APPLICATION OF RESISTIVITY IMAGE PROFILING METHOD FOR HYDROLOGICAL ANALYSIS IN SOIL STRUCTURAL REMAINS

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ABSTRACT:

In order to predict the behaviour of water in the soil structural remains, ground structure were estimated by using resistivity image profiling method and unsaturated hydraulic property was estimated by HYDRUS-1D. Resistivity image profiling method was applied in the field survey conducted in the *Miyahata* site located in Fukushima prefecture, and two-dimensional resistivity distribution under the remains was obtained. Also soil boring was performed to make sure the ground structure in vertical direction and resistivity of the soil layer that included the remains was measured. Once the correlation between resistivity and soil layer was obtained, it is possible to estimate two-dimensional ground structure from the results of resistivity image profiling method. In laboratory experiments, some parameters that determined water retention curve and hydraulic conductivity of unsaturated soil were estimated by inverse analysis with HYDRUS-1D. Based on the ground structure and unsaturated hydraulic properties obtained, behaviour of water in remains was predicted.

1. INTRODUCTION

Since 1960', Japan has held a large-scale land development and it caused a dramatic increase in the number of excavation of archaeological sites. Some sites considered to be important were planned for conservation and some of them have been exhibited to the public. Since exposed exhibition of excavated site is one of the most effective ways to inform the value and authenticity of sites, many studies about conservation methods of sites that are exposed for exhibition have been reported.

Except for arid land, usually water will be supplied to surface soil as rain, snow, dew and soil water supplied from lower soil because of the gradient of temperature. Therefore the two-way movement, namely, from soil into the atmosphere and the contrary movement, of water is maintained. When a remains is exposed for exhibition, usually some kind of structure will be built in order to protect them from deterioration factors like wind or rain. In this situation, although soil water will still evaporate into the atmosphere, water will be scarcely supplied. Then the movement of water will be almost one-way.

Among soil water, some sort of solute is usually contained and is transported with soil water. If water continues to evaporate at the surface of soil, some kind of salt will precipitate and will cause the exfoliation of surface soil. Furthermore, remains in the drying process will be deteriorated due to loss of plasticity in addition to salt precipitation. At the remains in wet state, since a large amount of water continues to evaporate, humidity inside the structure is always close to saturation. Under such environment, the remains will be deteriorated due to outbreak of mould or moss.

In order to protect the remains against deterioration mentioned above, various kinds of reagent have been applied to soil structural remains. In the past, acrylic resin was impregnated into the soil to make the surface of soil stiff to prevent the collapse by drying. However, exfoliation of these stiffed surface layer or precipitation of salt is still observed in some sites. In the recent years, rather than hardening the soil, hydrophilic polymer is applied to restrain evaporation of soil water (Aoki, 2005). According to the evaluation of effects of hydrophilic polymer on water movement, its effect is expected (Mitsuishi *et al.,* 2005). Although this kind of polymer is useful against the collapse by drying or exfoliation of surface, deterioration caused by salt precipitation has not been solved yet.

In order to predict water movement in the remains, it is indispensable to presume the spatial spread of soil hydraulic properties. These properties have a close relationship with ground structure where the remains locate. Since electrical and magnetic properties are different for each ground, its structure can be predicted by geophysical exploration. In the past, one of the geophysical explorations, ground penetrating radar was already applied to predict the ground structure (Hara and Sakayama*,* 1984). In the recent years, with the development of measurement and analysis technologies, visualization of ground structure (Sugano *et al*., 1998) and furthermore, distribution of physical properties such as hydraulic conductivity were attempted (Suzuki, 2002). In the field of environmental pollution, geophysical exploration was applied to observe the exudation (Paku *et al*., 2006). In addition to that the geophysical exploration is able to survey a large area, it will be applied as a non-destructive method. Therefore in this study, resistivity image profiling method was applied to predict the distribution of hydraulic properties in remains.

The resistivity image profiling method is one of the geophysical exploration methods. By measuring the resistivity of the ground to the current, two-dimensional distribution of resistivity is obtained. Resistivity of soil depends on many characters of soil such as porosity, extend of saturation, resistivity of pore water and temperature and so on. Therefore, supplementary survey is need to predict the two-dimensional ground structure from the results of this method.

