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**Effect evaluation of grass on shallow stability of unsaturated volcanic soil slope
in seasonal cold region**

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Abstract

This study investigates effects of grass on hydro-thermal-mechanical properties and shallow stability of unsaturated soil slope. A field measurement consisted of two cut slopes, namely bare slope and grassed slope, was carried out. Field measurement results shows that grass has effects on reducing the volumetric water content and increasing matric suction. There is a greater gap in matric suction between grassed soil slope and bare soil slope when the snow appears. Besides, the soil temperature in grassed slope is lower than bare slope in warm seasons. However, contrasted result of the soil temperature is recorded in winter. The triaxial tests were conducted for studying mechanical properties of grassed saturated soil with different grass ages. Experimental results reveal that there is increase in peak shear strength and effective cohesion of grassed soil as the grass age increases, whereas slightly higher effective angle of internal friction is observed. Furthermore, the volumetric strain decreased with the rise in grass root volume ratio. The approach of coupled nonisothermal-seepage numerical analysis for unsaturated soil slope considering impacts of grass is suggested. It is followed by slope stability analysis considering enhanced shear strength of soil due to grass roots. The good agreement regarding to soil temperature and volumetric water content between simulation and field measurement indicates that the proposed approach is feasible to consider the influences of grass on the hydro-thermal behaviors of unsaturated soil slope. Furthermore, the higher values of factor of safety (FOS) of grassed slope present that the grass is effective in resisting the shallow landslide-prone area.

Keywords: Grass; Soil temperature, Soil water content, Soil-water characteristic curve; Coefficient of permeability; Shallow stability

1. Introduction

Soil bioengineering using vegetation has been widely employed as an environmentally friendly restoration technique for stabilizing soil slopes through both hydrological and mechanical reinforcement. The effects of basic plant traits on their slope stability functions in compacted and planned green slopes have been summarized in the study of [Bordoloi and Ng 2020](#). In addition, the heat insulation due to grass leaves and reinforcement of vegetation cover effectively restrain the displacement of the slope's shallow soil in cold region ([Rui et al. 2018](#)). The hydrological benefits of vegetation have been widely experimentally investigated. 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 ([Leung et al. 2015](#), [Nguyen et al. 2020](#)). The past studies clearly show that the effects on soil hydraulic properties are inconsistent and depend on types of soil and vegetation species. The vegetation also has effects on transpiration ([Ni et al. 2018](#)). The higher matric suction induced by evapotranspiration results in lower coefficient of permeability hence the soil slope is further stabilized. In contrast, the long-term field measurements of vegetated soil are rarely carried out. [Ng. et al \(2020\)](#) conducted a field study to investigate the effect of vegetation growth and spacing on hydraulic properties of soil. The vegetation species were *Schefflera arboricola* and *Cynodon dactylon* which are drought tolerant. Seldom have studies paid attention to vegetation species which are commonly used in the seasonal cold region.

[Cui et al. \(2010\)](#) and [An et al. \(2018\)](#) examined the hydro-thermal behavior of embankment under climate effects. The numerical approach proposed in these studies reproduced well as compared to the field monitoring data for bare soil. On the contrary, numerical simulation approach which consider the influence of vegetation on hydro-thermal properties of unsaturated soil are not well understood. [Pagano et al. \(2019\)](#) reported that the hypothesis of bare soil cannot be used to analyses vegetated conditions. [Nguyen et al \(2018\)](#) and [Ni et al. \(2018\)](#) reported that the seepage behavior under rainfall infiltration in vegetated soil could be reasonably predicted if the hydraulic properties of vegetated soil including SWCC and saturated/ unsaturated coefficient of permeability are properly considered. Several numerical studies were performed to evaluate the effect of evapotranspiration on only hydraulic behaviors of soil. However, vapor transport was not taken into account in the numerical simulation. It is noted that considering the coupled transport of heat and water in soil is important when investigating the hydro-mechanical behavior of soil during evaporation ([An et al. 2018](#)). Therefore, vapor transport plays important role to properly study the soil water content near the soil

surface. [Ni et al. \(2019\)](#) presented that soil temperature had influences on transpiration. The root water uptake was inhibited due to low soil temperature. Without considering soil temperature effects on transpiration, the soil water content was underestimated by around 50% in autumn period. Since only the seepage analysis has been performed in [Ni et al. \(2019\)](#) study, soil temperature near surface was estimated based on empirical model. The coupled non isothermal-seepage analysis, which take both the vapor transport and the effect of vegetation cover on the reduce of soil temperature into account, is useful to the numerical assessment of vegetated soil slope performance.

Soil shear strength at the potential slip surface of slope is increased due to the enhanced shear strength provided by roots. As a result, the shallow landslide-prone areas might be resisted due to the effective mechanical effects of vegetation. Shear strength behaviors of root-reinforced soil were studied by direct shear test in both experimental laboratory and in-situ condition ([Wood et al. 2016](#), [Mahannopkul and Jotisankasa 2019](#), [Yildiz et al 2020](#)). The drawback of the direct shear test is that failure plane is commonly assumed. However, stress and strain in a sample are uneven and complicated and the weakest surface may not be the assumed shear plane in reality. In addition, the whole process of a test, from loading to breaking, can be monitored closely, in which shear strength, stress–strain relationship, and changes of the sample volume can be measured simultaneously ([Zhang et al, 2010](#)). Few past researches employed the root-induced changes in shear strength properties of vegetated soils to numerically access the stability of unsaturated soil slope ([Feng et al. 2020](#)). The cohesion of rooted soils in these researches were empirically estimated by [Wu et al \(1998\)](#), and [Liang et al \(2020\)](#) models. There is a limited research which determine the effect of natural roots on increase in shear strength properties of soils by triaxial test. The effects of roots on the factor of safety of vegetated soil slope is more properly determined by employing shear strength parameters of rooted soil which are studied from triaxial test.

This study aims to propose a numerical simulation approach considering the effects of grass on thermal-hydro properties, and to access the shallow stability of grassed unsaturated soil slope. Aiming this goal, influences of grass on variations in soil water content, matric suction, and soil temperature in unsaturated soil slopes are firstly investigated baes on field measurement. After that, hydraulic properties of grassed soil are derived from [Nguyen’s study \(2020\)](#) which conducted the research use the same Komaoka soil and grass in this study. A series of triaxial tests were then performed to investigate the influences of grass roots on shear strength behaviors of saturated soil. The seepage analysis and slope stability analysis employed the

suggested approach have been conducted hence its validity is verified by comparing the numerical results with measurements results.

2. Field measurements of Komaoka soil slopes

2.1. Outline of soil slopes

Two neighboring cut slopes consisting of Komaoka volcanic soil were constructed in Makomanai district, Hokkaido prefecture, 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 and Table 1. Komaoka soil is classified as gravelly sand of fine fraction nature (SFG) according to the method of classification of geomaterials for engineering purposes (JGS 2009a).

A mixture of three grass species is selected in this study, namely: Kentucky Bluegrass, Creeping Red Fescue, and Tall Fescue. These species are cold tolerant and hence widely used in a seasonal cold region like Hokkaido. The mixed-grass seeds with a density of 18 g/m² (Table 2) are chosen based on hydroseeding specification for general bio-engineering purposes in Hokkaido and uniformly 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 (CST-SEN-DD6, Climatec Inc., Japan) were installed at the crest, 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 (CHG - 2100 AET, Climatec Inc., Japan) were installed at 0.25 m depth in the crest, centre, 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 two soil slopes to record the climate variables every 10 minutes. The meteorological data included solar radiation, air temperature, rainfall intensity, snow fall, wind speed, and relative humidity are measured. In addition, two high resolution cameras were installed to capture the change in snow depth against time in winter at two cut-slopes. 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. The time interval of collecting data was set to be 10 min. Measured results of sensors near the top of slopes and recording data from the meteorological station during a 1-year period from May 11th, 2017 to May 11th, 2018 are presented and discussed in this study.

2.2 Field measurement results

2.2.1 Meteorological data

[Fig.3](#) presents meteorological data during 1-year period. Solar radiation was relatively similar from 2017 May to 2017 July ($25 \text{ MJ.m}^{-2}.\text{day}^{-1}$), then significantly decreased to somewhere in the vicinity of $2 \text{ MJ.m}^{-2}.\text{day}^{-1}$ in 2018 January. After that, the solar radiation rose dramatically until 2018 May. Relatively low rainfall events were observed. Rainfall events were mainly occurred from 2017 September to 2018 March. The wind speed varied from 1.2 to 8.2 m/s. After increasing from 2017 May (13°C) to 2017 July (26°C), air temperature dropped to minimum value of about -11°C in 2018 January. Next, it was increased until the end of presented period. The general trend of 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. Snow fall happened from November 17th, 2017 when the temperature was below 0°C . After reaching the maximum depth of 89 cm on March 2nd, 2017, snow began melt due to the rise in both air temperature and solar radiation hence the snow depth was dramatically decreased from March 2nd, 2017 to March 31st, 2017.

2.2.2 Volumetric water content of soil

The measured volumetric water contents (VWCs) of bare slope and grassed slope are demonstrated in [Fig. 4](#). The volumetric water content in bare slope increased linearly from the surface to 0.35 m before remaining unchanged at about 26% at the greater depths. The volumetric water content in grassed slope was lower than in bare slope within the depth lower than around 0.55 m because the grassed not only minimized the rainfall infiltration ([Nguyen et al. 2020](#)) but also extracted water from the soil through transpiration process. There was an equal volumetric water content at the 0.55 m depth between bare slope and grassed slope.

[Fig. 5](#) compared the variations of volumetric water content at 0.05 m depth between bare slope and grassed slope. The VWC in bare slope doubled as compared to that from grassed slope. Furthermore, there was a highly fluctuated in VWC under rain and snowmelt infiltration in the former, while the VWC in the

latter was much stable. The VWC of the bare slope dramatically rise by nearly 30% (from 7.4 % to 20.2 %) due to snowmelt infiltration on March 3rd, 2018. However, there was an increase by 15% (3.7% to 5.6%) on the same date in VWC of grassed slope.

2.2.3 Matric suction

The comparison in matric suction at 0.25 m depth between bare slope and grassed slope is indicated in Fig. 6. Matric suctions in both bare soil and grassed soil decreased in the middle of 2017 June because many rainfall events happened. After that, the matric suctions in two soil slopes increased rapidly until 2017 August because there were few rainfall events. The relatively high solar radiation and air temperature also led to a high amount of moisture flowing from the ground to the atmosphere. The dramatic increase in matric suction of grassed slope was attributed to the transpiration process. The low solar radiation and low air temperature, as well as the occurrence of several light rainfall events in 2017 September to the end of 2017 October caused a drop in matric suction.

