MEASUREMENT AND NUMERICAL ANALYSIS FOR INFILTRATION AND EVAPORATION BEHAVIOUR IN UNSATURATED SOIL

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It is known that infiltration and evaporation are the essential part of the hydrological cycle. The study of infiltration and evaporation behaviour in unsaturated soil can be conducted using several methods. This paper presents the analysis of a study on infiltration and evaporation behaviour in unsaturated soil from field measurement results.

A numerical simulation for the phase change of the pore water due to the change in temperature and pressure was carried out to obtain the infiltration and evaporation behaviour in unsaturated soil during rainy and no-rainy days. The numerical simulation results were then compared to the field measurement results.

Key Words: suction, infiltration, evaporation, field measurement, numerical simulation

1. INTRODUCTION

Kagoshima Prefecture lies at the southern tip of Kyushu Island where volcanic products such as Shirasu are present widely over the ground surface. Consequently, natural disasters due to heavy rainfall such as slope failures and debris flows occur almost every year. It is essential to estimate the ground condition of water content and temperature in order to predict the slope failure and prevent natural disasters due to heavy rainfall. A number of field measurements of rainfall and volumetric water content have been conducted by several researchers to study the infiltration of rainwater and evaporation behaviour1)-4).

Kitamura et al.5) summarized their mechanical model for unsaturated soil as shown in Fig.1. A numerical simulation for the phase change of the pore water due to the change in the temperature pressure was carried out to obtain the infiltration and evaporation behaviour in unsaturated soil during rainy and no-rainy days by using KITA-MIYA model in Fig.1.

This paper presents the analysis of a study on infiltration and evaporation behaviour in unsaturated soil obtained from field measurement with example of volcanic soils. The work carried out in this study is a part of the research study on measurement of evapotranspiration in unsaturated soils where infiltration, evaporation and transpiration aspects will be examined. Field measurement of suction, volumetric water content and temperature at several depths were conducted during rainy and no-rainy days. Suction is measured using a tensiometer which measures the negative pore water pressure where the pore air pressure is atmospheric (i.e. $u_a=0$). Rainfall data was also obtained using a tipping bucket rain gauge. The results obtained from measurement were then used as the input parameter for the numerical simulation. In order to quantify the validity of the proposed model, the numerical simulation results were compared with the results obtained from the meas-
measurement. Miyamoto and Kitamura performed a laboratory test to verify the calculation of coefficient thermal diffusion of unsaturated soil.

2. FIELD MEASUREMENT SITE

The field measurement site is located in Niidome Primary School, Kamou Town, Aira District, Kagoshima Prefecture, Japan. The location is about 35 kilometers away from Kagoshima University. The field measurement site is mainly underlain by volcanic soil.

The installation system at the field measurement site is shown in Fig.2. Fig.3 shows a schematic of the installation position of the equipment that has been installed at the field measurement site. The installation system at the field measurement site consists of tensiometers, a tipping bucket rain gauge, temperature sensors, soil moisture sensors, a solar panel and data loggers. There are four tensiometers, five soil moisture sensors, four temperature sensors and one rain gauge installed at the field measurement site. Prior to installation, the tensiometers and soil moisture sensors were calibrated in the laboratory. The tensiometers were installed to measure suction at 20 cm, 40 cm, 60 cm and 80 cm depth. The tensiometer is composed of a porous cup, an acrylic pipe filled with de-aired water, water tank and a semiconductor pressure sensor. The porous cup is made of ceramic which is saturated so that the air can not pass through under a pressure smaller than its air entry value of 200 kPa (Kitamura et al.). Three temperature sensors were installed to measure the temperature at 10 cm, 20 cm, 30 cm depth, while another was installed to measure the air temperature and was put inside the storage box. Five soil moisture sensors were installed to measure the volumetric water content of soil at 20 cm, 40 cm, 60 cm, 80 cm and 100 cm depth. A tipping bucket rain gauge was used to collect rainfall data. Suction, volumetric water content, rainfall and temperature data were recorded through the data loggers at 10 minutes intervals. Soil samples from the field measurement site were taken and brought to the laboratory for their index tests. The soil properties of volcanic soil samples are summarized in Table 1. The grain size distributions of volcanic soil samples are shown in Fig.4.
3. KITAMURA MODELS FOR UNSATURATED SOIL

(1) KITA-SAKO model

Kitamura et al. proposed a numerical model for seepage of pore water in unsaturated soil. The model for voids and soil particle in a soil mass is shown in Fig. 5. Fig. 5(a) shows a soil element with a few soil particles. The soil element with a few soil particles can be modeled as shown in Fig. 5(b) where voids fill with water and air are represented by a pipe with a diameter \( D \). Based on Fig. 5(b), the void ratio, volumetric water content, suction and unsaturated-saturated permeability coefficient can be derived as follows.

