturated infiltration theory. However, the numerical results are sometimes criticized, i.e. results do not agree with the observed data when parameters are identified, by physical test, using basin soil. This is mainly attributed to the inadequacy of the test and the existence of pipe flow which cannot be calculated by the unsaturated infiltration theory. The main reasons lying behind this discrepancy are: a) the basin is consisted of heterogeneous soil with various unsaturated characteristics and b) various soil parameters are determined from a small number experiments carried out in a few soil samples.

This can be called "representatives of the parameters".

The problem of the representative parameters can be studied taking two different approaches. One is based on the statistical characteristics of the permeability of the soil; the other is based on the size of soil samples, i.e. how big a soil sample should be to give the representative value for the soil permeability.

Osada (5) applied the former approach and investigated the heterogeneity of saturated permeability of sandy soil meadow with area of 0.5 ha. He used a sampling pipe with inner diameter of 47mm and height of 50mm. Maximum and minimum values of the permeability was found one order of difference, out of 100 samples he examined. Freeze (1) also investigated the saturated permeability of 16 kinds of soils and found that permeability of soil follows logarithmicnormal distribution. Ohta et al. (2), on the other hand, took latter approach by using 5 kinds of sample sizes to determine the representative value of the sample for saturated permeability of the soil in the forest of cedar (area of about 6 m^2). Their results show that as the diameter of the soil sample increases the variance of the permeability decreases. Ohte et al. (3, 4) compared the hydraulic characteristics of two different sizes of samples, i.e., one bigger sized sample with diameter of 195mm and height of 780 mm, and the other smaller sample with diameter of 50 mm and height of 51 mm. They determined the relationship between unsaturated hydraulic conductivity ,K, and capillary pressure ,ψ, by steady state method while the relationship between moisture content , θ, and ψ was investigated by instantaneous profile method. Comparing the hydraulic characteristics of the two different sample sizes, they concluded that the bigger sample size gives more realistic parameters than the smaller one.

Although several researches have been reported on the heterogeneity of the soil, we felt that the available information on the heterogeneity of the soil is not sufficient. The purpose of this paper is to present a critical discussion on the variability and spatial correlation of these parameters, based on the measured saturated hydraulic conductivity,Ks, parameters of K-ψ relationships,η, ψ_{cr}, void ratios,n, of sampled soils from two locations of forested basin.

SITE DESCRIPTION AND SAMPLING METHOD

Soil sampling was done in two locations in Kanedaira test basin (Gifu Prefecture, Japan), as shown in Fig. 1. The vegetation of Kanedaira basin are Japanese Cedar and Japanese Cypress. The geology of the basin is Ryoke granite. The soil is classified by Brown forest soil. Based on the core boring done near the site it could be seen that the bedrock under the topsoil is deeply weathered one.

The sampling locations **a** and **b** are on slopes with inclination of 34° and of 28° respectively. Pipe like macropore which may cause a preferential flow during the infiltration was not observed in these sites.

In this research The diameter of sampler was, therefore, determined based on the research of Shigematsu (6) on the representative volume of the sample for unsaturated permeability test of the soil. The sampler used in this research was 2mm thick PVC(polyvinylchloride) pipe with the inside diameter of 108mm, and the length of 600mm. The bottom edge of the sampler was sharpened for the sake of easy penetration. Several holes were made on the side of the sampler to install ceramic cups of tensiometers for the measurement of capillary suction during the permeability experiment. These holes were, however, closed by vinyl tape while sampling.

On the sampling location **a,** soil up to 40 cm depth was sampled. The sampler was pushed into the soil by hand initially. When it becomes difficult to push by hand alone, a piece of wood was put on the sampler and hammered to make the sampler to go further into the soil. When it reached 40cm depth, the soil around the sampler was removed by shovel and the sample was carefully taken out. The bottom of the sample was cleaned and capped, and the space above the soil was filled by another soil kept in vinyl bag to avoid the movement of soil sample.