The grassed slope always remained higher matric suction as compared to the bare slope. This is corresponding to the lower volumetric water content in a shallow depth of grassed slope compared to that in bare slope as have mentioned previously. In addition, the vegetated soil has higher matric suction than bare soil due to the differences in soil water characteristic curves (Nguyen et al. 2020). The differences in SWCCs are later explained. It is noted that the gap in matric suction between grassed slope and bare slope was greater in winter season with the occurrence of snow. There are two reasons for the differences in matric suction due to the grass root existence. The first reason is that the soil pores are occupied by grass roots hence the diameters of soil pores are reduced hence matric suction is increased due to the capillary law (Scanlan and Hinz, 2010). Another reason might be attributed to the exudates released by grass roots (Carminati et al, 2016). Since the effect of grass roots on reducing soil pore was similar in both warm and winter seasons, the enhanced matric suction under the snow cover might be mainly attributed to the second reason. The exudates might be released more by grass roots in winter. This explanation is not yet conclusive. However, it should be noted that this phenomenon has been occurring and repeated for continuously 3 winters (from winter of 2017 to winter of 2019).

2.2.4 Soil temperature

Soil temperatures of the bare slope and the grassed slope at different depths are shown in Fig. 7. In warm season when the temperature and solar radiation are relatively high, the temperature in bare slope was higher

than grassed slope. The reason was because of the grass leaves partially prevented the net radiation from reaching to heat the soil. There was an increase in soil temperature from 2017 May to 2017 August before reducing to about lower than 2 °C in 2018 January. This observation was consistent with the trend of solar radiation and air temperature as shown in Fig. 3.

The variations in soil temperature at 0.05 m in both bare slope and grassed slope during period of one year is indicated in Fig. 8. There was a higher soil temperature in bare slope from 2017 May to 2017 July. The soil temperatures in two slopes were contracted from December 10th, 2017 to April 3rd, 2018. This phenomenon was happened as the soil temperature and solar radiation are lower than 16 °C and 16 MJ.m⁻².day⁻¹, and 5 °C and 2.7 MJ.m⁻².day⁻¹, respectively. When the air temperature dropped below 0 °C, the soil temperature in bare slope was remained constant at nearly 0 °C. Whereas there was a slightly higher in soil temperature of grassed slope. The reason was also due to grass leaves which provided heat insulation effect. Rui et al. 2018 also presented that the grass leaves has heat insulation property to a certain extent in winter hence the frost depth in grassed slope was lower than bare slope.

3. Effects of grassroot on shear strength behavior of soil

3.1. Test apparatus

In order to study the influence of grass roots on mechanical behaviours of soil, a consolidated drained (CD) compression tests were performed by triaxial test apparatus. Fig. 9 illustrated a schematic diagram of the triaxial apparatus for saturated/unsaturated soil. The monotonic triaxial compression tests were performed using this apparatus by employing axis translation technique along with pressure membrane method. Pore air pressure (u_a) and pore water pressure (u_w) were separated during testing. Pore water pressure was exerted to specimens through a hydrophilic acrylic copolymer membrane filter (Versapor membrane filter, Air Entry Value =110 kPa) which was attached to the water plumbing path. Meanwhile the pore air pressure was applied through a hydrophobic polyflon filter on the top of the specimen. Moreover, triaxial compression test under saturated condition could be performed just by removing the Versapor membrane and the polyflon filter. The axial load was applied through a Direct Drive Motor (DDM). The axial stress (σ_a) was measured by using a load cell installed inside the triaxial cell. While an external displacement transducer was used to determine the axial strain (ε_a). The volumetric strain (ε_v) and the volume of drainage (ΔV_w) were measured through differential pressure transducers attached to pedestal and double tube burette respectively.

3.2 Soil specimen preparation

The PVC mold with an internal diameter of 70 mm and height of 200 mm were used to prepare the soil specimens. The PVC mold was pre-cut along the axial axis and held with tapes and clamps which were later released when the soil specimens were removed for testing. Komaoka soil with volumetric water content of 24.5% was mixed by quartering method (JGS 2009b) to establish the identical soil water content and uniformity in grain-size distribution. Next, the air pluviation method and slight compaction were employed to make Komaoka soil specimen. The soil specimens have the same in-situ porosity and in-situ dry density as presented in Table 1. The soil specimen has 170 cm in high and 70 cm in diameter. After that, the mixture of grass seeds, which used in grassed soil slope as mentioned above, was uniformly germinated on the surface of Komaoka soil specimens. All soil specimens were placed inside growth room with regulated temperature (around 25 °C). In addition, the fluorescent bulbs were used to simulate daylight. The soil specimens were placed on the porous stone for two days for internal drainage when the grasses have grown to a certain age varying from 1 month to 8 months. It was followed by cutting grass shoots carefully before putting soil specimens into refrigerator for 12 hours. The mold was then released after moving out soil specimen from refrigerator. He et al. (2023) reported that no frost heaving or expansion in soil specimens is observed when the soil specimens are taken out from the refrigerator because soil samples have low volumetric water content after inside drainage. After that, soil specimen was accommodated into triaxial test apparatus. The examples of grassed soil specimens and grass roots at grass age of two months are presented in Fig. 10. Two replicates were used for each soil specimen to verify and improve the universality of the test results.

3.3 Test procedures

Monotonic triaxial compression tests were conducted after specimen preparation. At first, each frozen specimen was set into pressure cell under a cell pressure of 20 kPa for unfreezing. It was followed by the consolidation process. Double vacuuming method (Ampadu and Tatsuoka 1993) which extracted the pore air from the top of the specimen by giving a negative air pressure for saturated condition, is employed to saturate soil specimen. Meanwhile de-aired water was supplied from the bottom of the specimen. Next, a back pressure up to 200 kPa was applied to make sure that the B value would excess 0.96. When the soil specimen was fully saturated, the isotropic consolidation would continue in fully drained condition under preset effective confining pressures (σ'_c) of 25 kPa and 49 kPa. Cell pressures (σ_c) of 225 and 249 kPa

respectively and pore water pressure (u_w) of 200 kPa are applied till there were no changes in axial displacement or in drainage volume.

After completing consolidation process, soil specimen was sheared continuously by applying an axial deviator stress (q) under fully drained condition (CD test). The shear velocity for volcanic soil was set to 0.2 %/min (Ishikawa et al. 2009). The shear process was finished as the axial strain (ϵ_a) reached 25%.

3.3 Test results

The relationship between deviator stress (q), volumetric strain (ϵ_v), and axial strain (ϵ_a) of grassed soils with different grass ages during CD test under saturated condition are presented in Fig. 11. BK and GK in this figure denote the bare Komaoka soil and grassed Komaoka soil, respectively. It is followed by the grass age (e.g. GK-1). It can be seen that the peak shear strength of grassed soil is higher than that of bare soil, excepting the grass soil at growing age of 1 month. In addition, there is an increase in peak shear strength of grassed soil with higher grass age. In contrast, volumetric strains in grassed soil is lower than that of bare soil. Grassed soil with higher grass age has lower volumetric strain. The volumetric strains of bare soil experienced an increase (strain hardening) and reach peak at the axial strain of somewhere in the vicinity of 12 % and 15 % under confining stress of 25 kPa and 49 kPa, respectively. After that, the volumetric strains dramatically decrease (strain softening) as the axial strain increase continuously. However, there is a gradually decrease in volumetric strains of grassed soils. It is worth noting that the volumetric strains of grassed soils with lower grass age experience shaper drop after reaching the peak values. than that with higher grass age. The reason for these phenomena is attributed for the effects of grass roots. As the axial strain increases, the friction between roots and soil particles resists the volume expansion. In addition, not only the shear strength of soil but also the tensile strength of roots resists the shear stress due to applying load.

The root volume ratio (R_v) is defined as the volume of roots to the volume of soil specimen (V_r/V). Fig 12a indicated that the root volume ratio is higher as grass age increases. As root volume ratio rises corresponding to an increase in grass age, the friction force between root and soil particles is increased because there is larger contact area between root-soil interface. This results in better mobilization of soil-root surficial interaction. Therefore, the shear stress of grass root significantly increases, whereas the volumetric strain is decrease with the rise in grass age. It is noted that the diameters of grass root might be higher when grass become older (Leung et al. 2018). Several past studies reported that the tensile strength

of root decreases with the increase in root diameter (De Baets et al. 2008, Loades et al. 2010). Therefore, the enhanced shear strength and reduced volumetric strain observed in this study are attributed to the higher root volume ratio. The relationships between peak shear strength with root volume ratio are shown in Fig. 12b.

The average results of shear strengths for both bare soil and grassed soils under confining pressures of 25 kPa and 49 kPa are employed to draw Mohr-Coulomb failure envelopes. Fig. 13a shows that there is a significant increase in effective cohesion (c') of grassed soil with the increase in root volume ratio. The bare soil has effective cohesion of 0.22 kPa which indicates that the volcanic soil is considered as cohesionless soil. The effective internal friction (ϕ') of grassed soil just exhibits a slight increase as root volume ratio increase (Fig. 13b). The effective internal friction of soil with grass age of 8 month is just higher than that of bare soil by around 1.8° (40.7° as compared to 42.5° , respectively). The higher effective cohesion might also contribute to the higher shear stress of grassed soil with higher grass age as mentioned above.

4. Governing equations

4.1 Atmospheric flux balance

The mass balance at the soil surface is expressed as follows:

$$P = I + RO + AE \quad (1)$$

where P (m/day) is the flux of rainfall; I (m/day) is the infiltration rate; RO (m/day) represents the runoff rate on soil surface; AE (m/s) is the actual evaporation rate.

The energy balance at the soil surface is expressed as follows:

$$R_n = G + L + H \quad (2)$$

where R_n ($\text{MJ.m}^{-2}.\text{day}^{-1}$) is the net radiation flux; G ($\text{MJ.m}^{-2}.\text{day}^{-1}$) is the soil heat flux; L ($\text{MJ.m}^{-2}.\text{day}^{-1}$) is the latent heat flux; H ($\text{MJ.m}^{-2}.\text{day}^{-1}$) is the sensible heat flux.

4.2. Coupled non iso-thermal seepage flow

Moisture and vapor flow beneath soil surface is governed by hydraulic head gradients, vapor pressure gradients and temperatures gradients. Moisture flow governing equation is presented as follows:

$$\frac{\partial}{\partial x} \left[(k_x^w + k^{vd}) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[(k_y^w + k^{vd}) \frac{\partial h}{\partial y} - k^{vd} \right] + S_{root} = -\gamma_w m_2^w \frac{\partial h}{\partial t} \quad (3)$$

where h (m) is total hydraulic head; k_x and k_y (m/day) are coefficient of permeability of soil in x - and y - directions, respectively; k^{vd} (m/s) is pore-water vapor conductivity by vapor diffusion within the air phase; S_{root} is actual transpiration sink term (1/day); γ_w is unit weight of water (9.81 kN/m^3); m_2^w is slope of soil-

water characteristic curves.

