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Measurement of Soil-Water Content by Specific Resistance

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Abstract

Theoretical considerations of measurement of soil-water content and related experiments are presented. In an earlier paper (Tominaga, 1980a), the theoretical relation between the apparent specific resistance of soil and the soil-water content was proposed. There are several obstructions to the application of this method in the field. These are the nonuniformity of the soil in the ground, disturbances of soil after the burial of the electrodes for the measurement of specific resistance and the unknown value of the specific resistance of the soil-water. Theoretical considerations are performed to eliminate these obstructions. These considerations, which are the relation between the specific resistance and the soil-water content and the elimination of the obstructions mentioned above, are confirmed by the experiments. The results of these experiments show the validity of this method, and its strong points in field use are presented on the bases of these results.

1. Preface

Soil-water content in the ground, which is supplied by rain infiltration, plays an important part in the development of natural disasters, such as landslides, failure of slopes or dikes. These kinds of disaster generally occur during or after rainfall. Therefore, investigations of the mechanisms of these kinds of disaster require time-continuous or short periodic observation of the change in soil-water content in the ground. For this purpose, electrical methods are available. In an earlier paper (Tominaga, 1980a), the relation between the soil-water content and the apparent specific resistance of soil is considered. The specific resistance of mixed materials is the harmonic mean of the weighted specific resistance of each material.

The results are clear and easy to understand. But difficulties are inevitable in field investigations of the soil-water content, main difficulties are disturbances in the soil layer and irregular contact between the electrodes and the surrounding soil.

In the following sections, the relation between soil-water content and the specific resistance is summarized, theoretical considerations are performed to eliminate the difficulties existing in field use, and the experimental results are given.

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Nomenclature

S	m^2	area of closed surface
S_i	m^2	part of S occupied by material i
V	m^3	volume, inner part of S
N_i		ratio of S_i to S, simultaneously, V_i to V
n		number of materials
I	A	total current
$\boldsymbol{J}$	A/m^2	current density
$\boldsymbol{E}$	V/m	electric field strength
$\boldsymbol{r}$	m	position vector
$\boldsymbol{C}(\boldsymbol{r})$	$1/m^2$	current distribution for unit source of current
k		ratio of specific resistances along the boundary surface
ρ	$\Omega\cdot m$	specific resistance
ϕ	V	potential difference
$\boldsymbol{n}$		unit vector normal to the boundary surface

suffix i indicates the value of material i, especially, w indicates the soil-water.

2. Summary of the relation between the soil-water content and the apparent specific resistance of soil

The natural ground is not uniform; it has several layers in macroscopic view. There are soils of different particle sizes and shape. Boundary sections are not always along the plane. Additionally, soil-water includes ions from the materials of soil particles. Therefore, the specific resistance of soil-water will be different at different places in the soil. The rectangular parallelopiped is often used as a soil model for convenience (Katsurayama, 1957, Yamashita, 1971). The conductive characteristics can be expressed easily by it. But this is unnatural, because the soil is composed of materials whose shapes are fine particles and the macroscopic characteristics of soil must be considered uniform in actual use. Therefore, the following hypothesis is proposed:

[Hypothesis]

On any closed surface S, in which a point source of current is included, any N_i which is the ratio of the area of sectional surface S_i occupied by material i to the total area of the surface S, is uniform (see **Fig. 1**);
where:

$$N_i = \frac{S_i}{S} \quad , \quad \sum_{i=1}^{n} N_i = 1$$

In this hypothesis, N_i also equals the ratio of the volume V_i/V.

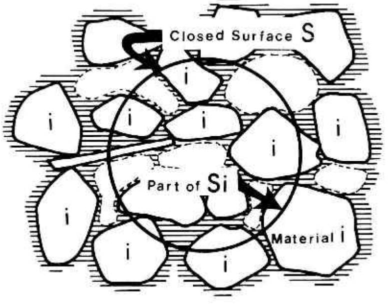


Fig. 1 Sectional area occupied by material i on S is totaled S_i. The ratio $N_i = S_i/S$ is constant on any closed surface S for any material i.

