Numerical analysis of in-situ water content and temperature variations due to effects of grass

Binh T. Nguyen i), Tatsuya Ishikawa ii), Takumi Murakami iii)

i) Ph.D. Student, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-Ku, Sapporo 060-8628, Japan.
ii) Professor, Faculty of Public Policy, Hokkaido University, Kita 13, Nishi 8, Kita-Ku, Sapporo 060-8628, Japan.
iii) Undergraduate Student, Undergraduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-Ku, Sapporo 060-8628, Japan.

ABSTRACT

Vegetation has been recognized as an environmentally friendly method for stabilizing soil slope. Whereas hydrological effects of vegetation are experimentally investigated by several researchers, the field studies are rarely conducted and gain less attention. In this research, a field study was carried out on unsaturated soil slopes. The field measurement consisted of two neighboring cut slopes, namely bare soil slope and grassed soil slope. Field measurement results reveal that grass has influences on reducing and stabilizing the soil water content, increasing matric suction, and lowering soil temperature in warm seasons. The approach of coupled nonisothermal-seepage numerical analysis for unsaturated soil slope considering impacts of grass is suggested. The good agreement in comparisons between simulation and field measurement indicates that the proposed approach is useful to consider the influences of grass on the soil behaviors against climate variations.

Keywords: Numerical analysis, water content, soil temperature, unsaturated soil, grass.

1 INTRODUCTION

Vegetation has been recognized as an environmentally friendly restoration technique for stabilizing soil slopes through its mechanical and hydrological benefits. The hydrological benefits of vegetation have been widely experimentally investigated. The induced soil suction due to transpiration was evaluated (Ng et al. 2013a). Recent experimental studies reveal that the presence of roots affects the soil hydraulic properties such as soil water characteristic curve (SWCC), coefficient of permeability, infiltration, and surface runoff (Scholl et al. 2014, Vergani and Graf 2015, Leung et al. 2015, Nguyen et al. 2017). The results show that the effects on soil hydraulic properties are inconsistent and depend on types of soil and vegetation species.

In contrast, the long-term field measurements of vegetated soil are rarely carried out. The variations in soil temperature, soil water content, and soil suction are essential to evaluate the performance of soil slopes. These soil parameters are measured by buried sensors for a targeted period. However, unpredictable problems during sensors’ operation over the long-term period might happen. Indirect numerical methods are extremely useful in this case.

Cui et al. (2005) conducted a field monitoring program and simulation for soil construction during one-month period. The calculated results agreed well

with the field measurements at depths greater than 0.25 m. On the other hand, it found that the effects of vegetation resulted in less agreement near the surface (i.e. 0.15 m). In fact, the differences in soil hydraulic properties and the transpiration caused by vegetation were neglected in most numerical studies. To evaluate the enhancement in safety factor of vegetated soil slope, Rahardjo (2014) directly implemented the variations of matric suction measured in the field in slope stability analysis. Currently, there is a lack of numerical study considering properly the influences of vegetation on soil parameters against climate variations over a long-term period. Therefore, this study aims to investigate the impacts of grass on soil water content and soil temperature in unsaturated soil slopes. Furthermore, a coupled nonisothermal-seepage analysis approach considering the influences of grass is suggested.

2 FIELD MEASUREMENTS

2.1 Outline of soil slopes

Two neighboring cut slopes consisting of Komaoka volcanic soil were constructed in Hokkaido, Japan. Each cut slope has 6.8 m long, 4 m wide, and 4 m high. The grain size distribution and physical properties of Komaoka volcanic soil are presented in Fig.1.

Three types of grass, which are common in a seasonal cold region like Hokkaido, were selected,
namely: Kentucky Bluegrass, Creeping Red Fescue, and Tall Fescue. The mixed grass seeds with a density of 0.9 kg/m³ were weighed in accordance to hydroseeding specification for general civil engineering work in Hokkaido and germinated over the surface of one cut slope on early of June 2016. The slopes covered with and without grass are named as “grassed slope” and “bare slope”, respectively.