The pore-water vapor conductivity is computed as follows:

$$k_{vd} = \frac{\beta \theta_a g D_v \omega_v \rho_{sv0} h_r}{\rho_w R (273.15 + T)} \quad (4)$$

where, β is soil tortuosity of a dimensionless factor, θ_a (m^3/m^3) is volumetric air content, g (m/s^2) is gravity acceleration, D_v (m^2/s) is molecular diffusivity of vapor in soil pore air, ω_v (kg/mol) is molecular weight of vapor, ρ_{sv0} is saturated vapor density, h_r is relative humidity, R ($\text{J}/\text{mol}\cdot\text{K}$) is universal gas constant, T ($^{\circ}\text{C}$) is air temperature.

The heat transfer beneath soil surface is mainly governed by thermal conduction. Heat flow governing equation is given as follows:

$$\frac{\partial}{\partial x} \left(\lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_y \frac{\partial T}{\partial y} \right) = (C + L_f m_2^i) \frac{\partial T}{\partial t} \quad (5)$$

where λ_x , λ_y ($\text{J}/\text{m}\cdot\text{day}\cdot^{\circ}\text{C}$) are thermal conductivity of soil in x-, y-directions, respectively; C ($\text{J}/\text{m}^3 \cdot ^{\circ}\text{C}$) is volumetric heat capacity of soil; L_f (J/m^3) is volumetric latent heat of soil; m_2^i ($\text{m}^3/\text{m}^3 \cdot ^{\circ}\text{C}$) is the rate of change in unfrozen water content with temperature (e.g the slope of soil freezing characteristic curve); T ($^{\circ}\text{C}$) is temperature; t (day) is time.

4.3 Net radiation

The net radiation (R_n ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$)). is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl} ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$)).

$$R_n = R_{ns} - R_{nl} \quad (6)$$

The net shortwave radiation is calculated as follows:

$$R_{ns} = (1 - \alpha) R_s \quad (7)$$

where α is a canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop, R_s is the incoming solar radiation ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$).

The net longwave radiation is expressed as follows:

$$R_{nl} = \sigma \left[\frac{T_{\max, K}^4 + T_{\min, K}^4}{2} \right] \left(0.34 - 0.14 \sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \quad (8)$$

where σ is Stefan-Boltzmann constant ($4.903\text{E-}9 \text{ MJ}\cdot\text{K}^{-4}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$); $T_{\max, K}$ and $T_{\min, K}$ (K) are maximum and minimum absolute temperature during 24 hour period; e_a is actual vapor pressure; R_s/R_{so} is relative shortwave

radiation; R_s ($\text{MJ.m}^{-2}.\text{day}^{-1}$) is solar radiation; and R_{so} ($\text{MJ.m}^{-2}.\text{day}^{-1}$) is clear-sky radiation.

$$R_{so} = (0.75 + 2 \cdot 10^{-5} z) R_a \quad (9)$$

where z (m) is the station elevation above sea level.

The extraterrestrial radiation for daily periods (R_a) for each day of the year can be estimated from solar constant:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_s] \quad (10)$$

where G_{sc} is solar constant ($0.082 \text{ MJm}^{-2}\text{min}^{-1}$); d_r is inverse relative distance Earth-Sun; ω_s is sunset hour angle (rad); φ is latitude (rad); δ is solar declination (rad).

The inverse relative distance of Earth-Sun (d_r) and solar declination (δ) are given by:

$$d_r = 1 + 0.033 \cos \left(\frac{2\pi}{365} J \right) \quad (11)$$

$$\delta = 0.409 \sin \left(\frac{2\pi}{365} J - 1.39 \right) \quad (12)$$

where J is the number of the day in the year.

The sunset hour angle can be computed using arctan function:

$$\omega_s = \frac{\pi}{2} - \arctan \left[\frac{-\tan \varphi \tan \delta}{X^{0.5}} \right] \quad (13)$$

$$X = 1 - [\tan \varphi]^2 [\tan \delta]^2 \quad (14)$$

The net radiations for bare slope and grassed slope are computed and shown in Fig. 14. The net radiation in the latter is lower than that in the former. The reason is that the grass leaves partially prevent net radiation from reaching to the soil surface (Blight 2002). This phenomenon results in the lower soil temperature in grassed soil slope as compared to bare soil slope as presented in field measurement result.

4.4 Potential evapotranspiration

The amount of potential evapotranspiration in vegetated soil is calculated based on FAO Penman-Monteith equation (Allen et al. 1998) as follows:

$$PE_g = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (15)$$

where ET_0 is reference evapotranspiration (mm.day^{-1}); R_n is net radiation at the crop surface ($\text{MJ.m}^{-2}.\text{day}^{-2}$),

G is soil heat flux density ($\text{MJ.m}^{-2}.\text{day}^{-2}$); T is mean daily temperature at 2 m height ($^{\circ}\text{C}$); u_2 is wind speed at 2 m height; e_s is saturation vapor pressure (kPa); e_a is actual vapor pressure (kPa); $e_s - e_a$ is saturation vapor pressure deficit (kPa); Δ is slope vapor pressure curve ($\text{kPa.}^{\circ}\text{C}^{-1}$); γ is psychometric constant ($\text{kPa.}^{\circ}\text{C}^{-1}$).

$$e^o(T) = 0.6108 \exp \left[\frac{17.27T}{T + 237.3} \right] \quad (16)$$

where $e^o(T)$ is saturation vapor pressure at the air temperature T (kPa).

$$e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \quad (17)$$

$$e_a = \frac{e^o(T_{\min}) \frac{RH_{\max}}{100} + e^o(T_{\max}) \frac{RH_{\min}}{100}}{2} \quad (18)$$

where e_a is actual vapour pressure (kPa), $e^o(T_{\min})$ is saturation vapor pressure at the air daily minimum temperature $T_{\min}$ (kPa), $e^o(T_{\max})$ is saturation vapour pressure at the air daily maximum temperature $T_{\max}$ (kPa), $RH_{\max}$ is maximum relative humidity (%), $RH_{\min}$ is minimum relative humidity (%).

Potential evaporation from bare soil (PE_b (mm/day)) can be estimated as follow:

$$PE_b = 1.15 PE_g \quad (19)$$

4.5 Actual evaporation

Actual evaporation (AE) accounts for the movement of water from the soil surface to the air. [Fredlund et al. \(2016\)](#) presented an equation to compute a ratio of AE/PE as follows:

$$AE / PE = \exp \left(\frac{-sg\omega_v\delta_{corr}}{\zeta(1-RH)\gamma_w R(T_s + 273.15)} \right) \quad (20)$$

where ζ is a dimensional empirical parameter with a suggested value of 0.7; RH is relative humidity of overlying air; s (kPa) is matric suction; ω_v is molecular weight of water (9.807 kN/m^3); g is gravity acceleration (m/s^2); δ_{corr} is correction factor; R is universal gas constant (8.314 (J/mol.K)); T_s is soil surface temperature ($^{\circ}\text{C}$).

Correction factor (δ_{corr}) is computed as following equation.

$$\delta_{corr} = -\log_{10} s_r + 3.48 \quad (21)$$

where s_r (kPa) is residual soil suction. The maximum correction factor for coarse sand soils is 3.48, whereas no correction is required for clayey soils with a high air-entry value.

4.6 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.

[Ritchie \(1972\)](#) equation is used for the calculation of potential transpiration (PT).

$$PT = PE(-0.21 + 0.7 LAI^{0.5}) \text{ when } 0.1 \leq LAI < 2.7 \quad (22)$$

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.

$$PRU = \frac{RSF \cdot PT}{R_t} \left(1 - \frac{R_n}{R_t} \right) \quad (23)$$

where PRU (m³/day) is potential root uptake rate per unit time; RSF is root distribution shape factor (e.g. triangular); R_t (m) is total thickness of root zone; and R_n (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. This study used the PLF presented by [Garg et al. 2015](#).

Actual transpiration (AT) is calculated by modifying the potential transpiration values when suctions is reduced.

$$AT = (PRU)(PLF) \quad (24)$$

4.7 Shear strength of soil under unsaturated conditions

The shear strength of an unsaturated soil is expressed based on Bishop's effective stress principle by [Vanapalli et al. \(1996\)](#) as given by:

$$\tau = c' + (\sigma_n - \sigma_a) \tan \phi' + (u_a - u_w) [\chi \tan \phi'] \quad (25)$$

where, τ (kPa) is shear strength of soil, σ_n (kPa) is net total stress, u_a (kPa) is pore air pressure, u_w (kPa) is pore water pressure, c' (kPa) is effective cohesion, ϕ' (°) is effective angle of internal friction, and χ is

parameter related to the degree of saturation. According to Vanapalli et al. (1996), the magnitude of parameter χ can be expressed in terms of volumetric water content as,

$$\chi = (\theta_w - \theta_r) / (\theta_s - \theta_r) \quad (26)$$

where, θ_w (m³/m³) is volumetric water content, θ_s (m³/m³) is saturated volumetric water content (m³/m³) and θ_r (m³/m³) is residual volumetric water content.

4.8 Factor of safety

Slope stability has been analysed using limit equilibrium technique based on the method given by Morgenstern and Price (1965). The Morgenstern and Price method is a widely used as slope stability method in general geotechnical engineering practice. The factor of safety equations with respect to moment equilibrium (F_m) and force equilibrium (F_f) considering the unsaturated shear strength of soil are given in Eq. (27) and Eq. (28) respectively. The unsaturated soil shear strength in the factor of safety is considered based on the nonlinear relationship given by Vanapalli et al. (1996) as explained above.

$$FS_m = \frac{\sum [c'lR + \{N - u_w l \chi - u_a l (1 - \chi) R \tan \phi'\}]}{\sum W_x - \sum Nf \pm Dd \pm Aa} \quad (27)$$

$$FS_f = \frac{\sum [c'l \cos \alpha + \{N - u_w l \chi - u_a l (1 - \chi) \tan \phi' \cos \alpha\}]}{\sum N \sin \alpha - \sum D \cos \omega \pm A} \quad (28)$$

where, W (kN/m²) is the total weight of a slice of width b and height h , N (kN) is the total normal force on the base of the slice, D (kN) is an external point load. R (m) is the radius of a circular slip surface, x (m) is the horizontal distance from the centerline of each slice to the center of rotation or to the center of moments, d (m) is the perpendicular distance from a point load to the center of rotation or to the center of moments, f (m) is the perpendicular offset of the normal force from the center of rotation or from the center of moments, a (m) is the perpendicular distance from the resultant external water force to the center of rotation or to the center of moments, A (kN) is the resultant external water forces, ω (°) is the angle of the point load from the horizontal, α (°) is the angle between the tangent to the center of the base of each slice and the horizontal and l (m) is the base length of each slice.