On the sampling location **b**, the method of sampling was similar to that used at location **a**. However, at the location **b** soil up to 20 cm depth was sampled first by hand pushing. Another 20cm soil sample under the first sample was taken out using another sampler by hand push to avoid the compression of soil due to hammering. The numbers of soil samples obtained from location **a** was 27 from 27 points, and from location **b** was 15 from 8 points. The layout of sampling points for two

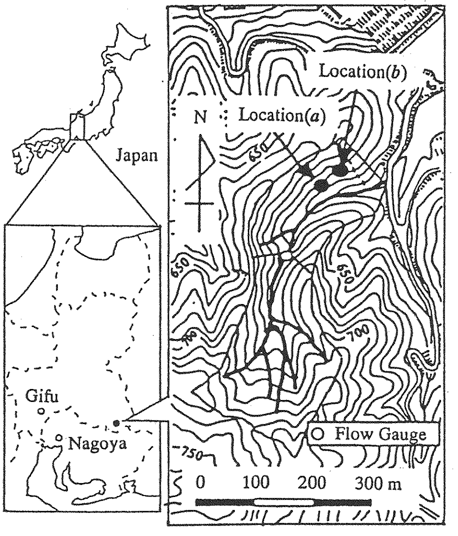

Fig.1 Sampling locations (*a*) and (*b*)

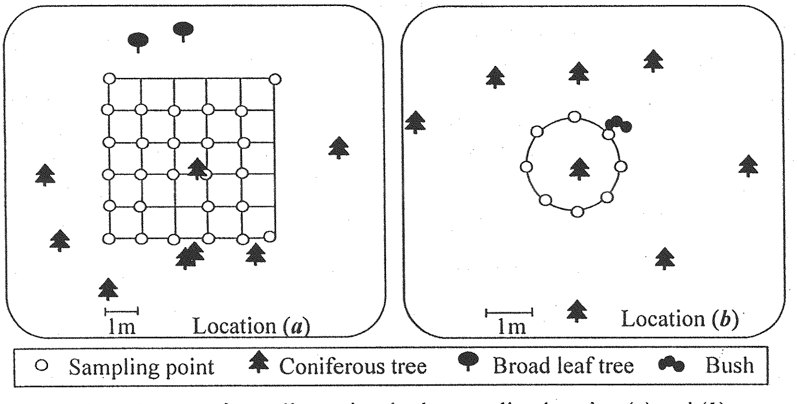

Fig.2 Layout of sampling points in the sampling location (*a*) and (*b*)

locations and the relation with the surrounding trees are shown in Fig. 2. The distances between two neighboring points were measured along the slope. Sample at node **i, j** of sample location **a** is denoted by $\mathbf{a}_{i\text{-}j}$ and sample at point **i** of location **b** by $\mathbf{b}_i$. We couldn't get the sample at $\mathbf{b}_4$ (depth 20-40cm) because of the presence of a big rock.

EXPERIMENTAL METHODS

Unsaturated Permeability Experiment

Unsaturated permeability of the soil was measured using an apparatus shown in Fig. 3. The setup consists of a rainfall simulator, soil column and soil suction measurement device. The rainfall simulator is made of 10cm diameter PVC ring of 5cm height with two plates attached at both ends. More than 60 needles are installed on bottom plate to make raindrops. Rainfall rate is controlled by a micro-tube pump.

For the sample **a**, porous cups, connected to pressure gauge or water manometer, were installed at the depths of 5cm, 15cm, 25cm and 35cm from the soil surface to measure suction heads.