Measurement sensors including tensiometers, soil moisture meters, thermometers were installed in two soil slopes to monitor the changes in matric suction, soil water content, and soil temperature against the variations of climate. In each soil slope, two arrays including twelve soil moisture sensors and twelve thermometers in total were installed perpendicularly to the slope surface. One array consisting of six soil moisture sensors and six thermometers was installed near the shoulder, while the remaining array was inserted near the toe of soil slope. These sensors were inserted at different depths varying from 0.05 m to 0.55 m. The distance between each sensor was 0.1 m. It is noted that the depths of these two types of sensors were same. Moreover, three tensiometers were installed at 0.2 m depth in the shoulder, center, and toe of soil slope. The locations and depths of above-mentioned sensors are clearly illustrated in Fig. 2.

The meteorological station was built on the top of soil slopes to record the climate variables every 10 minutes. The meteorological data included solar radiation, air temperature, rainfall intensity, snow depth, wind speed, and relative humidity. Therefore, the changes in soil water content, matric suction, and soil temperature within two soil slopes against climate variations over the long-term period are studied. Measured results of sensors near the toe of slopes and recording data from the meteorological station during a 4-month period from 11 May 2017 to 11 September 2017 are presented and discussed in this study.

2.2 Field measurement results

2.2.1 Meteorological data

Meteorological data are presented in Fig.3. Net radiation was computed based on solar radiation and air temperature by Irmak (2003) model. Solar radiation was similar from May to July, then decreased until the end of surveyed period.
Seven relatively intense rainfall events happened on May 27, June 1, June 22, July 16, July 25, August 12, and August 22. The rainfall intensities were 34.5, 31.5, 44.5, 25, 32, and 27.5 mm/day, respectively. The wind speed varied from 1.6 to 8.2 m/s. Minimum relative humidity slightly increased from May to July before decreasing to somewhere at the vicinity of 35% at the end of the monitoring period, whereas the maximum relative humidity remained stable at about 100%. The general trend of minimum relative humidity was similar to that of air temperature. However, the daily changing pattern of air temperature was in general opposite to the pattern for minimum relative humidity. When the air temperature was high, the low value of humidity was observed and vice versa.

2.2.2 Volumetric water content of soil

The measured volumetric water contents of bare slope and grassed slope are demonstrated in Fig. 4. In this figure, B and G denote the bare slope and the grassed slope, respectively.

![Fig. 4: Volumetric water content of bare slope and grassed slope.](image)

The volumetric water content in bare slope increased linearly from the surface to 0.35 m before remaining unchanged at 25% at the greater depths. The influenced depth of evaporation may be only within 0.35 m. The volumetric water content in grassed soil slope was lower than in bare soil slope within the depth lower than around 0.20 m because the grassed not only minimized the rainfall infiltration (Nguyen at al. 2017) but also extracted water from the soil due to transpiration. Interestingly, higher volumetric water content was observed in grassed soil at somewhere at the vicinity of 0.3 m depth. The ability to retain higher water content of grassed soil as compared to bare soil might be a reason for this phenomena. The higher value of volumetric water content might be observed at which the influence of evaporation was small.

In general, the root shape zones are classified as a triangular root zone or a rectangular root zone. According to Ni et al. (2017), the root zone of grass has a triangular shape which shows the linear decrease in root area index (RAI) from the top to the end of root depth. The lower values of RAI at a greater depth results in the less water extracted from the surrounding soil due to transpiration. In fact, the water contents at depths greater than 0.35 m in grassed soil were just slightly lower compared to bare soil.

2.2.3 Matric suction

The comparison in matric suction at 0.2 m depth between bare slope and grassed slope is indicated in Fig. 5. Starting at 16 kPa and 19 kPa on May 11, matric suctions in both bare soil and grassed soil decreased by 2 kPa in the middle of June because many rainfall events happened. After that, the matric suctions in two soil slopes increased rapidly until August because there were few rainfall events. In addition, the relatively high solar radiation and air temperature led to a high amount of moisture flowing from the ground to the atmosphere. The sharper increase in matric suction of grassed soil was attributable to the contribution of the transpiration process. The low solar radiation and low air temperature, as well as the occurrence of several light rainfall events in September caused a slight decrease in matric suction at the end of the measurement. By the way, the grassed soil always remained higher suction as compared to the bare soil during the measured period. This is consistent with the lower volumetric water content in a shallow depth of grassed slope compared to that in bare slope as have mentioned previously. In addition, other researches (Ng et al. 2013b, Leung et al. 2015, Ng. et al 2016) reported that the vegetated soil remains higher matric suction than bare soil.