5 Numerical simulation approach

The incoming energy from net radiation is received for heating ground surface and evaporation in bare slope. However, net radiation is partially intercepted by grass leaves and the rest of net radiation reach to heat the soil in grassed slope. As a result, the soil temperature in grassed soil is lower than bare soil. The

grass roots have the effects on hydraulic properties of soil. [Ni et al. 2019](#), [Nguyen et al. 2020](#) presented that the grassed soil has higher capacity to retain matric suction than the bare soil. Whereas the coefficient of permeability of the former is lower than that of the latter since soil pores are clogged by grassroots. Furthermore, the grass roots reinforce the shear strength of soil by increasing the effective cohesion and slight increase in effective angel of internal fraction as discussed above.

From above-mentioned contexts, this study recommends an approach to simulate the soil water content/matric suction and soil temperature of grassed unsaturated soil slope ([Fig. 15](#)). The non-isothermal seepage simulation is to predict a soil water content/matric suction and soil temperature distributions inside grassed soil slope under climate variations. The net radiation is computed and it is followed by the calculations of PE , AE , PT , and AT . Next, the difference in soil hydraulic function (SWCC and coefficient of permeability) between bare soil and grassed soil are considered. Mass balance and energy balance are used to obtain soil water content distribution and soil temperature distribution, respectively.

After conducting seepage analysis, a traditional limit equilibrium technique based on the [Morgenstern and Price \(1965\)](#) method is used to compute the factor of safety (FOS) in the slope stability analysis. The reinforced shear strength of soil due to grass roots is properly considered and will be discussed in a later section. The proposed numerical simulations are performed using a finite element code, namely: SVOFFICE 2009TM ([SoilVison Systems Ltd, Saskatoon, Saskatchewan, Canada](#)). SVFlux and SVHeat modules of SVOFFICE 2009TM are used to perform nonisothermal coupled seepage flow. It is followed by employing SVSlope module to carry out the slope stability analyses.

6. Numerical simulation of Komaoka soil slopes

6.1 Model geometry and analytical conditions

The geometry and boundary conditions of two slopes for numerical simulation are demonstrated in [Fig. 16](#). Two-dimensional model of the slope has a total height of 8 m and a length of 18 m. The coupled nonisothermal-seepage analyses were performed for both bare slope and grassed slope. Three stages of analyses conducted for each soil slope. Firstly, the steady-state analysis was 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 were assumed to be 10 °C and 5 °C. These values of temperature were equal to the average air temperature and estimated soil temperature at the bottom of the slope on 11 May 2012. After that, a transient analysis was performed to set the soil water content/matric suction and soil temperature distributions into

soil slopes in second stage. 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 was applied on the slope surface. Impermeable and adiabatic boundaries were set for two lateral sides, while a bottom of the model was assigned as ‘unit gradient’. In this case, the downward flux was equal to the coefficient of permeability at the points in the bottom edge. In other words, the boundary downward flux was 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 meteorological station in cut-slopes during 11 May 2017 to 11 September 2017 as presented in Fig. 3 was applied in the third stage. The bottom of the model was applied temperature (T_z) implemented from Andersland and Ladanyi (2004) equation as follows.

$$T_z = T_m + A \cdot \exp\left(-z \sqrt{\frac{\pi}{\alpha_u p}}\right) \cdot \sin\left(\frac{2\pi t}{p} - z \sqrt{\frac{\pi}{\alpha_u p}}\right) \quad (29)$$

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; α_u (4.89 E-7 W/m² °C) is thermal diffusivity.

6.2 Soil and grass parameters

6.2.1 Soil hydraulic properties

Nguyen et al. 2020 conducted experimental study to investigate the effects of root volume ratio on hydraulic properties of Komaoka soil. The saturated coefficients of permeability of grassed soil at different grass ages were measured by permeability test apparatus. Soil specimen with diameter of 100 mm, length of 120 mm are used. In addition, the hydraulic gradient (i) of 2.5 is applied when the permeability test is carried out. Whereas SWCCs and unsaturated coefficients of permeability were determined by column test apparatus. The soil types, soil properties, and grass species were identical to this study. Therefore, the saturated coefficient of permeability of bare soil measured from permeability test was employed in this simulation. In order to determine the hydraulic properties of grassed soil, R_v was measured from sampling at grassed slope. It can be seen from Fig. 17a that R_v slightly increased from 2.98E-3 (May 11st, 2017) to 4.23E-3 (December 11st, 2017). The saturated coefficients of permeability of grassed soils were interpolated based on relationship of R_v and k_s (Nguyen et al. 2020) as presented in Fig. 17b. In Fig. 17, GF and BF were referred to grassed slope and bare slope, respectively. It is followed by the measured date. It can be seen that the saturated

coefficients of permeability of the grassed soil were lower than bare soil. In addition, saturated coefficient of grassed soil was slightly decreased against time. It is corresponding to the rise in R_v of grassed soil. Since the R_v was increased, more soil pores were occupied by grass roots and hence the flow channels were more clogged.

To verify the applicability of measured results obtained from the laboratory test, the saturated coefficients of permeability of bare soil were determined by conducting constant head infiltration apparatus in field (JGS 2017) as shown in Fig. 18. The measurements were carried out at the top of soil slopes in two different days (July 11st 2019 and December 24th 2019). The constant head infiltration apparatus has 0.5 m height and 0.2 m internal diameter. After preparing the ground for execution, the infiltration cylinder was inserted to a depth of 0.03 m below the soil surface. Infiltration was initialed with a constant head applied to the soil surface. Once the infiltration started, infiltration flow rate was recored along with time. The saturated coefficient of permeability (k_{fs} (m/day)) are computed as follows:

$$k_{fs} = \frac{\alpha G Q_s}{r_0 \alpha h + r_0 + G \alpha \pi r_0^2} \quad (30)$$

where Q_s is steady state infiltration flow rate (m^3/s); h (m) is infiltration head (water depth in test hole); r_0 (m) is radius of test hole; α (= 12) is soil texture/structure parameter set according to the type of soil. G is shape factor that is determined by the following equation for a test hole of radius r_0 (m) and penetration depth d (m).

$$G = 0.316(d / r_0) + 0.184 \quad (31)$$

The results of saturated coefficient of permeability of bare soil measured in filed were plotted in Fig. 17b. It can be seen that saturated coefficient of permeability measured in the filed agreed well with that in laboratory.

The SWCC and unsaturated coefficient of permeability of grassed soil are estimated by models proposed by Nguyen et al. (2020), which is based on the Van Genuchten (1980) models. In Nguyen et al. (2020) models, the SWCC of grassed soil is estimated based on SWCC of bare soil and measured R_v . After that, the unsaturated coefficient of permeability is estimated based on SWCC and saturated coefficient of permeability of grassed soil. The models to compute SWCC and unsaturated coefficient of permeability of grassed soil are presented in Eqs. 33 and 34, respectively. The average values of saturated coefficient of permeability and R_v of grassed soil were employed for estimations. The estimated parameters are summarized

in Table 3. The differences in the hydraulic properties of these soils are illustrated in Fig. 19. It can be seen clearly that the grassed soil retains higher water content at a given matric suction compared to bare soil. Furthermore, air entry value (AEV) of the former is around 7 kPa, while there is lower AEV in the latter (3.7 kPa). In contrast, the grassed soil also has a lower coefficient of permeability than the bare soil. It is noted that there is hysteresis of SWCC and coefficient of permeability of unsaturated soil (Zhai et al 2020, Ng. et al 2022). However, this study simply employed the SWCC and coefficient of permeability obtained from drying curve to avoid the complexity in simulation. Past studies (Shao et al, 2018; Ni et al 2019) shown that using drying curves of hydraulic conductivity function is feasible to performing seepage analysis for unsaturated soil.

The void ratio of vegetated soil is calculated as the following equation.

$$e' = \frac{e_0 - R_v(1 + e_0)}{1 + R_v(1 + e_0)} \quad (32)$$

where e_0 and e' (dimensionless) are void ratio of bare soil and grassed soil, respectively; R_v (m^3/m^3) is the root volume ratio.

In order to consider the effects of active grass roots on hydraulic properties of soils, the SWCC and unsaturated coefficients of permeability of grassed soil is computed as following Eqs. 33 and 34, respectively.

$$S_r = \left[1 + \left(\frac{se'^{m_4}}{m_3 \exp(\kappa' R_v)} \right)^{m_2} \right]^{-m_1} \quad (33)$$

where S_r is the degree of saturation of soil; m_1 (dimensionless), m_2 (dimensionless), m_3 (kPa), m_4 (dimensionless) are the model parameters. m_1 and m_2 control the shape of the SWCC, while m_3 and m_4 are related to the air-entry value (AEV). Considering that the void ratio has neglectable effects on SWCC at high matric suction range, the product $m_1 m_2 m_4$ can be set to 1 (Gallipoli, 2012).

$$\frac{k(s)}{k_s} = \left[\frac{\left\{ 1 - (a \exp(\kappa' R_v) s)^{nm} \left[1 + (a \exp(\kappa' R_v) s)^n \right]^{-m} \right\}^2}{\left[1 + (a \exp(\kappa' R_v) s)^n \right]^{m/2}} \right] \quad (34)$$

where $k(s)$ (m/day) is the unsaturated coefficient of permeability of soil; k_s (m/day) is saturated coefficient of permeability; n and m are material parameters ($m = 1 - 1/n$).

6.2.2 Thermal properties

Improved Johansen – Lu et al (2007) model as shown in Eq.35 is used for the estimation of thermal

conductivity of soil.

$$\lambda = (\lambda_{sat} - \lambda_{dry}) \lambda_e + \lambda_{dry} \quad (35)$$

where λ , λ_{sat} , λ_{dry} (J/day.m.°C) are the thermal conductivities of soil, saturated soil, and dry soil, respectively;

λ_e is the Kersten number, which is related to degree of saturation.

$$\lambda_{sat} = (\lambda_s)^{1-n} (\lambda_w)^n; \lambda_{dry} = -0.56n + 0.51; \lambda_e = \exp \left\{ \alpha \left[1 - S_r^{(\alpha-\beta)} \right] \right\} \quad (36)$$

where λ_s , λ_w (J/day.m.°C) are thermal conductivity of soil particle and water, respectively; n is porosity of

soil; α (0.728) is parameter related to soil texture; β (1.165) is shape parameter.

Volumetric heat capacity of soil is estimated by [Jame \(1977\)](#) and [Newman \(1995\)](#) model as presented in [Eq.37](#).

$$C = \gamma_d (c_s + c_w w_u) \quad (37)$$

where C (J/m³.°C) is volumetric heat capacity; C_s and C_w (J/m³.°C) are mass specific heat of solid soils and unfrozen water, respectively.

The results of estimated thermal conductivity and volumetric heat capacity of Komaoka soil is presented in [Fig. 20](#).

6.2.3 Grass parameters

LAI and R_t of grass were measured each month from 2017 May to December and were illustrated in [Fig. 21](#). LAI increased from around 1.35 (May 2017) to 2.5 (July 2017) before remaining constant at this value until middle of December, whereas the R_t is slightly increased from 0.57 m to 0.68 m over 4 months. It is noted that the whole result of measured LAI and the average value of R_t (0.63) were assigned in the simulation of grassed slope.