The surface of remains is generally unsaturated zone that consists of solid, liquid and gas phases. The hydraulic property of this zone, namely unsaturated hydraulic property is quite complicated compared to that of saturated zone like aquifer. In order to predict the water and solute movement in unsaturated zone, it is necessary to evaluate water retention curve, which express the relationship between volumetric water content and pore-water pressure head, and unsaturated hydraulic conductivity, which is a function of pore-water pressure head. Regarding water retention curve, volumetric water content and pore-water pressure head can be measured directly by suction method and pressure-plate method (Nakano *et al.,* 1995). However, it is difficult to measure unsaturated hydraulic conductivity because of difficulties to control water flow and soil-pressure head in unsaturated soil.

In recent years, numerical calculation by computer become faster, several inverse analysis methods based on parameter optimization for soil hydraulic functions such as multistep outflow method (Inoue *et al.,* 1998; Fujimaki and Inoue*,* 2003). The evaporation method is one of the inverse analysis methods. In this method, parameters are estimated from the variation of pore-water pressure in the evaporation process (Šimůnek *et al.*, 1998), and the optimum experiment conditions were investigated (Sakai and Toride*,* 2007).

In this study, resistivity image profiling method and soil boring were carried out to estimate ground structure at *Miyahata* site located in Fukushima city. Furthermore, inverse analyses that estimate parameters in soil hydraulic functions were also carried out with the soils of remains by evaporation method using HYDRUS-1D. Based on the results of estimated ground structure and unsaturated hydraulic properties, the time variations of water content of remains soils were simulated on the assumption that the soil structural remains are exposed for exhibition.

2. FIELD SURVEY AND EXPERIMENTS

2.1 Field survey

2.1.1 Soil boring: Soil boring was performed as a supplementary survey. In soil boring, drilling mud was not used until initial groundwater level was detected. This investigation was conducted in the four corners of the remains as shown in Fig. 1. The depth of each was approximately 5 to 5.5 m.

2.1.2 Electric conductivity and soil water content: In order to correlate the results of resistivity image profiling method to that of soil boring, electric conductivities (expressed as EC for short) of soil, which are reciprocal of resistivity, were measured in situ.

Vertical section of soil layers was exposed in depth of about 3 m next to the southwest of the remains, and sensors to measure electric conductivity were installed to the layer that included remain. Electric conductivity were measured continuously from September 2008. The sensor measuring electric conductivity is 5TE made by DECAGON DEVICES.

2.1.3 Resistivity image profiling method: *Miyahata* site, survey field of this study is located on the plateau developed between *Abukuma* River and *Abukuma* Mountains, and is located on eastern edge of *Fukushima* Basin. There are some terraces formed by sediments of the flood plain of *Abukuma* River around the sites. *Miyahata* site is a loose slope toward the northwest direction from the southeast and northwest edge of the site is located at the edge of the terrace.

Field survey of resistivity image profiling method was conducted around soil structural remains in *Miyahata* site in October 2007. Fig.1 shows nine measuring lines arranged among the remains. Seven measuring lines of them were arranged perpendicular to the slope of the remains, from northeast to southwest. The other two lines were arranged parallel to the slope. The equipment used was Handy-ARM made by OYO corporation. Electrodes were made of stainless steel that had a diameter of about 1 cm with 30 cm long. It is general that electrode interval is about one-tenth of depth of exploration (Shima *et al.*, 1995). Thirty-two electrodes were placed at intervals of 0.5 m and the length of measuring lines was 15 m. Thus, the exploration depth was about 5 m. As shown in Fig.2, electrodes were placed by pole-pole array. In the analysis, the ground was divided into 50 cm rectangles by finite element method. Resistivity of each cell is modified one after another, and the model, which was most consistent with the observation, was estimated by nonlinear least squares method (Sasaki, 1988).

2.2 Laboratory experiments

2.2.1 Soil test: Soil tests were conducted for two kinds of soil. One was the surface soil of remains and the other was soil taken from layer just below the layer including the remains. The former soil is expressed as surface soil and the latter is expressed as lower soil in this paper.

Grain density ρ_s, mechanical analysis, water content w, liquid limit LL, and plastic limit PL were measured with disturbed sample for surface and lower soils. Grain density test was conducted using pycnometer according to JIS A 1202.