![Fig. 5: Soil suction of bare slope and grassed slope.](image)

2.2.4 Soil temperature

Soil temperatures of the bare slope and the grassed slope at different depths are shown in Fig.6. The temperature in bare slope was higher than grassed slope. The reason is because of the grass leaves. It partially prevents the net radiation from reaching to heat the soil, whereas grass leaves is not taken into account of the energy interception in the bare soil. Another reason is that the thermal properties of grassed soil might be different from that of bare soil due to the existence of grassroots.
There was an increase in soil temperature from May to July before reducing to about 15°C in September. Besides, the gap between soil temperature in bare slope and the grassed slope was closer at the end of the surveyed period. These observations are consistent with the trend of solar radiation and air temperature as shown in Fig. 3.

3 GOVERNING EQUATIONS

3.1 Non iso-thermal seepage flow

The governing equation for two-dimensional seepage flow is given by Richards (1931) and Childs and Collins-George (1950).

\[
\begin{align*}
\frac{1}{\rho_w} \frac{\partial}{\partial x} \left( D_w \frac{\partial P}{\partial x} \right) + \frac{1}{\rho_w} \frac{\partial}{\partial y} \left( D_w \frac{\partial P}{\partial y} \right) + \frac{\partial}{\partial x} \left( k_x \frac{P}{\rho_w g} \frac{\partial x}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{P}{\rho_w g} \frac{\partial y}{\partial y} \right) + Q = m_w \frac{\partial P}{\partial t}
\end{align*}
\]

where, \(\rho_w\) (kg/m\(^3\)) is density of water, \(P\) (kPa) is total atmospheric pressure, \(P_v\) (kPa) is vapor pressure of soil moisture (kPa), \(k_x\) and \(k_y\) (m/s) are hydraulic conductivity in the x-direction and y-direction, respectively, \(Q\) (m/s) is seepage boundary flux applied over a unit length, \(D_w\) (kg/m/(kN.s)) is diffusion coefficient of water vapor through soil, \(g\) (9.81 m/s\(^2\)) is acceleration due to gravity, \(m_w\) (1/\(\text{KPa}\)) is slope of the soil water characteristic curve SWCC, \(\gamma_w\) (kN/m\(^3\)) is unit weight of water, and \(t\) (days) is time.

The governing equation for two-dimensional thermal flow is given by Harlan and Nixon (1978).

\[
\begin{align*}
L_w \frac{\partial}{\partial x} \left( D_y \frac{\partial \theta}{\partial x} \right) + L_w \frac{\partial}{\partial y} \left( D_y \frac{\partial \theta}{\partial y} \right) + \frac{\partial}{\partial x} \left( k_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial \theta}{\partial y} \right) + Q + \xi \theta_x \frac{\partial T}{\partial x} + \xi \theta_y \frac{\partial T}{\partial y} = \left( \zeta + L_w \frac{\partial \theta_{\text{air}}}{\partial t} \right) \frac{\partial T}{\partial t}
\end{align*}
\]

where, \(T\) (°C) is temperature (°C), \(\zeta\) (kJ/(m\(^3\).°C)) is volumetric heat capacity of soil; \(k_x, k_y\) (kJ/(day.m.°C)) are thermal conductivity in the x- and y-directions, respectively, \(V_x\) and \(V_y\) (m/s) are the Darcy water velocity in x- and y-directions, respectively, \(Q\) (kPa) is thermal boundary flux applied over a unit length, \(L_w\) (kJ/kg) is latent heat of water, and \(\theta_{\text{sw}}\) (m\(^3\)/m\(^3\)) is unfrozen volumetric water content.