6.2.4 Mechanical properties

Unsaturated shear strength of both bare soil and grassed soil were estimated using saturated shear strength properties by [Vanapali \(1996\)](#) model as shown in [Eqs. 25, 26](#). The estimated results of unsaturated shear strength are presented in [Fig. 22](#). Starting at 0.22 kPa and 2.95 kPa, the unsaturated shear strength of two soils were increased with the rise in matric suction. The gap between two curves was greater at higher matric suction. After reaching around 30 kPa for bare soil and 70 kPa for grassed soil, these values decreased rapidly to the initial value which was equal to effective cohesion (c') at unsaturated condition.

6.3 Numerical results

6.3.1 Volumetric water content

The results of volumetric water content at 0.05 m and 0.35 m depths derived from the numerical simulation and field measurement are selected to be presented in Fig. 23. Volumetric water content of grassed soil is lower compared to that of bare soil. Furthermore, the volumetric water content in the latter is far fluctuated against rainfall infiltration as compared to the former. This is caused by the lower coefficient of permeability as shown in Fig. 19b. The numerical simulation captures well the variations in volumetric water content of soil against the climatic variations.

6.3.2 Matric suction

The comparisons of matric suction at 0.25 m depths between the numerical simulation and field measurement are illustrated in Fig. 24. Matric suction of grassed soil doubled as compared to bare soil. This is corresponding to the results of volumetric water content as presented in Fig. 23. The close similarity is observed between numerical simulations and field measurement.

6.3.3 Soil temperature

Fig. 25 presents the comparisons in soil temperature between field measurement and numerical simulation for both bare and grassed slopes. The soil temperature at 0.05 m depth more fluctuates because it is significantly affected by the variation of air temperature and net radiation. The numerical simulation can reasonably reproduce the changes in soil temperature of both two soil slopes by considering the effect of grass leaves on reducing the net radiation hence decrease the soil heat on soil surface. This simulation shows that the influence of grass leaves causes the lower soil temperature in grassed soil.

6.3.4 Factor of safety

A comparison in FOS of bare slope and grassed slope derived from slope stability analysis are illustrated in Fig. 26. FOS of the former slightly fluctuates at somewhere in the vicinity of 2.15 over four-month period. Whereas the FOS of the latter is higher than the former by around 20 %. The higher value of FOS of grassed slope is attributed to the higher in matric suction as presented in Fig. 24. Furthermore, the higher shear strength of soil due to reinforcement of grass roots is also contributed.

Fig. 27 presents the example of slip failure and FOS of grassed slope computed in 1858 day of numerical simulation. Since this numerical simulation started from May 11st, 2012, day 1858 is corresponding to June 11st, 2017. A maximum depth of slip surface in grassed slope is greater than bare slope (1.2 m and 1.0 m,

respectively). These values are nearly two times as higher as the total thickness of grass root zone (R_r) (0.63 m). In addition, it is clearly seen that there were also the differences in length and volume of slip failure. As have mentioned above, the grassed soil has higher matric suction and shear strength. As a result, the shallow landslide-prone areas are resisted.

7. Conclusions

Several findings are drawn in this study as follows:

- The field measurement shown that matric suction in grassed soil is higher than bare soil. The reason is the differences in soil hydraulic properties (SWCC and coefficient of permeability). Another attributable reason is the transpiration due to soil-plant-atmosphere interaction. It is corresponding to the lower volumetric water contents in grassed slope as compared to the bare slope. Furthermore, the volumetric water content in the grassed slope is less fluctuated against rainfall infiltration than in bare slope, especially when the snow melt occurs.

- The gap of matric suction between grassed slope and bare slope is greater in winter with the existence of snow cover. It might be because more exudates are released by grass roots.

- In warm season, lower soil temperature is observed in grassed slope. The reason is that the grass leaves intercept net radiation by shading the ground surface. In contrast, the higher soil temperature in the bare slope is observed in winter due to the insulation of grass leaves.

- The experimental results from CD tests reveal that shear strength of root permeated soil is enhanced. There is an increase in effective cohesion (c'), effective angel of internal fraction (ϕ'), and peak shear strength (Q_{max}) with the increase in R_v . In addition, a rise in R_v results in a decrease in volume strain.

- The good agreement between field measurements and numerical simulation results present that the recommended numerical approach considering the changes in hydraulic properties (e.g. SWCC and coefficients of permeability of grassed soil), grass parameters (e.g. plant limiting factor, LAI , and R_r) is useful to accurately simulate the variations in volumetric water content and soil temperature against the climate variations for a long-term period.

- The slope stability analysis proves that the grass root resists the shallow landslide-prone area by minimizing the infiltration, enhancing matric suction due to modifications of soil hydraulic properties and transpiration process, and increasing shear strength of soil.

It should be noted that this research conducted the consolidated drained test by employing triaxial test

apparatus to investigate the mechanical behaviours of rooted soil in saturated condition. The effect of grass roots on angle indicating the rate of increase in shear strength with respect to a change in matric suction (ϕ^b) in unsaturated shear strength should be furthered examined. The enhanced matric suction due to exudates released by the grass roots in winter season should be further investigated.

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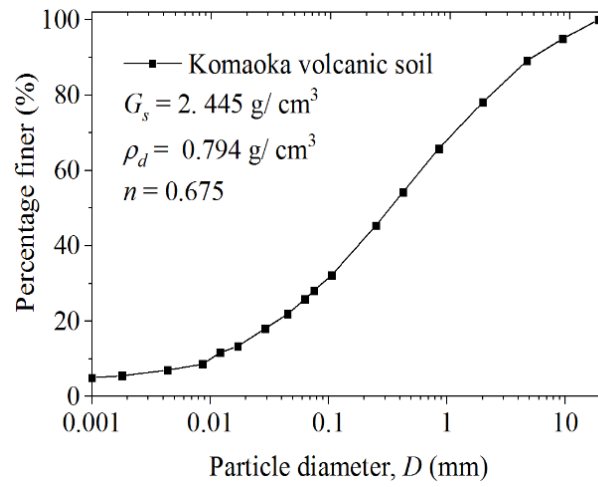


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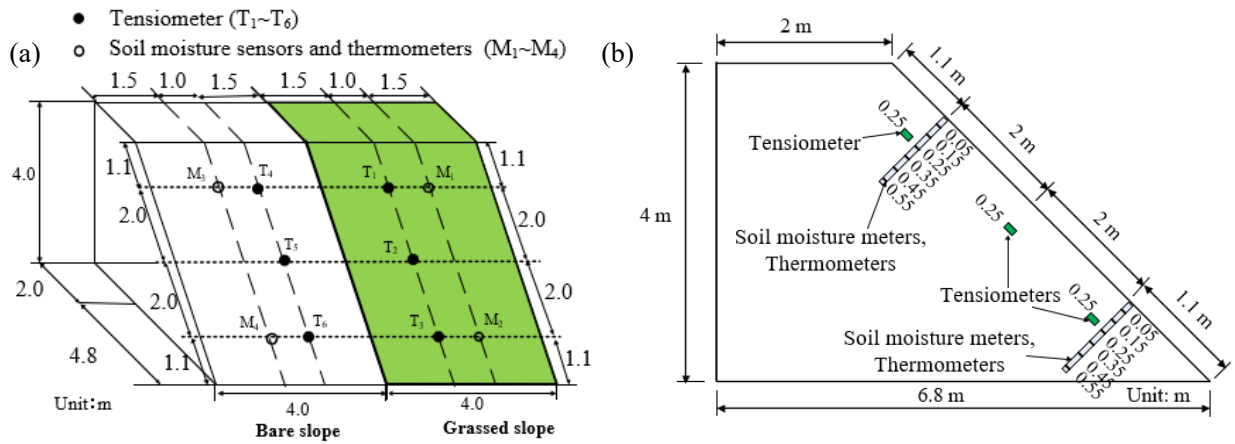


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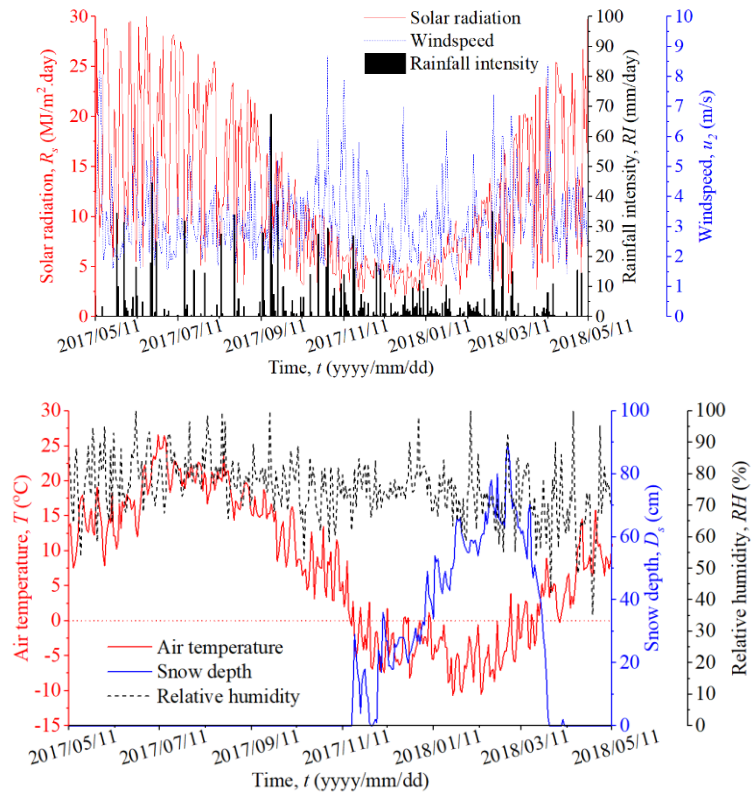


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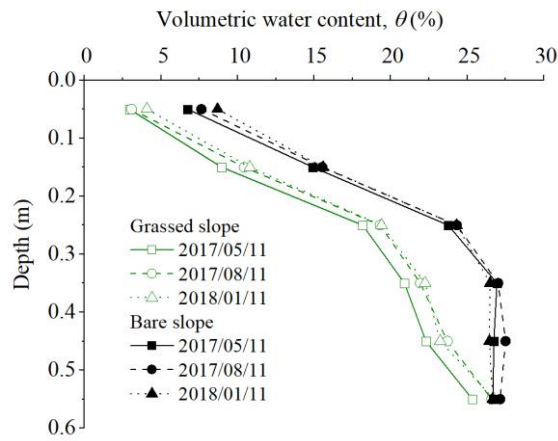