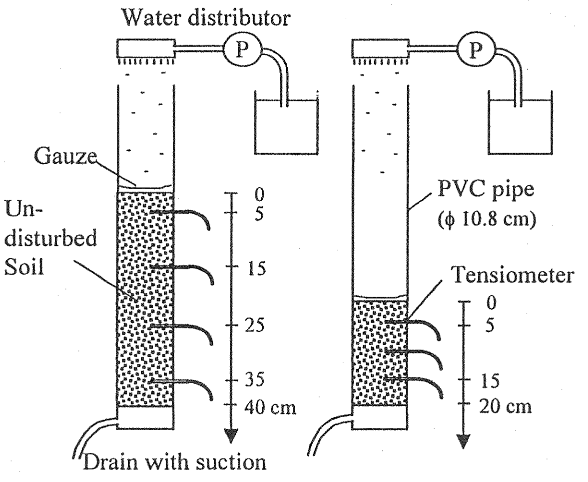

Fig.3 Experimental setups for unsaturated hydraulic conductivity

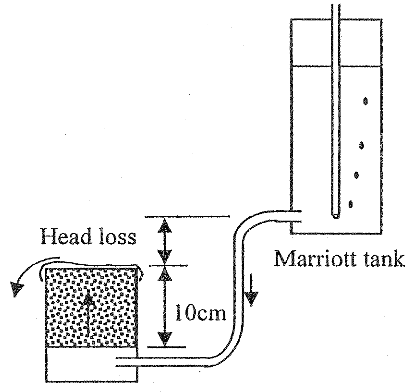

Fig.4 Experimental setup for saturated hydraulic conductivity

For the sample **b**, porous cups were installed at 5cm, 15cm and 25cm depths. A gauge was placed on the surface of soil to maintain the uniform distribution of rainfall into the soil. Soil is carefully placed on the filter plate to avoid the discontinuity of water flow at the bottom of the soil column.

During each experiment a certain rate of rainfall was continuously applied to the column and a suction of 15 to 25 cm H_2O was applied at the outlet of the column until the outflow rate and suction head of each tensiometer reached steady state. It took 7 to 48 hours depending on the rainfall rate.

While suction heads and flow rate were measured at the steady state, soil air pressure was also checked to make sure that it was at atmospheric pressure. For each sample, 3 to 7 different values of rainfall rates were used. Unsaturated hydraulic conductivity for each soil block was determined by dividing rainfall rate by total potential gradient of that block. K value obtained was related to average suction head of the block to derive K-ψ function.

To make the foregoing discussion easy, let's denote blocks of soil column as **aU** for depth 5-15cm of sample **a**, **aM** for 15-25cm, **aL** for 25-35 cm, **bU** for 5-15cm of sample **b** and **bL** for 25-35cm.

Saturated Hydraulic Conductivity Experiment

After the experiment on unsaturated permeability was over, soil samples were cut into blocks **aU, aM, aL, bU, bL**, and saturated hydraulic conductivity was measured for these soil blocks. The experimental setup consists of soil column and Marriott tank to supply water at a fixed hydraulic head (Fig. 4). The direction of the flow in the soil columns was made upward to avoid the effect of residual air which may exist if the flow direction is downward. The soil sample was set upside down to make the flow in the soil consistent with the flow under the field condition. During the experiment, a gauze was placed on the top of the sample to protect the soil from erosion.

Porosity Calculation

After the experiment on saturated hydraulic conductivity, PVC pipe containing soil sample was carefully cut and removed. Based on the observation of soil side surface, vertical stratum was partitioned and categorized referring the "Forestry soil survey and soil characteristics"(1982). No empty space between soil and PVC pipe was observed, which would otherwise seriously affect the saturated permeability test.

Tab.1 Statistical characteristics of soil permeability

		aU	aM	aL	bU	bL
η	μ	2.42	1.42	1.55	3.11	2.11
	σ^2	1.94	0.54	1.10	5.87	0.31
	σ/μ	0.58	0.52	0.68	0.78	0.27
log Ks	μ	-1.57	-2.06	-3.06	-1.53	-1.54
	σ^2	0.02	0.39	0.61	0.01	0.01
	σ/μ	-0.09	-0.30	-0.26	-0.05	-0.06
log $\lvert\psi_{cr}\rvert$	μ	-0.28	-0.52	-0.24	-0.52	-0.25
	σ^2	0.53	0.80	6.35	0.55	0.06
	σ/μ	-2.59	-1.72	-10.29	-1.43	-1.02
n	μ	0.74	0.69	0.62	0.77	0.73
	σ^2	0.002	0.002	0.002	0.001	0.001
	σ/μ	0.06	0.07	0.08	0.05	0.04

μ:Mean σ^2:Variance

Main roots were removed from the soil and dry bulk density was measured. Porosity was calculated from dry bulk density, assuming soil density ρ=2.65 (g/cm^3).