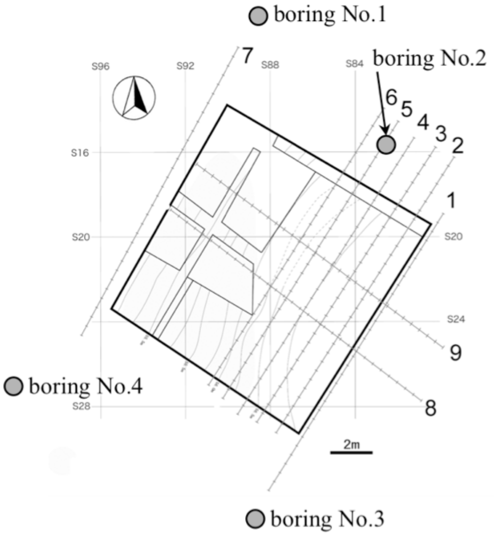
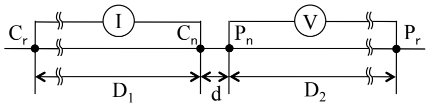


Figure 1. Location of measuring lines and soil borings



C$_n$ (n=1,2,3・・) : Current electrode
P$_n$ (n=1,2,3・・) : Potential electrode
C$_r$, P$_r$: Remote electrode
d, D$_1$, D$_2$: Electrode interval, ($D_1, D_2 \geq 10d$)

Figure 2. Pole-Pole array

Mechanical analysis was conducted according to JIS A 1204. After coarse particles were separated with a sieve, sedimentation analysis was applied to fine particles using specific gravimeter. Water content was calculated after soil samples were dried in oven at 110 ℃ until the weight became constant. Liquid limit and plastic limit were measured according to JIS A 1205. Wet density ρ_t and saturated hydraulic conductivity K_s were measured with non-disturbed samples for both soils. Wet density was measured according to paraffin method. Dry density ρ_d and saturation ratio S_r were calculated from the results of tests mentioned above.

2.2.2 Unsaturated hydraulic property: If water vapour transfer is not taken into consideration, unsaturated soil water movement in a vertical direction is represented by the following equation, Richards` equation (Miyazaki, 2000).

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad (1)$$

where θ = volumetric water content ($L^3\ L^{-3}$)
h = matric potential of soil water (L)
K = unsaturated hydraulic conductivity ($L\ T^{-1}$)
t = time (T)
z = spatial coordinates (L), z is positive upward with the surface 0.

In order to predict the actual water movement based on this equation, it is necessary to express water retention curve and unsaturated hydraulic conductivity, which is function of matric potential h with appropriate functions and parameters. Many empirical equations have been suggested that express water retention curve and unsaturated hydraulic conductivity. Especially, van Genuchten-Mualem model that is a connection model of van Genuchten model and Mualem model is widely used. The former model is expressed with saturated volumetric water content θ_s, residual volumetric water content θ_n, parameters α and n that determine the form (van Genuchten, 1980). The latter model is expressed with saturated hydraulic conductivity K_s and pore-connectivity coefficient l (Mualem, 1976). As shown in the following equations, in the van Genuchten-Mualem model, water retention curve $\theta(h)$ and unsaturated hydraulic conductivity $K(h)$ are expressed as functions of matric potential h.

$$\theta(h)=\left(\theta_s-\theta_r\right)\frac{1}{\left[1+|\alpha h|^n\right]^m}+\theta_r \qquad (2)$$

$$K(h)=K_s S_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (3)$$

where S_e(effective saturation) = $(\theta-\theta_r)/(\theta_s-\theta_r)$
θ_s=saturated volumetric water content
θ_r=residual volumetric water content
α (L^{-1}), n(-), m(=1-1/n)(-) = specific parameters to each soil that determine form of water retention curve
K_s = saturated hydraulic conductivity ($L\ T^{-1}$)
l = pore-connectivity coefficient. l=0.5 is usually recommended (Mualem, 1976)