The seepage flow in Eq. 1 and thermal flow in Eq. 2 are linked by the relationships given by Edlefsen and Anderson (1943).

\[
P_v = P_v \left( e^{\frac{-\theta_{\text{sw}}}{T}} \right) = P_v h_t \quad (3)
\]

where, \(P_v\) (kPa) is saturated vapor pressure of pure free water, \(\rho\) (kg/m\(^3\)) is density of water vapor or ice, \(w\) (kg/kmol) is molecular mass of water vapor, \(R\) (kJ/(kg.m/s.°C)) is universal gas constant, \(T\) (°C) is soil temperature, and \(h_t\) is relative humidity of air.

3.2 Actual evaporation

Actual evaporation (AE) accounts for the movement of water from the soil surface to the air. Wilson equation (1994) is used for the calculation of AE.

\[
AE = \frac{\Gamma Q_{E}}{\Gamma + \eta E_s} \quad (4)
\]

Where, \(\Gamma\) (kPa/s/°C) is slope of saturation vapor pressure versus temperature curve at the mean temperature in the air, \(Q_e\) (mm/day) is net radiation at the soil surface, \(\eta\) (0.06733 kPa/°C) is psychrometric constant, \(E_s\) is flux associated with “mixing”, \(E_{ai}\) (mm/day) = \(f(u) u_{\text{air}}\), \(f(u) = 0.55(1+0.146W_s)\), \(W_s\) (km/h) is wind speed, \(u_{\text{air}}\) (kPa) is water vapor pressure in the air above ground surface, \(h_t\) is relative humidity in the air above the ground (i.e., \(h_t = u_{\text{air}}/u_{\text{air}}\)), \(h_s\) is relative humidity at the soil surface (i.e., \(h_s = u_{\text{sw}}/u_{\text{sw}}\)), \(u_{\text{air}}\) (kPa) is water vapor pressure in the air above ground surface, \(u_{\text{sw}}\) (kPa) is saturated vapor pressure at the mean air temperature, \(u_{\text{sw}}\) (kPa) is vapor pressure in the soil at ground surface, \(u_{\text{sw}}\) (kPa) is saturated vapor pressure in the soil at ground surface.

3.3 Actual transpiration

Transpiration is the term used to describe evaporation from vegetated surfaces. Transpiration accounts for the movement of water within plants and the subsequent loss of water as a vapor through stomata in its leaves.

Leaf area index (LAI) presents the effect of the vegetation cover on the energy available to extract the water from the ground surface. The LAI is defined as the surface area of the leaves divided by the surface area covered by the soil. The plant cover with larger LAI has a larger potential to extract water. In the simulation, LAI is used to reduce the amount of net radiation reaching the soil surface, which in turn reduce
the computed actual evaporation. In other words, LAI controls how the energy at the surface is portioned between that available for direct evaporation from the soil and that is available to the plants in their attempt to transpire water.

Ritchie (1972) equation is used for the calculation of potential transpiration (PT).

\[ PT = 0 \text{ when } LAI < 0.1 \]  \hspace{1cm} (5)

\[ PT = PE(-0.21 + 0.7 LAI^{0.5}) \text{ when } 0.1 \leq LAI < 2.7 \]  \hspace{1cm} (6)

\[ PT = PE \text{ when } 2.7 \leq LAI \]  \hspace{1cm} (7)

where \( PT \) (mm/day) is potential transpiration rate, \( PE \) (mm/day) is potential evapotranspiration rate.

The zone over which plant transpiration is assumed to extract water is dependent upon the depth of the roots and the distribution of the roots. The grass root zone has triangular shape in this study.

The potential root uptake at a point within root zone under consideration is defined.

\[ PRU = \frac{RSF \times PT}{R_f} \left(1 - \frac{R_o}{R_f}\right) \]  \hspace{1cm} (8)

where \( PRU \) (m³/day) is potential root uptake rate per unit time, \( RSF \) is root distribution shape factor (i.e., triangular), \( R_f \) (m) is total thickness of root zone in length units, and \( R_o \) (m) is depth to the given point in length units.