According to the discussion in the paper (Tominaga, 1980a), the following relation is obtained:

$$\frac{1}{\rho} = \sum_{i=1}^{n} \frac{N_i}{\rho_i} \qquad (1)$$

where:

ρ = apparent specific resistance of soil

The specific resistance of soil-water ρ_w is smaller than that of any other material in soil. Therefore, **Eq. 1** becomes:

$$\frac{1}{\rho} \doteqdot \frac{N_w}{\rho_w} \qquad (2)$$

where:

$$N_w = \frac{S_w}{S} = \frac{V_w}{V}$$

3. Mathematical consideration for field use

Generally speaking, it is difficult to get information about soils under the ground. Therefore, some kind of apparatus must be used to obtain this information. Electrodes are used to measure the specific resistance of soil. Obstacles in field application arise from the chemical and physical irregularities in the soil; main obstacles are the conditions of the contact between the electrodes and the surrounding soil and the specific resistances of the soil-water; the latter cannot be measured independently.

However, qualitative information is valuable; some examples of such information are the time-varying locations of the wetting front of the infiltrating water, and the discrimination between transient condition and stationary condition. Hence, ways to overcome the obstacles of the unknown value of the contact condition between the electrodes and the surrounding soil and of the specific resistance of the soil are discussed in the following section.

3.1 Disturbance of the soil following the burial of the electrodes

Specific resistance is usually obtained by measuring the potential difference between two electrodes under a stationary electrical current. The potential can be measured because of the moisture of soil unless the electrodes are completely separated from the soil. On the other hand, the shape of the current field varies with the heterogeneity of the specific resistance of the soil. For example, current density should have the same value on the surface of a sphere in which the point source of the current is located in the center. However, actual current density is not same on the surface of the sphere because of the heterogeneity of the specific resistance in it. Nevertheless, current density is proportional to the total current supplied at the point source; therefore, current density $\boldsymbol{J(r)}$ can be described as:

$$\boldsymbol{J(r)} = I\boldsymbol{C(r)} \qquad (3)$$

where:

I = total current (A)

$\boldsymbol{C(r)}$ = current distribution for unit source of current ($1/\text{m}^2$)

$\boldsymbol{C(r)}$ represents the distribution of the current density which is influenced by the disturbances of the soil mentioned above, but the actual form of $\boldsymbol{C(r)}$ cannot be known.

Now the effect of a change in the water content which will appear in $\boldsymbol{C}(\boldsymbol{r})$ must be discussed.

Under a stationary current field, the following relations are established:

$$\nabla \cdot \boldsymbol{J} = 0 \tag{4}$$

$$\boldsymbol{E} = -\nabla \phi \tag{5}$$

$$\boldsymbol{J} = \boldsymbol{E} / \rho \tag{6}$$

If the specific resistance of the material is constant,

$$\nabla \cdot \boldsymbol{J} = \nabla \cdot \boldsymbol{E} / \rho = \nabla \cdot (-\nabla \phi) / \rho = 0$$

$$\therefore \nabla^2 \phi = 0 \tag{7}$$

Therefore, the shape of the current distribution is not influenced by a change in specific resistance. On the other hand, the current changes its direction at the boundary surface between two materials with different specific resistances. This occurs in any disturbed soil. The shape of the current distribution may change according to changes in specific resistance. Even in that case, the shape of the boundary surface itself originating from the disturbance of the soil will not necessarily change. Only variation in current density may be taken as the cause of changes in $\boldsymbol{C}(\boldsymbol{r})$. The current density satisfies the following equations (see **Fig. 2**):

$$(\boldsymbol{J}_i - \boldsymbol{J}_j) \cdot \boldsymbol{n} = 0 \tag{8}$$

$$(\boldsymbol{E}_i - \boldsymbol{E}_j) \times \boldsymbol{n} = \boldsymbol{0} \tag{9}$$

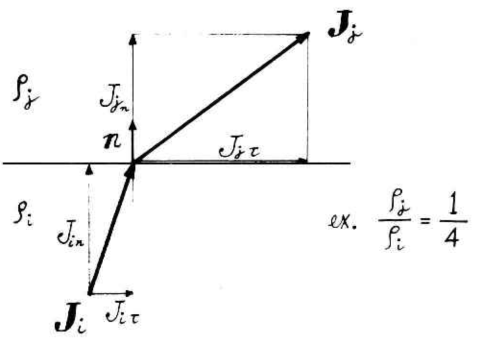


Fig. 2 Refraction of current density on the boundary surface between matieral *i* and *j*.