2.2.3 Evaporation method: Parameters of the soils that were taken from same soil layers of surface soil and lower soil were estimated by evaporation method. Sample soils whose water content were approximately 0.40 kg kg^{-1} and 0.41 kg kg^{-1} respectively were filled in acrylic column whose inner diameter of 50 mm and height of 120 mm to be 1.31 g cm^{-3} and 1.27 g cm^{-3} respectively in dry density. Water was supplied from the bottom of the column and the soil was capillary-saturated by raising the water level occasionally. After that, the bottom of the column was sealed not to evaporate. A constant wind was sent to the top of the column using a small fan to promote evaporation. Tensiometers were inserted in depth of 1, 3, 5 and 9 cm horizontally to measure pore-water pressure head. Promotion of evaporation and multiple measurements of pore-water pressure head improve the reliability of estimated parameters (Sakai and Toride, 2007). Whole column was set on the electric balance to measure the weight periodically, and then cumulative evaporation was calculated. Pore-water pressure head and column weight were measured every 10 minutes. When the pore-water pressure head in depth of 1 cm reached -800 cm, the experiment ended. Then, the column was taken apart and sample soil was dried in oven to calculate mean volumetric water content. The parameters, θ_r, α and n shown in equation (2) and (3) were estimated from the results of the experiments by inverse analysis using HYDRUS-1D (Šimůnek *et al.*, 2005). Saturated water content θ_s was calculated from the losing weight during the evaporation experiment and drying in oven. Observed value of saturated hydraulic conductivity was substituted for K_s and recommended value, 0.5 was substituted for l.

2.2.4 Numerical experiment: Based on the parameters obtained above, one-dimensional time variation of matric potential was simulated using HYDRUS-1D on the assumption that the soil structural remains were exposed for exhibition. Numerical experiments were performed based on the result of soil boring No.3 and No.4 because ground structure and groundwater level were different between the northwest part and southeast part of remains. Each simulation based on soil boring No.3 and No.4 are expressed simulation No.3 and simulation No.4 respectively in this paper.

3. RESULTS AND DISCUSSION

3.1 Estimation of ground structure

Based on the observation of soil boring No.1, samples at 0 to about 3.15 m depth mainly consisted of silt, and silty sand was observed at 0.6 to 1.0 m depth. Under the silt layer (＞3.15 m), samples mainly consisted of sand and gravel. The surface of remains located in silt layer distributed from 1.60 to 2.15 m. The initial groundwater level was detected in depth of 1.8 m among the silt layer. The result of ground structure of No.4 was similar to that of No.1, but initial groundwater level was detected at boundary between silt and sand (about GL- 2.7 m).
Based on observation of soil boring No.2, samples at 0 to 1.25 m depth mainly consisted of silt and under the silt layer (＞1.25 m) sand was distributed as aquifer. The surface of remains located in silt layer distributed from 0.4 to 1.25 m. The result of ground structure of No.3 was similar to that of No.2.
From the results of soil boring, it can be concluded that soils mainly consist of silt from surface to the lower layer including the remains, and under the silt layer soil mainly consist of sand and gravel. These soils accumulate with a slope toward the northwest except for gravel. In the southeast part of remains, sandy soil is distributed as aquifer and in the northwest part

groundwater level exists among silt or boundary between silt and sand.

The results of resistivity image profiling method for measuring line No.6 and No.9 that were orthogonal each other are shown in Fig.3 and Fig.4. Almost same results were obtained from measuring line No.2 to No.7. In these measuring lines, small area indicating a slightly higher resistivity was observed at distance of about 4 m. There was a trench in depth of about 50 cm on the surface of ground. It is supposed that these results were false images derived from the irregularity of surface. In measuring line No.1 and No.8, resistivity scarcely changed and showed low value in both horizontal and vertical direction. In measuring line No.9, small area indicating relatively higher resistivity was observed near the surface of remains. Since the changes in resistivity were not successive, it is supposed that this local high resistivity did not derive from the change in soil layer.

The EC of soil including surface of remains measured in situ from September 2008 varied from 0.15 to 0.25 dS m^{-1} and it corresponds to 67 to 40 Ωm in resistivity. The resistivity of soil water taken from *Miyahata* site was about 50 Ωm. According to the results of resistivity image profiling method, it was observed that the resistivity of soils was low on the whole and was almost same with that of soil water. Therefore, the soil layer including surface of remains and groundwater level could not be identified from this survey. Generally, EC of clay minerals are high (namely resistivity is low) except for completely dried condition (Shima *et al*., 1995) and the EC of soil water is also high because of dissolved ions. Therefore it can be concluded that the soil of *Miyahata* site is abundant with clay minerals on the whole and contain large amount of water.