The plant limiting factor (PLF) is a function of the soil suction in the root zone. The PLF proposed by Feddes et al. (1976) is shown in Fig. 7. It was assumed that the grass transpires when soil suction is higher than ‘anaerobiosis point’ and lower than ‘wiling point’. The ability of root water uptake is maximum between 1 kPa and 40 kPa (limiting point), and PLF reduces linearly from 1 at 40 kPa to 0 at 1500 kPa.

\[ AT = (PRU)(PLF) \]  \hspace{1cm} (9)

4 NUMERICAL SIMULATION OF SOIL SLOPES

The numerical analyses are performed using a finite element code, VADOSE/W (GEO-SLOPE International Ltd., Calgary, Alberta, Canada).

4.1 Initial and boundary conditions

The geometry and boundary conditions of two slopes for numerical simulation are demonstrated in Figure 8. The two-dimensional model of the slope has a total height of 8 m and a length of 18 m.

![Fig. 8: Geometry and boundary condition of two soil slopes.](image)

The coupled nonisothermal-seepage analyses are performed for both bare slope and grassed slope. Three stages of analyses are carried out for each soil slope. Firstly, the steady-state analysis is performed by assuming the total head of 2 m at the bottom of the model, while the ground temperature at slope surface and bottom of the model are assumed to be 10 °C and 5 °C. These values of temperature are relatively equal to the average air temperature and assumed soil temperature at the bottom of the slope on 11 May 2012. After that, a transient analysis is performed to achieve the soil water content and soil temperature distributions in slopes. The climate boundary obtained from Automatic Meteorological Data Acquisition System (AMeDAS) provided by the Japanese Meteorological Agency (JMA) including rainfall, snowfall, air temperature, relative humidity, solar radiation, and wind speed over a period of 5 years from 11 May 2012 to 10 May 2017 is applied on the slope surface. Two lateral sides are impermeable and adiabatic boundaries. The bottom of the model is set as ‘unit gradient’. In this case, the downward flux is equal to the coefficient of permeability at the points in the bottom edge. In other words, the boundary downward flux is equal to the coefficient of permeability at the points in bottom edge multiplied by the edge boundary length. Finally, the climate boundary measured from the field during 11 May 2017 to 11 September 2017 as presented in Fig. 3.
is applied. Temperature \( T_z \) applied at the bottom of the model is implemented from Andersland and Ladanyi (2004) equation as follows.

\[
T_z = T_m + A \exp \left( -z \sqrt{\frac{\pi}{\alpha_s p}} \sin \left( \frac{2\pi t}{p} - z \sqrt{\frac{\pi}{\alpha_s p}} \right) \right)
\]

Where, \( T_m \) (6.4°C) is mean annual temperature, \( A \) (16.1°C) is surface temperature amplitude, \( z \) (8 m) is the depth, \( p \) (365 days) is corresponding period, \( t \) (day) is time, \( \alpha_s \) (4.89 E-7 W/m²°C) is thermal diffusivity.

### 4.2 Material properties

The soil water characteristic curves (SWCCs) and coefficient of permeability of bare and grassed soils are measured by column test apparatus (Nguyen et al. 2017) and fit by Fredlund and Xing (1994a,b) equations as shown in Eqs. 11 and 12.

\[
\theta_s = \theta_i \left[ \frac{\ln \left( 1 + \frac{s}{h_s} \right)}{\ln \left( 1 + \frac{1}{h_i} \right)} - \frac{1}{\ln \left( 1 + \frac{1}{h_i} \right)} \left[ \ln \left( \exp(1) + \frac{s}{h_i} \right) \right] \right]^{1/n}
\]

Where, \( \theta_s \) (cm³/cm³) is volumetric water content at any suction, \( \theta_i \) (cm³/cm³) is saturated volumetric water content, \( a_f \) (kPa) is material parameter which is primarily a function of the air-entry value of the soil, \( n_f \) is material parameter which is primarily a function of rate of water extraction from the soil once the air-entry value has been exceeded, \( m_f \) is primarily a function of the residual water content, \( h_i \) (kPa) is suction at residual water content, and \( s \) (kPa) is any soil suction value.