The materials along the boundary surface mentioned above are denoted by small *i* and *j*. Introducing k which is ratio of ρ_j to ρ_i, namely, ρ_j equals $k\rho_i$. **Eq. 9** can be written by **Eq. 6** as:

$$(\boldsymbol{J}_i - k\boldsymbol{J}_j) \times \boldsymbol{n} = \boldsymbol{0} \tag{10}$$

Replacing ρ_i, ρ_j by the use of Eq. 2,

$$k = \frac{\rho_j}{\rho_i} = \frac{(\rho_w / N_w)_j}{(\rho_w / N_w)_i} = \frac{\rho_{wj} \; N_{wi}}{\rho_{wi} \; N_{wj}} \tag{11}$$

That is, change in the water content causes change in k. Thus, current density changes with k. Finally, change in the current distribution occurs. k may vary on the surface of the boundary. On the contrary, the current density will not change except in proportion to changes in the total current when there are no changes in k. This demonstrates that the shape of the current distribution does not change. In this case, the potential difference can be expressed as:

$$\phi = \rho \int_{\boldsymbol{r}_1}^{\boldsymbol{r}_2} J(\boldsymbol{r}) \cdot d\boldsymbol{r} = \rho I \int_{\boldsymbol{r}_1}^{\boldsymbol{r}_2} \boldsymbol{C}(\boldsymbol{r}) \cdot d\boldsymbol{r} \qquad (12)$$

When the apparent specific resistances which are measured at times t_0 and t_1 are denoted by ρ_0 and ρ_1, respectively, **Eq. 13** can be obtained using **Eq. 12**:

$$\frac{\rho_1}{\rho_0} = \frac{\left(\frac{\phi}{I}\right)_{t_1} \Big/ \int_{\boldsymbol{r}_1}^{\boldsymbol{r}_2} \boldsymbol{C}(\boldsymbol{r}) \cdot d\boldsymbol{r}}{\left(\frac{\phi}{I}\right)_{t_0} \Big/ \int_{\boldsymbol{r}_1}^{\boldsymbol{r}_2} \boldsymbol{C}(\boldsymbol{r}) \cdot d\boldsymbol{r}} = \frac{\left(\frac{\phi}{I}\right)_{t_1}}{\left(\frac{\phi}{I}\right)_{t_0}} \qquad (13)$$

As a result, considering the sufficient condition for maintaining k as constant, the following is concluded.

Ignoring the time-varying changes in the specific resistance of soil-water, and if the soil-water content at every place changes at the same rate, the ratio of the specific resistances measured at different times at the same point will not be influenced by the current distribution in the soil.

Namely, obstacles arising from the burial condition of the electrodes and disturbances in the soil can be eliminated.

3.2 The specific resistance of the soil-water

The soil-water is an electrolytic solution and its specific resistance is due to materials in the soil particles where the water is to be found. Generally speaking, soil-water shows high specific resistance in sand, while it shows a low value in loamy soil. Ions in the infiltrating water are absorbed by sandy soil particles, and its specific resistance becomes high. In loamy soil, ions elute into the water from the soil particles and it shows low resistance.

The specific resistance of water can be assumed not to change at the same place in the natural ground, as the ions in the soil have been eluted out over a long period. Therefore, when the specific resistance of water does not change:

$$\frac{\rho_1}{\rho_0} = \frac{(\rho_w / N_w)_{t_1}}{(\rho_w / N_w)_{t_0}} = \frac{(N_w)_{t_0}}{(N_w)_{t_1}} \qquad (14)$$

where:

ρ_0, ρ_1 = apparent specific resistances at the same place measured at the time of t_0, t_1, respectively.

Therefore,

If the specific resistance of water does not change over time, qualitative changes in soil-water content can be observed by **Eq. 14.**

3.3 Summary

The above two conclusions can be reached on conditions that the specific resistance of soil-water does not change over time at the same place (it may change at different places), and the soil-water content at any place changes at the same rate of volumetric value.

The latter condition is the same as the hypothesis for the theoretical consideration of the relation between soil-water content and specific resistance mentioned in section 2. Therefore, the former condition is newly proposed in section 3. The discussions in this section can be summarized as follows:

To measure the soil-water content using specific resistance in the field, and especially to discover changes over time, the ratio of two specific resistances in which one is measured at a special time and the other is measured at any other time at the same place, (1) will not be influenced by the contact condition between the electrodes and the surrounding soil, and (2) will show the qualitative changes in the soil-water in the time domain; nevertheless, the value of the specific resistance of soil-water cannot be discovered.

Therefore, the movement of soil-water can be observed by measuring these ratios at any point in the soil in a vertical direction.