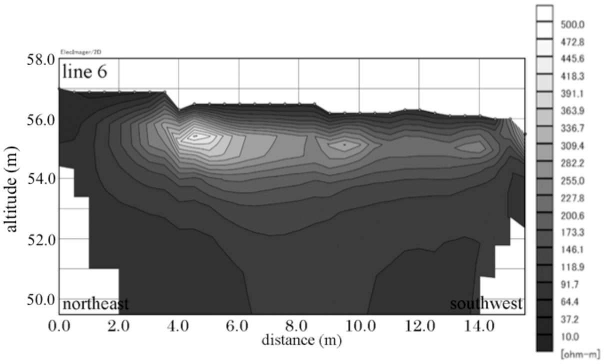


Figure 3. Resistivity image profile of line No.6

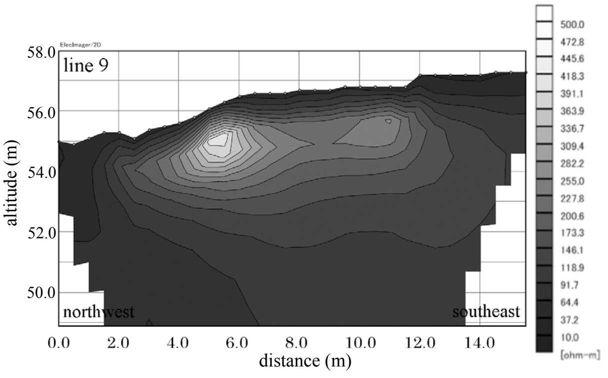


Figure 4. Resistivity image profile of line No.9

3.2 Soil test

Results obtained from each test are summarized in Table 5. Grain densities of surface soil and lower soil were 2.67 g cm^{-3} and 2.66 g cm^{-3} respectively and both grain densities were comparatively large. Wet density of each was 1.71 g cm^{-3} and 1.68 g cm^{-3} respectively and water content was 0.40 and 0.41 respectively. For an alluvium, wet density was large and water content was small. Since saturation ratio of each was 0.90 and 0.88 respectively, it is supposed that soil in this remains are consolidated well. From the results of mechanical analyses, both soil were classified into clay loam according to USDA. Saturated hydraulic conductivity of both soils was 1.02E-07 cm sec^{-1} and 7.42E-06 cm sec^{-1} respectively. It is supposed that hydraulic conductivities of both soils are relatively low because of high consolidation.

3.3 Hydraulic properties in unsaturated soils

3.3.1 Evaporation method: Table 6 shows saturated volumetric water content θ_s and the parameters estimated by inverse analysis using HYDRUS-1D based on the results of evaporation method. With the parameters obtained here, water retention curve and unsaturated hydraulic conductivity curve expressed with equations (2) and (3) are shown in Fig. 7 and Fig. 8.

As Fig. 7 shows, it was revealed that surface soil and lower soil had relatively indistinct air entry value around 150 cm and 100 cm in matric potential respectively and had a loose slope in water retention curve. That is, it is presumed that both soils have high water retentivity. Because both soils are consist of mainly silt or clay particle, it is predicted that pore-size of both soils are rather small. Therefore, water contained in the pore decreases little by little according to the decrease of matric potential. As Fig. 8 shows, it was revealed that at near saturation region, unsaturated hydraulic conductivity of surface soil is quite smaller compared to that of lower soil, but when both soils are dried to 0.4 cm^3 cm^{-3} in water content, which is almost same water content in situ, the hydraulic conductivity of both soils become almost same and quite small.

	surface soil	lower soil
grain density analysis		
ρ_s (g cm^{-3})	2.67	2.66
water content analysis		
w (cm^3 cm^{-3})	0.40	0.41
mechanical analysis		
gravel fraction (%)	0.0	0.0
sand fraction (%)	25.1	24.1
silt fraction (%)	39.5	41.6
clay fraction (%)	35.4	34.3
max particle size (mm)	2.00	2.00
LL and *PL* analysis		
LL (%)	49.9	51.6
PL (%)	26.4	25.2
plasticity index	23.5	26.4
wet density analysis		
ρ_t (g cm^{-3})	1.71	1.68
ρ_d (g cm^{-3})	1.23	1.19
other physical properties		
S_r (cm^3 cm^{-3})	0.90	0.88
hydraulic conductivity analysis		
K_s (cm sec^{-1})	0.816E-07	7.42E-06

Table 5. Results of soil test

Therefore, in the evaporation process, it is predicted that the surface of remains continues to dry until it collapse by dryness because supply of water from the lower is slow.