\[
k_s(s) = \frac{\theta(s) - \theta(0)}{\ln(1000000)} e^b \int_0^b \frac{\theta(e') - \theta(0)}{e'} e^{-e'} dy
\]

Where, \( k_s(s) \) is relative coefficient of permeability at suction \( s \), \( S_{ave} \) (kPa) is air-entry value of the soil, \( b \) is equal to \( \ln(1000000) \), \( y \) is dummy variable of integration representing suction, \( \theta' \) is derivative of Eq. 11.

The differences in the hydraulic properties of these soils are illustrated in Fig.9. It can be seen clearly that the grassed soil retains higher water content at a given matric suction compared to bare soil. The former also has a lower coefficient of permeability than the latter. The air entry value and residual suction are also different because of the existing of grassroots. Johansen (1975) and Newman (1995) equations are used for the estimation of thermal conductivity and volumetric heat capacity, respectively. As have mentioned previously, the soil temperature in grassed slope is lower than that in bare slope. The grass leaves intercept solar radiation by shading the underlying soil. In addition, the existing grassroots in the soil pores result in the different thermal properties of soil. To deal with the influence of grassroots, the lower thermal conductivity and volumetric heat capacity are assumed for grassed soil. These thermal properties of grassed soils are estimated after running sensitive analyses to achieve reasonable agreement in soil temperature between the simulation and field measurement results.
4.3 Numerical results

4.3.1 Volumetric water content

The results of volumetric water content at 0.05 m, 0.25 m, and 0.55 m depths derived from the numerical simulation and field measurement are selected to be presented in Fig. 10. It is clear that volumetric water content of grassed soil is lower at near surface (i.e., 0.05 m depth) compared to that of bare soil, whereas a higher volumetric water content is observed at 0.25 m depth in the former. An equal water content is seen at 0.55 m depth for both two slopes. Furthermore, the water content in bare soil is far fluctuated against rainfall infiltration as compared to the grassed soil at depths shallower than 0.55 m. This is caused by the lower coefficient of permeability of grassed soil. The simulation captures well the variations in volumetric water content of soil against the climatic variations.

![Fig. 10: Comparisons in volumetric water content in bare slope and grassed slope.](image)

4.3.2 Soil temperature

The comparisons in soil temperature between field measurement and numerical simulation for both bare and grassed slopes are indicated in Fig. 11. The soil temperature at shallower depth more fluctuates because it is significantly affected by the variation of air temperature. The differences in soil temperatures of two slopes at 0.55 m are relatively smaller than shallower depths. The numerical simulation can reasonably reproduce the changes in soil temperature of both two soil slopes. Since the effect of grass leaves on shading soil surface hence reducing the soil heat is neglected in this study, the simulation does not capture the difference in soil temperatures at 0.05 m depth. However, this simulation shows that excepting the influence of grass leaves, the lower soil temperature in grassed soil might be caused by the grassroots. Grassroots result in lower values of both thermal conductivity and volumetric heat.

![Fig. 11: Comparison in soil temperature in bare soil and grassed soil slope.](image)

4.3.3 Water balance at soil surface

The water balance at a given location in the soil surface is expressed by Blight (1997) equation:

\[ P = I + R + AE \]  \hspace{1cm} (13)

where \( P \) (mm/day) is precipitation rate, \( I \) (mm/day) is the infiltration rate, \( R \) (mm/day) is surface runoff rate, \( AE \) (mm/day) is the actual evaporation rate.

Fig. 12 compares the cumulative flux of \( I, R, AE \) calculated from water balance at a central point in the surface slope (i.e., coordinate \((X, Y) = (8.4 \text{ m}, 6.0 \text{ m})\) in Fig. 8). The precipitation and infiltration are considered as positive. In reverse, evaporation, transpiration, and runoff are regarded as losses and therefore taken as negative. As expected, the grass cover minimizes the amount of infiltration and accelerates the runoff because of its lower coefficient of permeability. The amount of actual evaporation in grassed slope is a half of that in bare slope due to effects of LAI. However, the cumulative actual evapotranspiration \((AE + AT)\) in grassed soil is higher.