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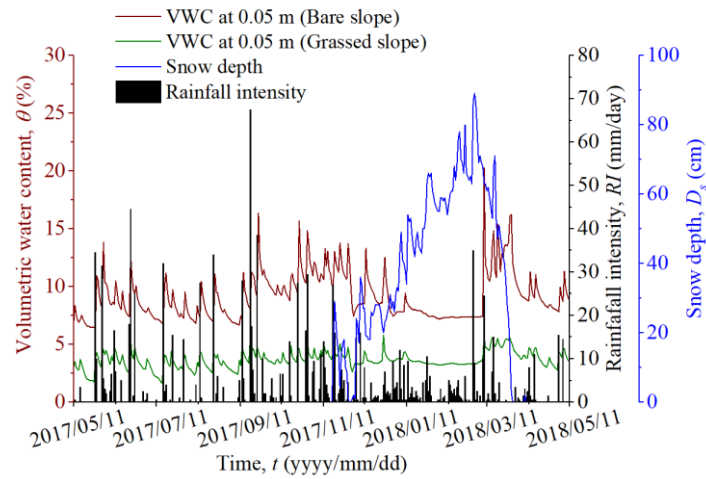


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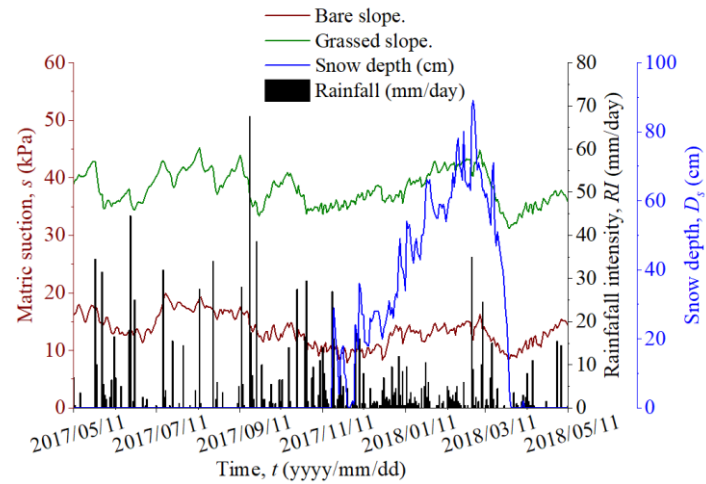


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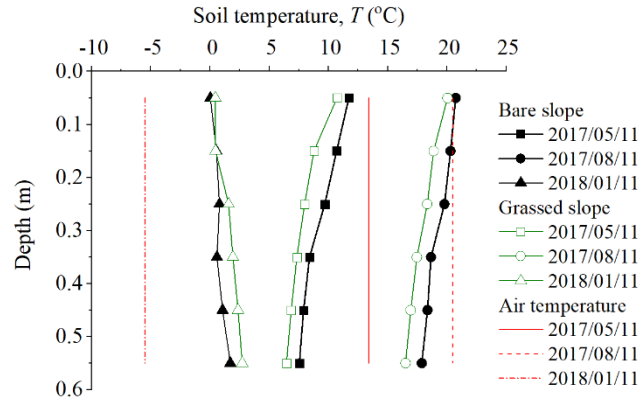


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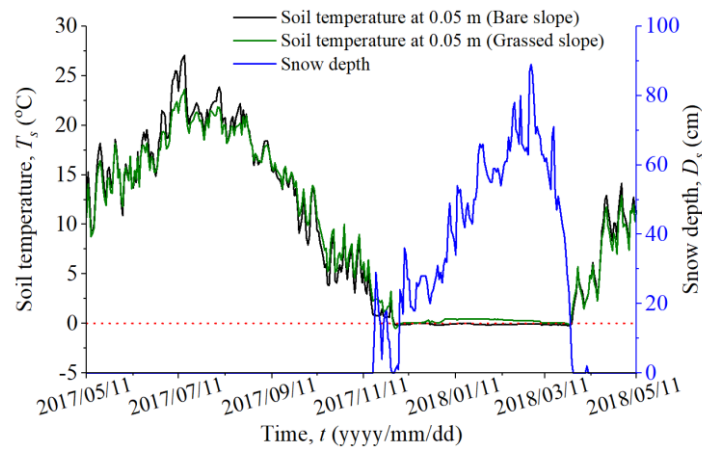


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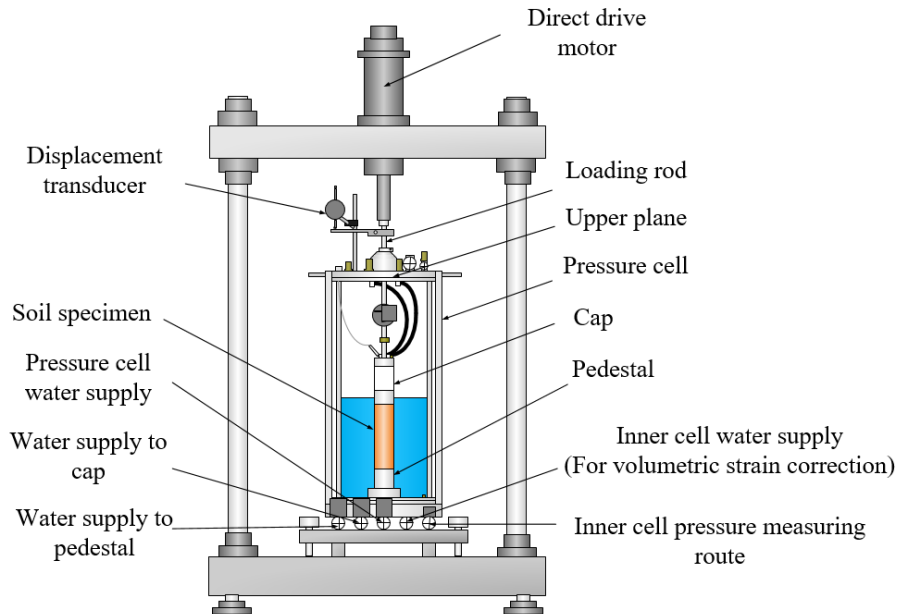


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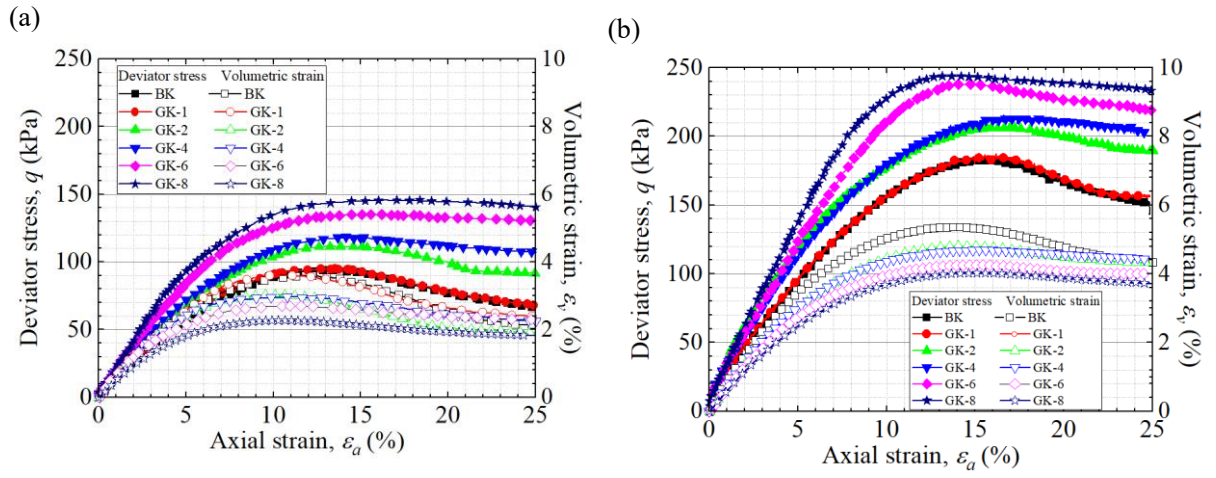


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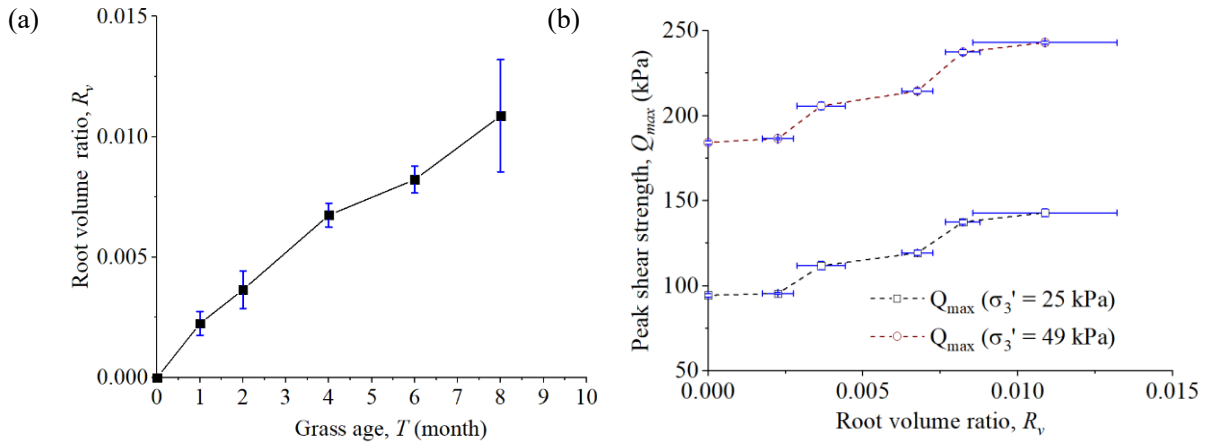


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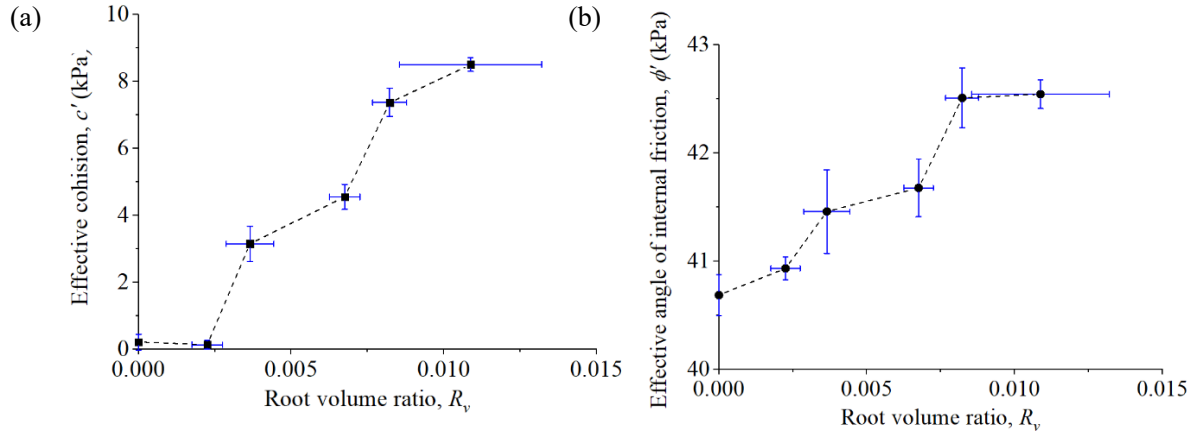