3.3.2 Numerical experiment: Based on the parameters obtained above, one-dimensional time variation of matric potential was simulated using HYDRUS-1D on the assumption that the soil structural remains were exposed for exhibition. In the numerical experiments, the upper end of the soil layer, which included the remains, was considered as the surface of remains and initial groundwater level was considered as constant one. Therefore, in simulation No.3, soil consists of three layers, which have a boundary in depth of 0.60 m and 0.85 m respectively from the upper end of the soil layer, and groundwater level corresponds to a depth of 1.24 m. In simulation No.4, soil consists of two layers, which have a boundary in depth of 0.40 m and groundwater level corresponds to a depth of 1.1 m. As Table 5 shows, since saturation ratios of both soils were considerably high, both soils were considered saturated at initial state. The evaporation ratio was estimated as 0.5 cm day^{-1} based on the result of evaporation experiment conducted at 25℃.

	surface soil	lower soil
θ_s (cm^3 cm^{-3})	0.53	0.52
θ_r (cm^3 cm^{-3})	0.15	0.28
α (cm^{-1})	0.142E-02	0.825E-02
n	1.42	1.22

Table 6. Saturated water content and estimated parameters

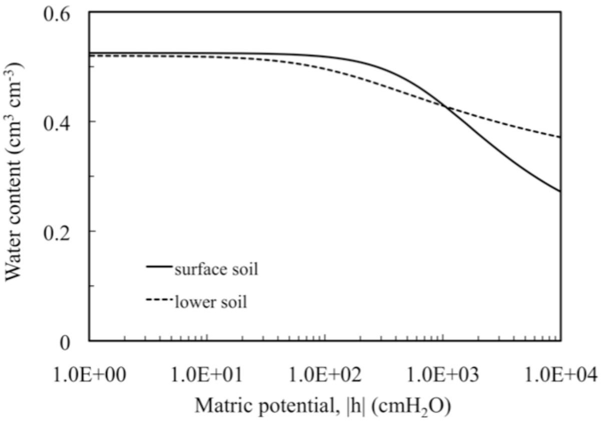


Figure7. Water retention curve of surface and lower soils

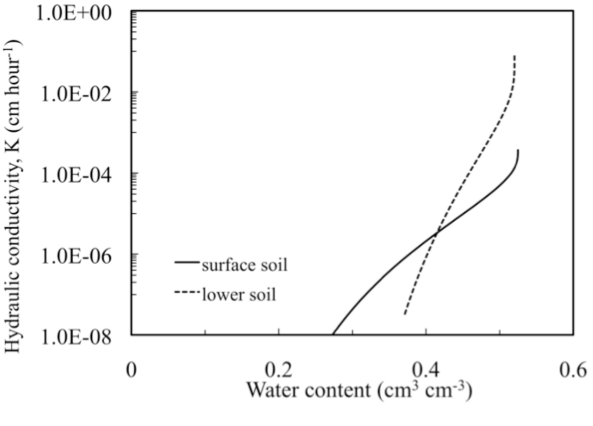


Figure8. Hydraulic conductivity of surface and lower soils

In simulation No.3, lower two layers, which were observed as sand, were considered same, because there were no more detailed information in addition to observation. Appropriate values for all parameters for lower soils in simulation No.3 were substituted from the database equipped with HYDRUS-1D (θ_r = 0.078, θ_s = 0.43, α = 0.036, n = 1.56, K_s = 1.04, l = 0.5). Observed value shown in Table 5 was substituted for K_s and recommended value 0.5 was substituted for l for each soil. Calculated value was also substituted for θ_s for each. Under the terms above, time variation of matric potential for 40 days were simulated.