4. Applications

4.1 Calibration of soil-water content and specific resistance

The experiments were conducted to confirm the relation in **Eq. 2.** A sand box 1.8m in length, 0.9m in width and 0.9m in depth was used as the soil model. The method for measuring the specific resistances was Wenner's four electrode method. For the purpose of this experiment, a vertical bar was made on which 21 electrodes were set at intervals of about 5cm. **Photo 1** shows the box and the electrodes. For electrodes, brass screw bolts, 3mm in diameter, 3cm in length and protruding about 6mm, were used. Four neighbouring electrodes were used for one measurement by Wenner's method, and 16 measurements were done along the bar. The induced electric motive force was $150V_{P-P}$, 34Hz square wave. Tap water was scattered over the sand box, and the measurements were conducted when the water content of the sand reached equilibrium. At the same time, the sand in the box was sampled and its water content was measured by the oven method. Eight data were got in one experiment. The sand in the box was removed completely after each experiment, and again the sand and the electrode bar were set for the next experiment. 15 experiments were conducted, one every week, when the condition of the sand box reached the equilibrium for each experiment. Therefore, the water-content, the specific resistance of the soil-water, and the contact between the electrodes and the surrounding sand were different for every experiment. The results of the experiments are shown in **Fig. 3** by the black points. The Concentration of data nearly on one line shows the validity of **Eq. 2** supposing that the specific resistance of the soil-water was constant.

White points in **Fig. 3** show the result of an experiment with glass beads 0.2mm in diameter. The experiment was performed approximately as above, but in a cube-shaped soil box with sides of 0.2m, and the interval between the electrodes was 2cm (see **Photo 2**). The water content was measured by the increasing total weight of the soil box. Induced electric power was $30V_{P-P}$, 34Hz square wave. The specific resistance of the water was about 3 5Ω·m. It is assumed from the inclination of the data in **Fig. 3** that the specific resistance of the water increased through ion-absorption by the surface of the glass particles.

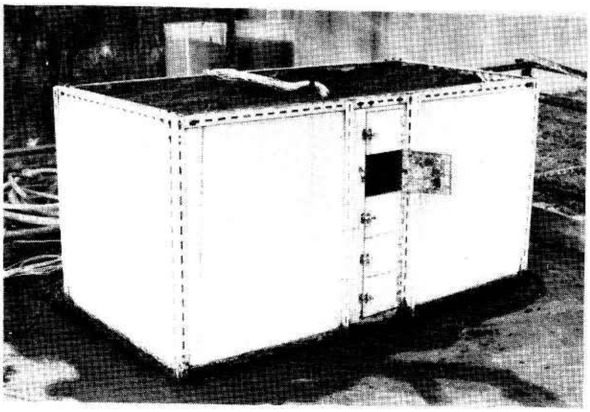
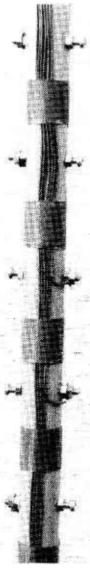


Photo 1 Experimental equipment for the calibration of the relation between the specific resistance and the water content.

(a) Soil box, 0.9m × 0.9m × 1.8m.



(b) Electrodes, 5cm apart.

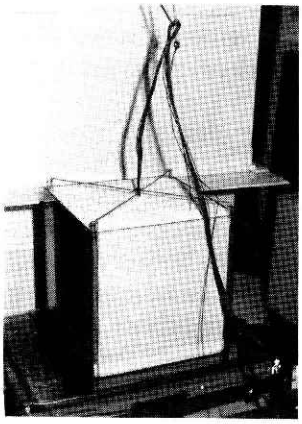
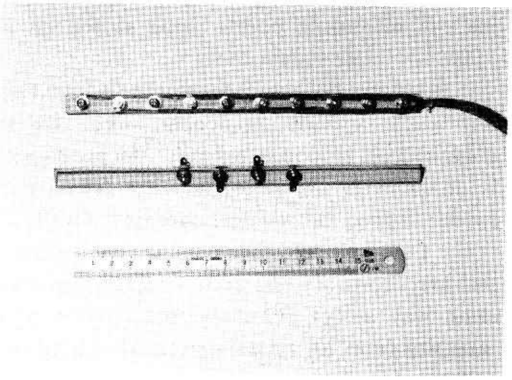


Photo 2 Laboratory test of the relation between the specific resistance and the water content.
(a) Box of glass beads, 0.2m × 0.2m × 0.2m.



(b) Electrodes, 2cm apart.