\[
e = \int \int \frac{V_p}{2} \cdot \frac{P_0(D) \cdot P_0(\theta)}{D} d\theta dD \quad (1)
\]

\[
W_v = \frac{e(D)}{1 + e} = \frac{1}{1 + e} \int \int \frac{V_p}{2} \cdot \frac{P_0(D) \cdot P_0(\theta)}{D} d\theta dD \quad (2)
\]

\[
s_u = \gamma_w \cdot h_c = \frac{4 \cdot T_s \cdot \cos \alpha}{d} \quad (3)
\]

\[
k = \int \int \frac{\gamma_w \cdot D^3 \cdot \tan \theta}{128 \cdot \mu} \cdot \frac{D}{\sin \theta + \frac{D}{\tan \theta}} \cdot P_0(D) \cdot P_0(\theta) d\theta dD \quad (4)
\]

where \( e \) is the void ratio, \( W_v \) is the volumetric water content, \( S_u \) is the suction, \( k \) is the unsaturated permeability coefficient, \( D_h \) is the height of container in Fig. 5(b), \( V_p \) is the volume of pipe in Fig. 5(b), \( V_c \) is the volume of container in Fig. 5(b), \( D \) is the diameter of pipe, \( P_0(d) \) is the probability density function of \( D \), \( P_0(\theta) \) is the probability density function of \( \theta \), \( d \) is the maximum diameter of pipe filled with water, \( T_s \) is the surface tension, \( \alpha \) is the contact angle between water and pipe, \( \gamma_w \) is the unit weight of water, \( h_c \) is the head of water column, \( \mu \) is the coefficient of viscosity.

(2) KITA-MIYA model

The pore water in unsaturated soil usually evaporates through the ground surface to the atmosphere as vapor during fine days. The amount of vapor being evaporated depends on the intensity of sunshine, wind, humidity of the air and water content of the soil. In KITA-MIYA model (Miyamoto et al.), the amount of evaporation is assumed to be able to calculate the thermal flux by the temperature gradient in unsaturated soil. A schematic condition that shows the heat transfer and evaporation near the surface ground is shown in Fig. 6.

The energy conservation (Fig. 6) is expressed as follows.

\[
q_x = q_{Tx} + q_{Px} \quad (5)
\]

where \( q \) is the thermal flux flown into the x-th layer, \( q_{Tx} \) is the consumed thermal flux for change in temperature in the x-th layer, \( q_{Px} \) is the consumed thermal flux for evaporation in the x-th layer.

The thermal flux between the adjacent layers is assumed to be able to calculate using the following equation.

\[
q_l = \lambda_i \cdot \Delta T \cdot \frac{A_l}{h} \quad (6)
\]
\[ q_x = \sum q_i (= q_{\text{soil particle}} + q_{\text{water}} + q_{\text{air}}) \quad (7) \]

where \( q_i \) is the thermal flux of phase \( i \) (soil particle, pore water and air), \( \lambda_i \) is the coefficient heat of phase \( i \), \( \Delta T \) is the temperature increment between adjacent layers, \( A_i \) is the section area of phase \( i \) that obtained from void ratio and degree of saturation, \( h \) is the distance between adjacent layers.

The change in temperature in the \( x \)-th layer between time \( (t) \) and \( (t+\alpha) \) can be expressed as follows.

\[ T_x(t + \alpha) = T_x(t) + \frac{\Delta q_{Tx}}{\sum c_i \cdot \rho_i \cdot V_i} \quad (8) \]

\[ \Delta q_{Tx} = q_{Tx} - q_{Tx+1} \quad (9) \]

where \( \Delta q_{Tx} \) is the supplied thermal flux in the \( x \)-th layer, \( c_i \) is the specific heat of phase \( i \) (soil particle, pore water and pore air), \( \rho_i \) is the density of phase \( i \) (soil particle, pore water and pore air), \( V_i \) is the volume of phase \( i \) (soil particle, pore water and pore air).

The thermal flux of the first layer \( (q_1) \) is calculated by assuming to 80\% of the total amount of thermal flux as follows (Kondo\(^{10}\)).

\[ q_{p1} = \beta' \cdot q_i \quad (10) \]

where \( \beta' \) is the coefficient depending on the radial energy (=0.8).

Substituting Equation (10) with Equation (5), the following equation is derived.

\[ q_{p1} = \beta \cdot q_{T1} \quad (11) \]

where \( \beta = \beta/(1-\beta') = 4.0 \) for \( \beta' = 0.8 \).