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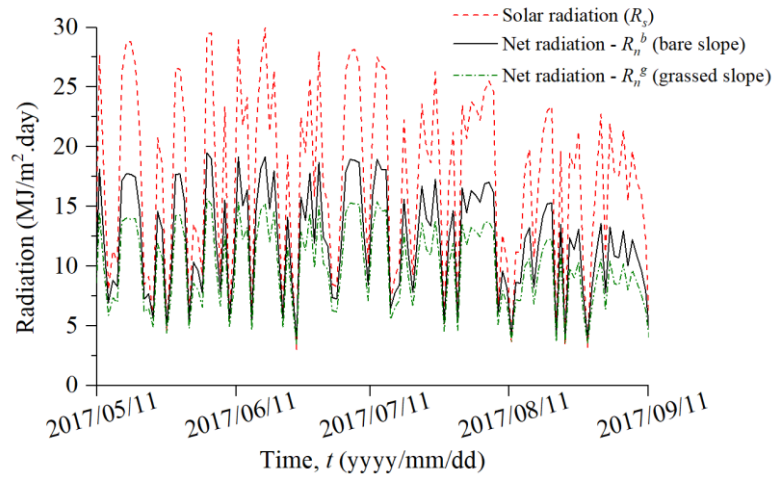


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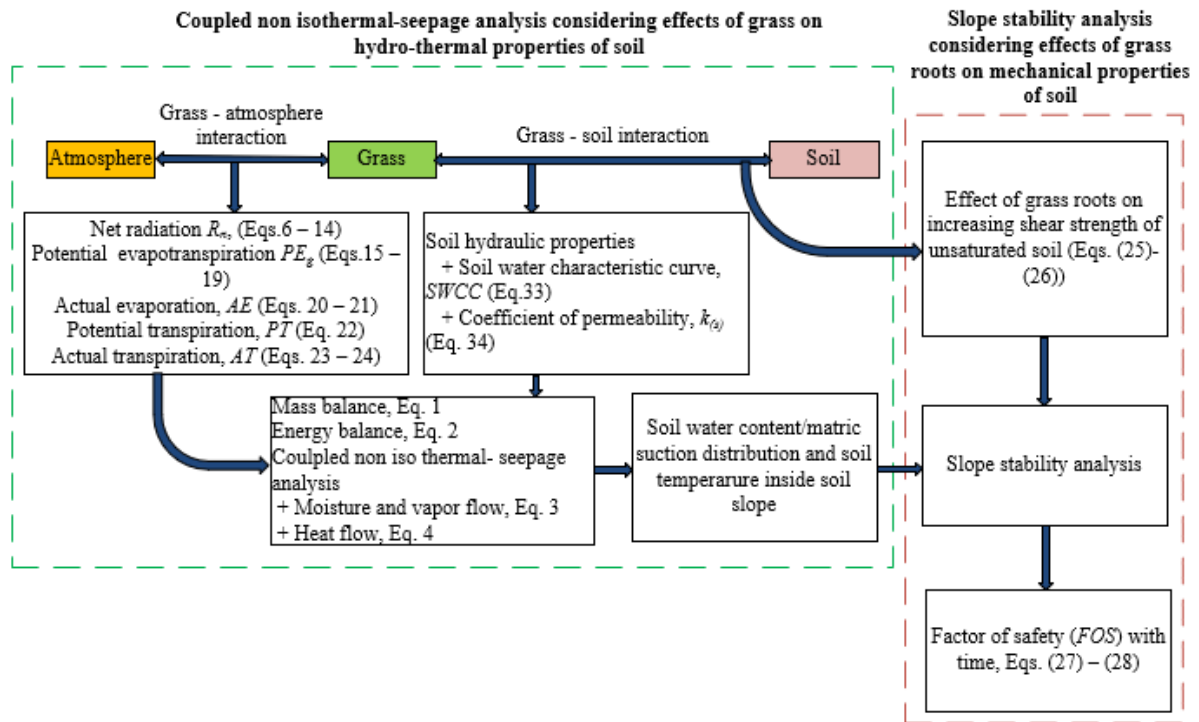


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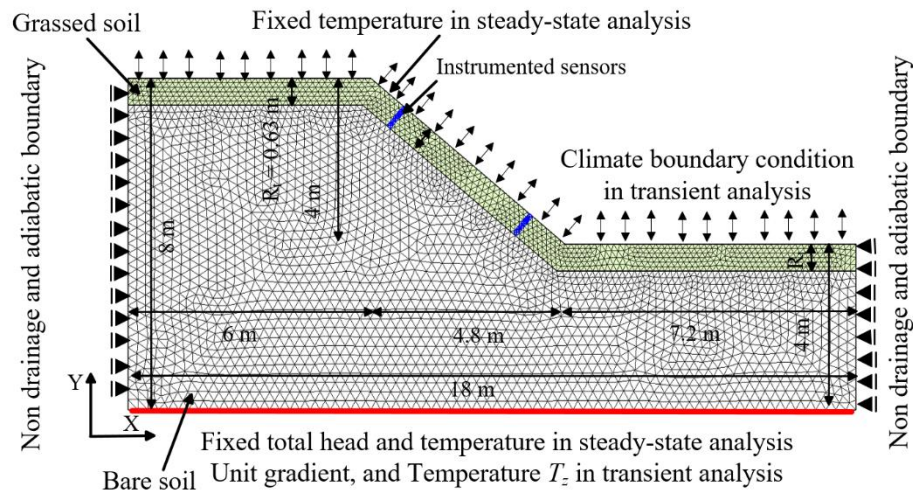


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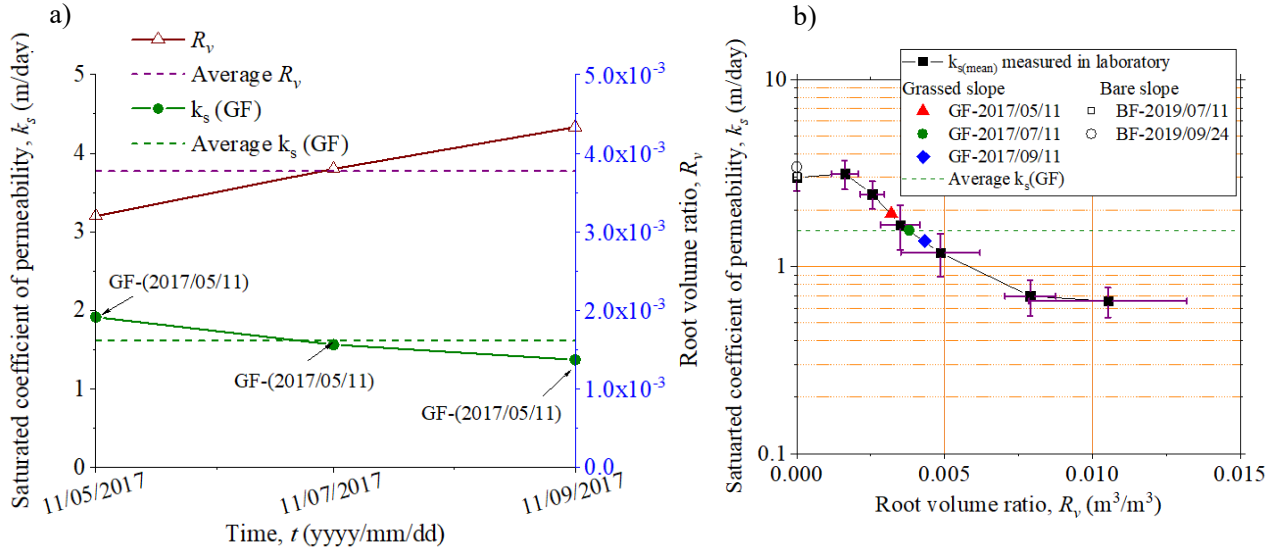


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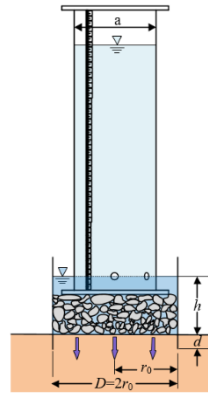


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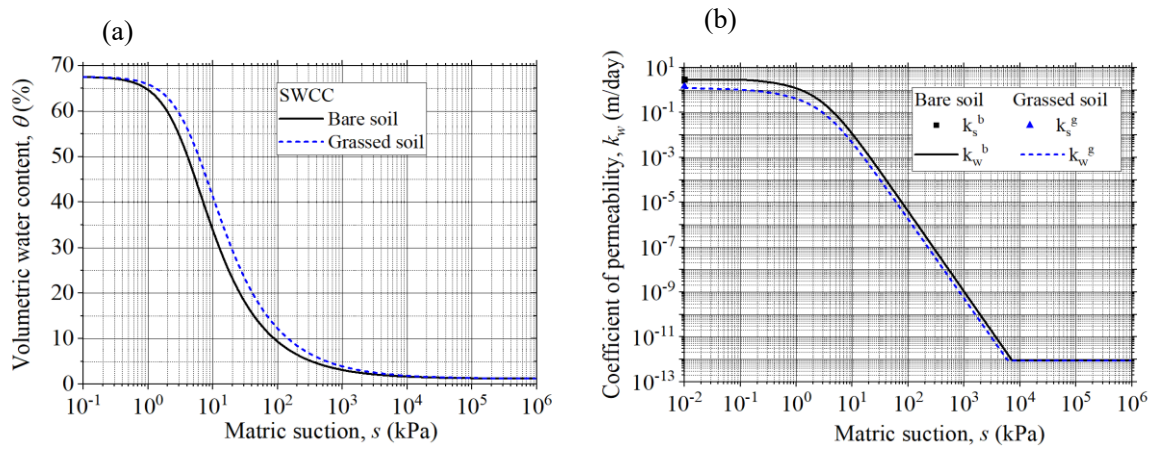


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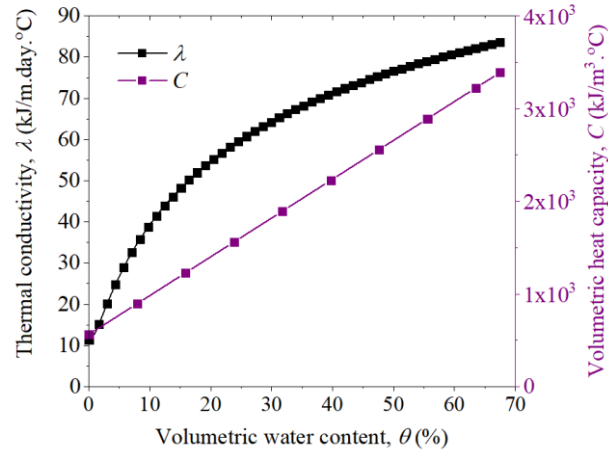