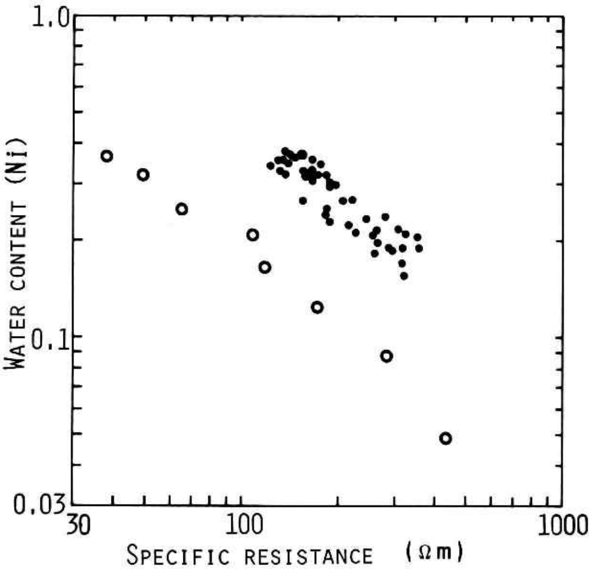


Fig. 3 Specific resistance and water cotent.

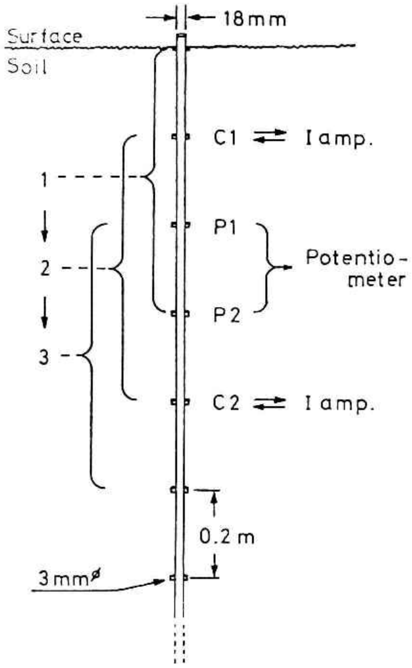


Fig. 4 Electrodes for measurement of specific resistance by Wenner's four electrode method.

4.2 Field observations of water infiltration in soil

Fig. 5 shows results of an experiment conducted at the National Research Center for Disaster Prevention for investigating rain infiltration to a depth of 2m (Tominaga, 1980b). The interval between the electrodes was 0.2m and Wenner's four electrode method was used (see **Fig. 4**). Eight values were measured in one measurement in a vertical direction by changing the measuring points using switch circuits. The induced electrical motive force was $300V_{P-P}$, 34Hz square wave.

(a) shows the actual measured specific resistances at each measuring point. **(b)** shows the normalized specific resistances, which are shown in section 3, the divided values of the measured specific resistances by the pre-experiment-measured specific resistances, respectively at the every measuring location. **(c)** shows the actual specific resistances in a three dimensional display: the vertical coordinate is the depth of the soil box, the horizontal coordinate is the time axis, and the time-varying specific resistances of the eight measuring points in the soil are shown by the contour lines. **(d)** is the normalized specific resistance shown in the same way as **(c)**. **(e)** shows the relation of inflow and outflow through the soil, rainfall intensity (mm/h), accumulation of rainfall (mm), outflow intensity from the bottom of the soil box (mm/h) and accumulation of the outflow (mm). The increase in the water content corresponds with a decrease in specific resistance in both figures **(a)** and **(b)**. The changes in normal specific resistance, which are shown in **(b)** an **(d)**, have the following meaning in addition to the meanings mentioned in section 3-3.

The wetting front reaches a point, when the specific resistance at this point begin to decrease.

The experiment in **Fig. 5** shows that:

(1) Water infiltration began with the beginning of rainfall and began to move downward.

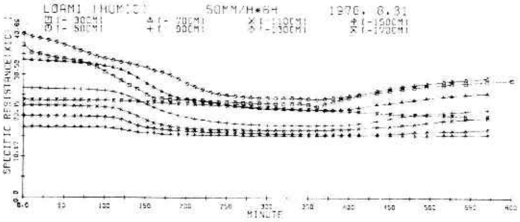
(2) At a point 80cm below the surface of the ground, infiltrating water reached the upper part of the capillary rise.

(3) The pressure through the capillary caused the outflow of water from the bottom of the soil box.