The cumulative actual evaporation and cumulative actual evapotranspiration of bare soil and grassed soil account for around 60% of total precipitation. This number is higher compared to the summary of
cumulative infiltration and runoff in bare slope and grassed slope (about 40% of precipitation in total). Therefore, the evapotranspiration should be taken into account properly in the simulations which attempt to investigate the soil parameters against climatic variations at the shallow surface.

![Cumulative infiltration, evaporation, transpiration, and runoff rates in bare slope and grassed slope.](image)

Fig. 12: Comparison in cumulative infiltration, evaporation, transpiration, and runoff rates in bare slope and grassed slope.

5 CONCLUSIONS

This study investigates the effects of grass on soil parameters against climate variations during long-term period based on comprehensive field measurement results. In addition, the approach of coupled nonisothermal-seepage analysis is proposed to consider properly influences of grass cover on soil water content and soil temperature. Several findings are drawn in this study as follows:

- The field measurement results reveal that the influenced depth of evaporation and evapotranspiration is around 0.35 m. The matric suction remains higher in grassed soil because of the differences in soil hydraulic properties and the contribution of transpiration due to soil-plant-atmosphere interaction. The volumetric water contents in grassed slope are almost lower than that in bare slope. The water content in the grassed slope is less fluctuated against rainfall infiltration than in bare slope.
- Lower soil temperatures are observed in grassed slope as compared to bare slope. The reasons are attributed to both grass leaves and grassroots. The grass leaves intercept net radiation by shading the ground surface, whereas the grassroots might result in lower thermal conductivity and lower volumetric heat capacity of the soil. Therefore, it may be better to take into account the effects of reducing soil temperature by grassroots in the numerical simulation.
- The good agreement between field measurements and numerical simulation results shows that the recommended approach considering the changes in SWCC, coefficient of permeability, grass parameters (i.e. LAI and total thickness of root zone), proper values of thermal conductivity as well as volumetric heat capacity of grassed soil is useful to accurately compute the volumetric water content and soil temperature for a long-term period against the climate variations.

- The water balance derived from the simulation shows that grass plays a key role in lowering the soil water content at near the slope surface by extracting significant amount of water from soil through the evapotranspiration process due to grass-soil-atmosphere interaction, minimizing the infiltration, and accelerating the surface runoff. Since the percentages of cumulative evaporation in the bare slope and cumulative evapotranspiration in the grassed slope are relatively high, they should be properly considered in numerical simulation for predicting the water content distribution of the shallow surface of soil slopes.

ACKNOWLEDGMENTS

This research was supported in part by Grant-in-Aid for Scientific Research (A) (16H02360) and Grant-in-Aid for Challenging Exploratory Research (15K14026) from Japan Society for Promotion of Science (JSPS) KAKENHI.

REFERENCES

1) Andersland, O.B., and Ladanyi, B. (2004). Frozen ground engineering. John Wiley & Sons.
2) Blight, GE. (1997). Interactions between the atmosphere and the Earth. Géotechnique, 47(4), 715-767.
3) Childs, E.C., and Collis-George, N. (1950). The permeability of porous materials. Proceedings of the Royal Society of London, Series A. Mathematical and Physical Sciences, 201(1066), 392-405.
4) Cui, Y.J., Lu, Y.F., Delage, P., and Riffard, M. (2005). Field simulation of in situ water content and temperature changes due to ground-atmospheric interactions. Géotechnique, 55(7), 557-568.
5) Edlefsen, N., and Anderson, A. (1943). Thermodynamics of soil moisture. Hilgardia, 15(2), 31-298.
6) Feddes, R.A., Kowalik, P., Kolinska-Malinka, K., and Zaradny, H. (1976). Simulation of field water uptake by plants using a soil water dependent root extraction function. Journal of Hydrology, 31(1-2), 13-26.
7) Fredlund, D.G., and Xing, A. (1994a). Equations for the soil-water characteristic curve. Canadian geotechnical journal, 31(4), 521-532.
8) Fredlund, D.G., Xing, A., and Huang, S. (1994b). Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal, 31(4), 533-546.
9) Harlan R.L., and Nixon J.F. (1978). Ground thermal regime. In: Andersland OB, Anderson DM (eds). Geotechnical engineering for cold regions. McGraw-Hill, New York, pp 103-63.
10) Irmak, S., Irmak, A., Allen, R.G., and Jones, J.W. (2003). Solar and net radiation-based equations to estimate reference evapotranspiration in humid climates. Journal of irrigation and drainage engineering, 129(5), 336-347.
11) Japan Meteorological Agency (JMA) (2012). Past weather data, (in Japanese), Date accessed: June 20th, 2018. http://www.data.jma.go.jp/gmd/risk/obsd/index.php