The amount of evaporation is calculated using the following equation.

\[ \Delta V_w = \frac{q_{p1}}{\rho_w \cdot Q_w} \quad (12) \]

where \( \Delta V_w \) is the volume of evaporation, \( Q_w \) is the latent heat of evaporation.

### 4. NUMERICAL EXPERIMENT

Numerical simulation was carried out to simulate one dimensional infiltration of rainwater and evaporation of pore water behaviour in unsaturated soil. Fig.7 shows model ground for one dimensional heat conduction and infiltration of rainwater in unsaturated soil. The one dimensional numerical simulation was carried out based on the field measurement condition as shown in Fig.3. The bottom and side boundaries are assumed to be insulated and undrained. In this model, the amount of rainfall and the temperature of surface ground are needed as the input parameter to simulate the change in suction and temperature in soil. The initial and boundary condition in the model ground were determined using the physical values summaries in Table 2. The calculation procedures are shown in Fig.8.
Table 2 Values of physical quantities in model ground.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Volcanic soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of layer</td>
<td>17</td>
</tr>
<tr>
<td>Cross sectional area</td>
<td>100 (cm²)</td>
</tr>
<tr>
<td>Thickness of layer</td>
<td>10 cm</td>
</tr>
<tr>
<td>Soil particle density</td>
<td>2.66 (g/cm³)</td>
</tr>
<tr>
<td>Specific heat</td>
<td>0.8 (j/(g.k))</td>
</tr>
<tr>
<td>Coefficient of heat conductivity</td>
<td>0.15 (j/(m.k))</td>
</tr>
</tbody>
</table>

5. RESULTS

(1) Measurement results
Fig.9 shows the example plots of pore water pressure, temperature and rainfall measurement results during rainy and no-rainy days for the measurement period of June 10 to June 18. As shown in Fig.9, the change of pore water pressure during rainy and no-rainy days is clearly seen. During rainy days, the pore water pressure increases and may lead to the development of positive pore water pressure meanwhile during no-rainy days the pore water pressure decreases. This is because during rainy days, infiltration of rainwater will saturates the soil and the pore may be filled with water. During no-rainy days, soil desaturates and the pores may almost be completely filled with air. It appears from Fig.9 that the pore water pressure value ranges from 0 kPa to -7 kPa. However, the difference of the pore water pressure value obtained at several depths was not really significant.

(2) Numerical results
Fig.10 shows example plots of numerical simulation results for the pore water pressure and temperature data obtained from field measurement. The temperature and rainfall data were used as the input parameter to simulate the changes of suction and temperature in soil. As shown in Fig.10, the pore water pressure ranges from -2 kPa to -11 kPa. Plots of the numerical simulation results show a similar pattern with the plots obtained from measurement results. However, there is a clear divergence of pore water pressure value obtained from numerical simulation and measurement results.
Fig.11 shows an example plots of comparison between numerical simulation and measurement results of pore water pressure and temperature for the period of June 14 to June 18. As shown in Fig.11, the pore water pressure ranges from -2 kPa to -9 kPa for the numerical simulation results meanwhile it ranges from 0 kPa to -6 kPa for the measurement results. From Fig.11, it can be seen that the numerical simulation results for the pore water pressure did not show a good agreement with the measurement results. This is because the unsaturated saturated permeability coefficient (k) value obtained from the numerical model proposed by Kitamura et al. is greater than the actual permeability test results (Fig.12). Because the unsaturated saturated permeability coefficient (k) value is high, therefore the volume of water flow (Q) and the change in volumetric water content values are also high. Thus this causes a greater pore water pressure range in the numerical simulation results.

6. CONCLUSIONS

Field measurement and numerical simulation were carried out to analyse the evaporation and infiltration behaviour in unsaturated soil. The measurement results show that during rainy days the pore water pressure increases and may lead to the development of positive pore water pressure meanwhile during no-rainy days the pore water pressure decreases. However, the differences of the pore water pressure value obtained at several depths was not very significant. Numerical simulation using the KITA-MIYA model was performed to simulate the changes of suction and temperature in the soil. The numerical simulation results were then compared to the measurement results. It was found that the nu-
Numerical simulation results show a similar pattern with the results obtained from measurements. However, there is a clear divergence of pore water pressure value obtained from numerical simulation and measurement results. The results obtained show that the numerical simulation did not show a good agreement with the measurement results. Therefore, more research is still needed to quantify the validity of the proposed model.
Fig.11 Plots of comparison between numerical and measurement results.
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