The results of simulation No.3 and No.4 are shown in Fig.9 and Fig.10 respectively. Both figures show time variation of matric potential in depth of 1, 5, 10, 30, 50, 100 cm from the surface. As Fig.9 and Fig.10 show, although hydraulic conductivities of each lower soil were quite different, no significant difference in drying rate of surface soils were observed. It is supposed that in the case with *Miyahata* site the drying rate is determined by hydraulic conductivity and water retentivity of surface soil, and the lower soils are irrelevant. It was observed that in the depth range of 5 cm, soil dried drastically until matric potential reached to -1000 cmH$_2$O, and then, drying ratio decreased gradually. As shown in Fig.7, since the surface soil has high water retentivity, it is supposed that the drying ratio is relatively slow after it dried some extent. In the depth deeper than 30 cm, it was observed that soil was maintained almost saturated during experimental period. As shown in Fig.8, since the surface soil is poorly permeable, it is supposed that the water is scarcely supplied from lower soil to the surface. As table 7 shows, plastic limit of surface soil is 0.264 kg kg^{-1} in gravimetric water

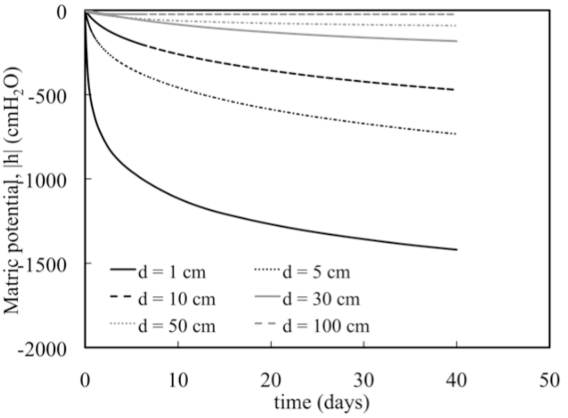


Figure9. Time variation of matric potential of No.3

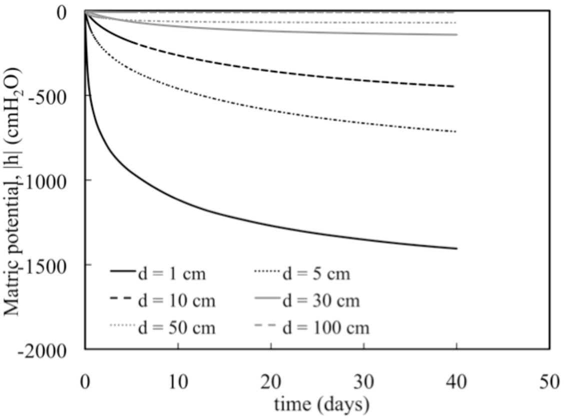


Figure10. Time variation of matric potential of No.4

content, which corresponds to approximately 0.36 cm^3 cm^{-3} in volumetric water content. The volumetric water content was estimated to approximately 0.4 cm^3 cm^{-3} after 40 days, and still decreased gradually. It is predicted that although the drying rate is relatively slow because of its high water retentivity, the water content will be fall below the plastic limit eventually.

4. CONCLUSIONS

In this study, estimation of ground structure using resistivity image profiling method and simulation of water movement using HYDRUS-1D were investigated.

Field study of resistivity image profiling method was carried out at *Miyahata* site located in Fukushima Prefecture. Result of resistivity distribution was investigated with the result obtained from soil boring. From the result of resistivity image profiling method, it could be estimated that *Miyahata* site was mainly consists of clay-loam soil and their water content were relatively high because low resistivity area was distributed throughout the remains. However, more specific knowledge such as more detailed distinction of layer or groundwater level could not be obtained.

Evaporation experiments were conducted with surface soil and lower soil in order to predict water retention curve and unsaturated hydraulic conductivity of each by inverse analysis using HYDRUS-1D. It was predicted that both soils had high water retentivity and poor water permeability. Based on the predicted parameters, numerical experiments about time variation of matric potential were conducted on the assumption that the soil structural remains were exposed for exhibition. As a result, it was predicted that the water content of near-surface soil was decreased drastically because of poor permeability. Therefore, in the case with *Miyahata* site, some method to restrain evaporation of soil water has to be considered. From the results described above, we may conclude that although the simulation of soil water movement is quite effective, more precise estimation of ground structure using resistivity image profiling method is necessary.

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