STATISTICAL CHARACTERISTICS OF SOIL PERMEABILITY

Based on Brooks and Corey's formulation for unsaturated hydraulic conductivity and suction head (Eq.1), statistics of parameters K_s, ψ_{cr} and η are intensively discussed in the following paragraphs. The Brooks and Corey's K-ψ relation is

$$K=K_s(\psi_{cr}/\psi)^{\eta} \qquad (1)$$

where K_s, ψ, ψ_{cr}, and η denote saturated hydraulic conductivity, capillary suction, air entry value of capillary suction and a exponent respectively. Two examples are shown in Fig. 5. Based on this figure, parameters of K-ψ relation were determined as follows:

At first, η was evaluated as the gradient of the line of plotted data. Then ψ_{cr} was calculated as the ψ value corresponding to K_s.

Table 1 shows the statistical features of soil parameters for each layer at locations **a** and **b**. All parameters are assumed to be independent in space. The mean, variance and coefficient of variation were estimated for each soil parameter η, *log*K_s, *log*$\lvert\psi_{cr}\rvert$ and *n*. The reason why we used the logarithm of K_s and $\lvert\psi_{cr}\rvert$ is obvious from Fig. 5. Further it is usually accepted that K_s follows logarithmic-normal distribution.

Before starting the discussion, it will be worthwhile to state that blocks **aU** and **bU** fall under **A** horizon (layer) and **aL**, **bL**, as **B** horizon (layer) but **aM** sometimes includes both **A** and **B** horizons and their fractions changes case by case.

Porosity, *n*, shows very large mean value, but rather small value of variation as a whole. This implies observed data are reliable. Samples obtain at location **a** has decreasing trend with the increase in depth while sample **b** does not show any obvious trend. Some decreasing trend with depth is found in saturated hydraulic conductivity. The observed characteristics of *n* and *log*K_s may be due to the sampling method to some extent, as deeper part of the sample **a** was somewhat compressed to have smaller porosity and hydraulic conductivity. It is also recognized that coefficients of variation are smaller in **aU**, **bU** and **bL**, and larger in **aM** and **aL**. Higher variance of **aM** may be caused by the