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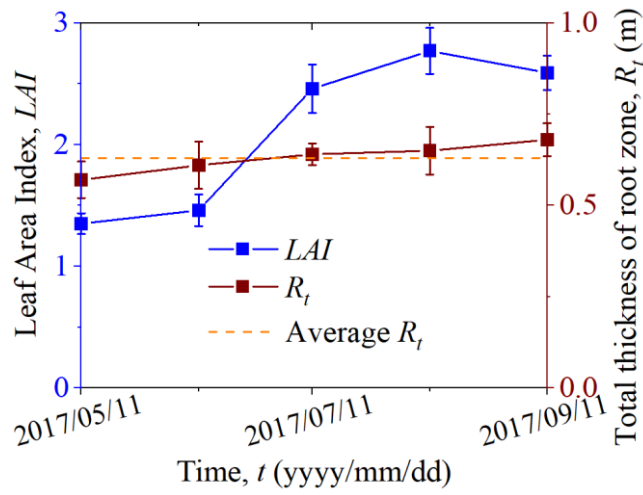


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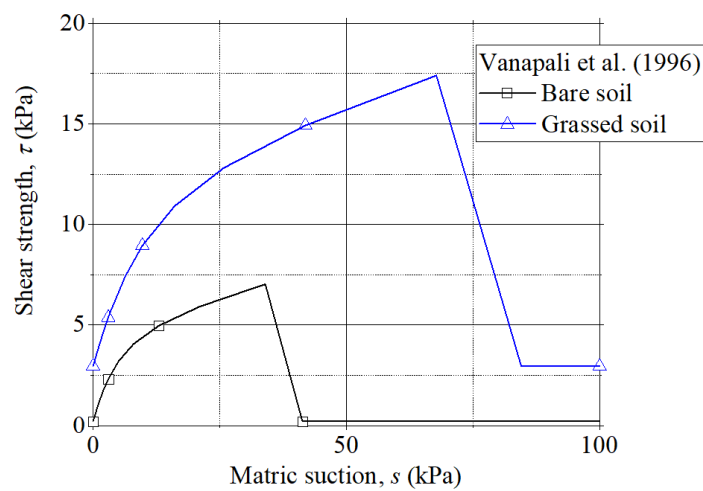


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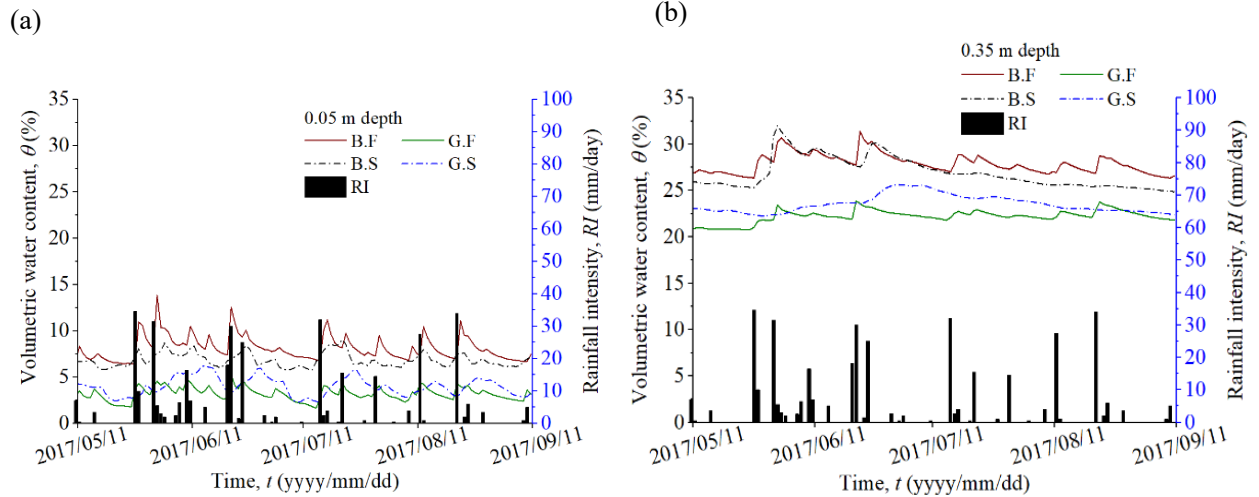


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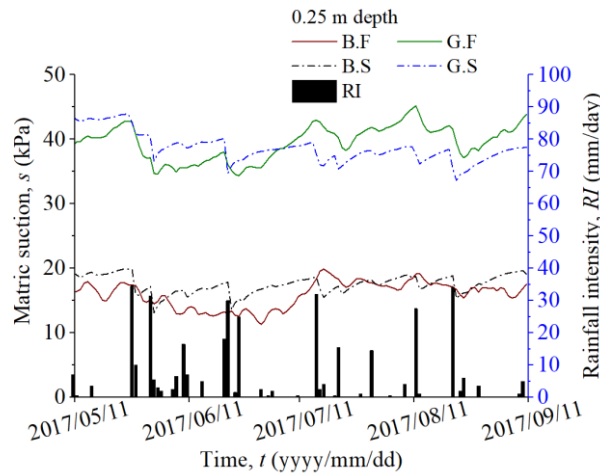


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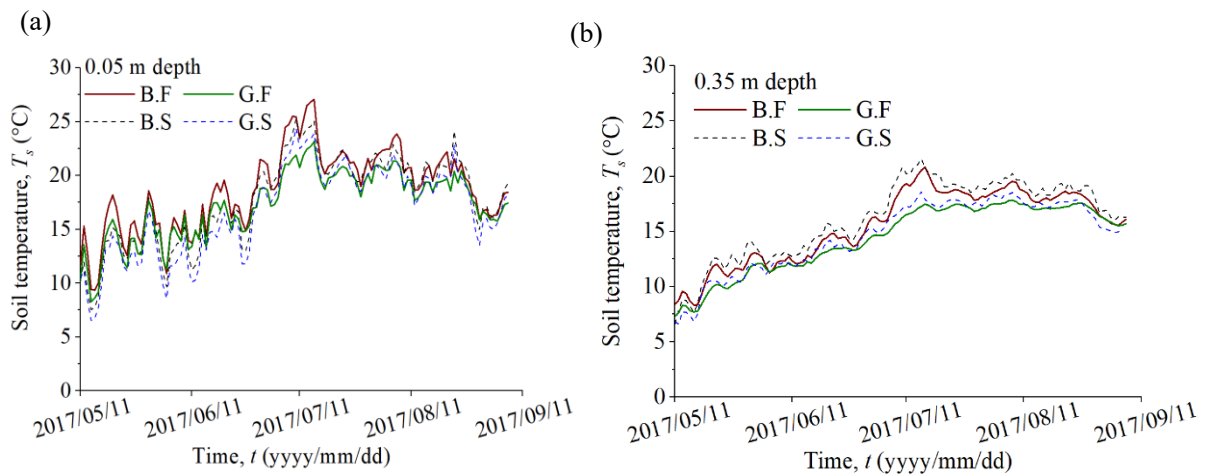


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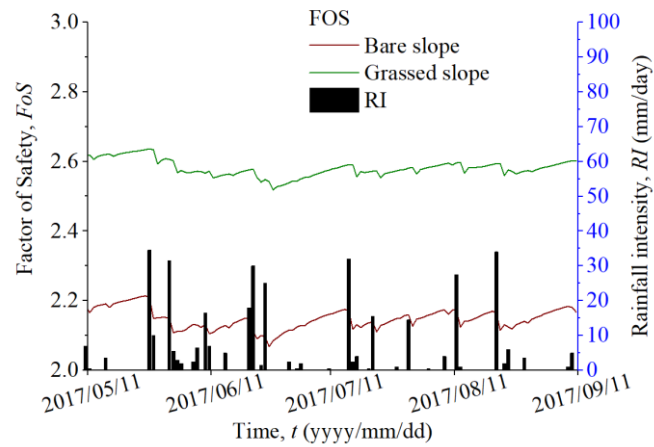


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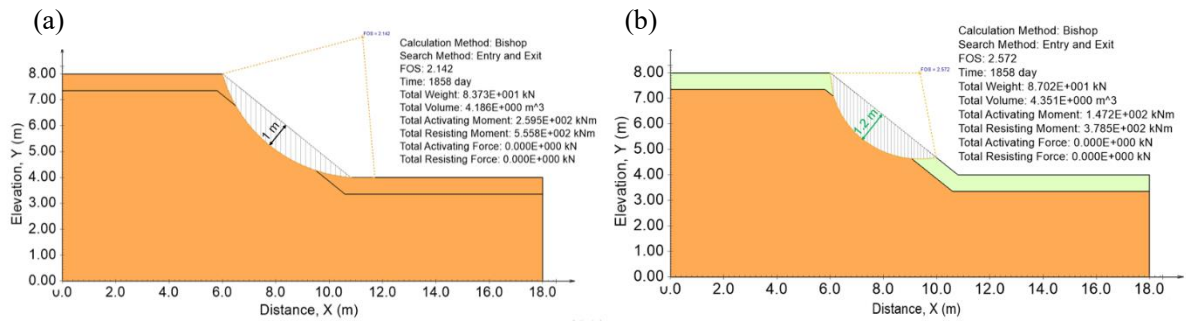


Fig.27 Example of slip surfaces of (a) bare slope, and (b) grassed slope.

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Table 1 Basic properties of Komaoka soil

Properties	Komaoka soil
Specific gravity, G_s	2.445
In-situ dry density, ρ_d (g/cm ³)	0.794
Maximum dry density, $\rho_{d\ max}$ (g/cm ³)	1.12
Minimum dry density, $\rho_{d\ min}$ (g/cm ³)	0.76
In-situ porosity, n	0.675
Mean grain size, D_{50} (mm)	0.27
Coefficient of uniformity, U_c	3.6
Fines content, F_c (%)	26.0

Table 2 Basic properties of a mixture of grass seeds (kg/100 m²).

Grass seeds	Kentucky Bluegrass	Creeping Red Fescue	Tall Fescue
Weight of grass seeds (kg)	0.2	0.4	1.2

877 **Table 3** Soil parameters used in simulations.

Descriptions	Bare soil	Grassed soil
Saturated coefficient of permeability, k_s (m/day)	2.99	1.62
m_1	0.355	--
m_2	1.672	--
m_3	11.787	--
m_4	1.686	--
a	0.27	0.14
m	1.63	0.39
n	1.63	0.39
c' (kPa)	0.22	2.95
ϕ' ($^{\circ}$)	40.7	41.4

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