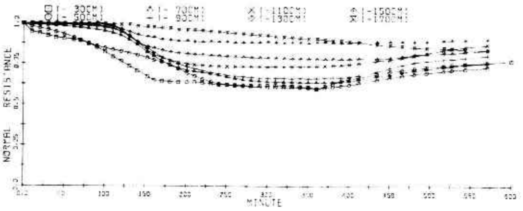
(4) Following the attainment of equilibrium in which the specific resistances of the soil did not change as time elapsed, the inflow of rain and the outflow of water were same value. (The difference between rainfall intensity and outflow intensity in **(e)** overflew from the surface of the ground in the experiment.)

(5) The specific resistance began to rise immediately the rainfall stopped.

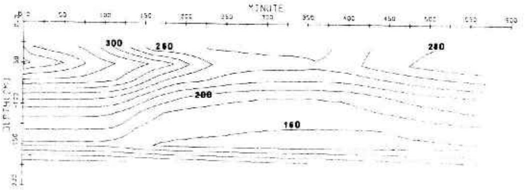
It is obvious that a comparison of **(d)** and **(e)** will have more meaning than a comparison of **(c)** and **(e)**.



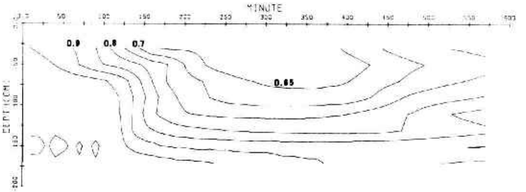
(a) Specific resistance curves showing time-varying vertical distribution of water content.



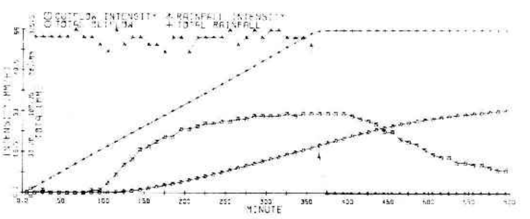
(b) Normalized specific resistance of (a)



(c) Contour map of specific resistance.



(d) Contour map of normalized specific resistance.



(e) Intensity of rainfall and discharge of ground water.

Fig. 5 Experimental result on rain infiltration in humic loam.

5. Conclusion

Field investigation of the soil-water content which plays an important part in the occurrence of geological calamities is difficult, but this is indispensable for the prediction of disasters. The measuring methods are classified into two types as the direct method and the indirect method. The indirect method, though, is only valid for observing the time-varying changes of soil-water content in the field. Of course, calibrating methods must be available in the indirect method. The method discussed in this paper covers the above restriction, although several hypotheses are needed to obtain a theoretical conclusion. From another point of view, the qualitative data give us the valuable information, and so the analysis of normalized specific resistance is discussed in detail.

The method presented in this paper has some strong points:

(1) The electrodes can be of any material, because it is sufficient to measure the potentials between two points in the soil, not to measure the characteristics of the electrolytic solution of the water itself. Many measuring points can be set in the soil. If brass is used for the electrodes, burial and maintenance are easy or not necessary. Therefore, the method can be used even in the moving soil such as the landslide areas or slopes.

(2) Rapid measurement can be performed for many measuring points, because the electrical instrumentation can be made up. In the examples mentioned in section 4, the manual method was used to change the measuring points, but only three minutes was needed to measure the specific resistances at 32 points.

There are no methods which can be used to measure the rapid changes shown in the example in this paper except the electrical method.

(3) The area to be investigated can be chosen by selecting the intervals between the electrodes. This is the most important difference from methods which use porous blocks holding the electrodes and measure the water content at one point in the soil.

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電気抵抗率による土中水分量の測定

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電気抵抗率による土中水分量測定法について理論的考察と実験結果を述べている．最初に土中水分量と電気抵抗率の関係（富永，1980 a）を述べている．この理論を実際に野外で利用するには，土層の不均一性，電極埋設時の土の乱れおよび土中水そのものの電気抵抗率が不明であることなどの障害が存在するので，それらを克服する手段について考察を行っている．その結果，土中の同じ電極系で測定された異なる時刻の抵抗率の比をとることによって上記の障害を克服できることを示している．つぎに水分量と抵抗率とのキャリブレーションを，実際の砂質土およびガラス粒によるモデル土について行なっている．最後に国立防災科学技術センター大型降雨実験施設で行なわれた降雨浸透実験によって，正規化された抵抗率の妥当性と有用性を確認している．

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