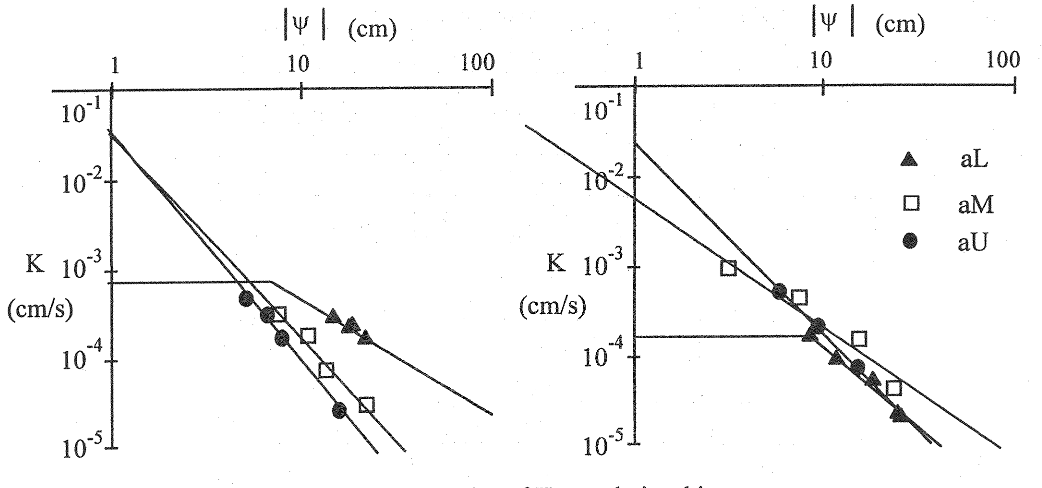

Fig.5 Examples of K-ψ relationship

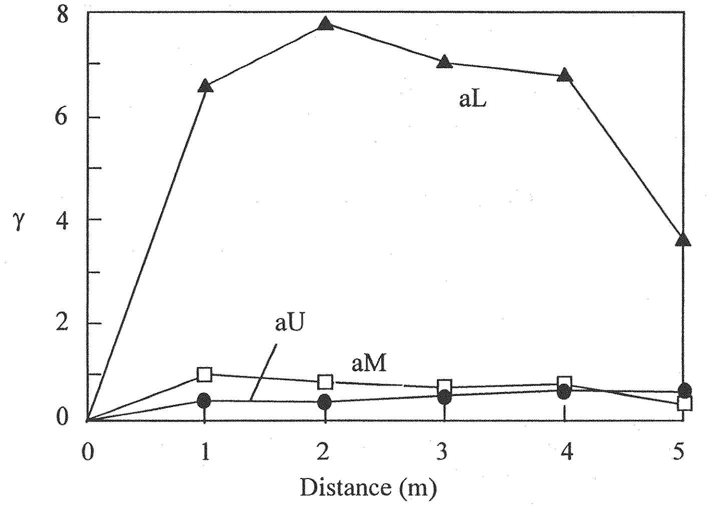

Fig.6 Semivariogram of η

variability of fractions of **A** and **B** layer's soil included in the sample.

Unsaturated permeability of the soil can be well explained by Brooks and Corey's formulation. However, the mean value of exponent has rather smaller value when compared to the values of 5.3 to 18.5 suggested for sand. The smaller value of η implies high varieties of pore sizes. This is expected as surface soil in Kanedaira basin is highly aggregated and mixed type. Mean value of ψ_{cr} in this basin shows more or less similar to the value obtained by Ohta but has very big coefficient of variation. This could be explained from the fact that errors in the estimation of η and K_s may be accumulated in the estimation of ψ_{cr}. The comparison of the results obtained from sample **a** and **b** shows that there are significant difference in K_s and η even the compression effect on sample **a** is deducted.

SPATIAL CORRELATION BASED ON SEMI-VARIOGRAM

Horizontal space-correlation of permeability is investigated based on the dense observation of sample **a**. Semi-variance γ(h) is utilized to evaluate the spatial correlation assuming the permeability is second order steady stochastic field. $\gamma(h)$ can be expressed as:

$$\gamma(h)=(1/2)E[\{Z(u_i)-Z(u_j)\}^2] \qquad (2)$$

where Z is a variable under consideration, u_i is the coordinate of point i, h is the distance between u_i and u_j, and E means the ensemble average of the variable. Semi-variogram is the relationship of $\gamma(h)$ with distance h. $\gamma(h)$ usually increase with distance h and reaches a constant value (sill value). The variable is then considered as independent to each other for larger distance.

Figure 6 shows a semi-variogram of parameter η for example. Figure 6 may tell that η is already independent when h is one meter for all layers. Same trend was found for other parameters. The drop of $\gamma(h)$ of sample **aL** at distance of 5m may be caused by the small number of data to calculate γ for this distance and we need larger extent of sample to discuss the spatial cyclic characteristics of variables.

CONCLUSION

In this research, 96 soil samples obtained from 35 points on the hillslope were analyzed to obtain hydraulic permeability parameters K_s, ψ_{cr}, η and porosity n, using the sampling pipe of diameter 108 mm. A certain difference of mean and variation in depth and location of sampling were observed. The coefficient of variation increases in the order of n, K_s, η, ψ_{cr}. This implies that the parameters relating saturated permeability are stable while unsaturated parameters show higher variation. The numbers of samples required to obtain the estimate of parameters with the accuracy of 0.1 of coefficient of variation are 2-10 for K_s ,and 20-30 for η. The horizontal space-correlation was examined and results showed that one meter of distance may be enough to be independent to each other.

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APPENDIX – NOTATION

The following symbols are used in t5his paper:

h	= distance between two points
K	= unsaturated hydraulic conductivity of a soil
Ks	= saturated hydraulic conductivity of a soil
n	= porosity of a soil
u	= coordinate of the point

Z	= Soil characteristics at the point u
γ	= semi-variance
η	= exponent of Brooks and Corey's equation
θ	= moisture content
ψ	= capillary suction
ψ_{cr}	= air entry value of capillary suction

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