12) Johansen, O. (1975). Thermal conductivity of soils, PhD Thesis, Trondheim, Norway (CRREL Draft Translation 637, 1977).

13) Leung, A.K., Garg, A., Coo, J.L., Ng, C.W.W., and Hau, B. C.H. (2015). Effects of the roots of Cynodon dactylon and Schefflera heptaphylla on water infiltration rate and soil hydraulic conductivity. Hydrological processes, 29(15), 3342-3354.

14) Newman, G.P. (1995). Heat and mass transfer in unsaturated soils, M.Sc. Thesis, University of Saskatchewan, Saskatoon, SK.

15) Ng, C.W.W., Leung, A.K., and Woon, K.X. (2013a). Effects of soil density on grass-induced suction distributions in compacted soil subjected to rainfall. Canadian Geotechnical Journal, 51(3), 311-321.

16) Ng, C.W.W., Ni, J.J., Leung, A.K., Zhou, C., and Wang, Z.J. (2016). Effects of planting density on tree growth and induced soil suction. Géotechnique, 66(9), 711-724.

17) Ng, C.W.W., Woon, K.X., Leung, A.K., and Chu, L.M. (2013b). Experimental investigation of induced suction distribution in a grass-covered soil. Ecological Engineering, 52, 219-223.

18) Nguyen, T. B., Ishikawa, T., and Subramanian, S.S. (2017). Rainfall infiltration and runoff characteristics of an unsaturated volcanic soil under grass cover. Second Pan American Conference on Unsaturated soils, November 12-15, 2017, Texas, USA, 135-145.

19) Ni, J.J., Leung, A.K., Ng, C.W.W., and So, P.S. (2016). Investigation of plant growth and transpiration-induced matric suction under mixed grass-tree conditions. Canadian Geotechnical Journal, 54(4), 561-573.

20) Rahardjo, H., Satyanaga, A., Leong, E.C., Santos, V.A., and Ng, Y.S. (2014). Performance of an instrumented slope covered with shrubs and deep-rooted grass. Soils and Foundations, 54(3), 417-425.

21) Richards, L.A. (1951). Capillary conduction of liquids through porous mediums. Physics, 1(5), 318-333.

22) Ritchie, J.T. (1972). Model for predicting evaporation from a row crop with incomplete cover. Water resources research, 8(5), 1204-1213.

23) Rasband, W.S. (2011). Imagej, US National Institutes of Health, Bethesda, Maryland, USA. http://imagej.nih.gov/ij/.

24) Scholl, P., Leitner, D., Kammerer, G, Loiskandl, W., Kaul, H. P., and Bodner, G (2014). Root induced changes of effective 1D hydraulic properties in a soil column. Plant and soil, 381(1-2), 193-213.

25) Vergani, C., and Graf, F. (2016). Soil permeability, aggregate stability and root growth: a pot experiment from a soil bioengineering perspective. Ecohydrology, 9(5), 830-842.

26) Wilson, G.W., Fredlund, D.G., and Barbour, S.L. (1994). Coupled soil-atmosphere modelling for soil evaporation. Canadian Geotechnical Journal, 31(2), 151-161.