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Temporal changes of soil temperature with soil water content in an embankment slope during controlled artificial rainfall experiments

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A B S T R A C T

Monitoring of soil water behavior is crucial for the prediction of disastrous slope failures. To improve the ability of engineers to detect temporal changes in soil water content on a slope, we investigated whether or not soil temperatures, which are relatively easy to obtain, could be used as indicators of changes in the soil water content. In order to evaluate the relationship between changes in soil temperature and soil water content, the soil temperature and volumetric water content in a slope on an embankment were measured during controlled rainfall experiments using a large-scale rainfall simulator at the National Research Institute for Earth Science and Disaster Prevention in Japan. Soil temperature was measured with highly accurate sensors at depths of 0, 0.2, 0.4, 0.6, and 0.8 m at four sites on the slope. Volumetric water content was measured at depths of 0.2 and 0.5 m at two sites. The results showed that for many sampling sites the soil temperature increased with the volumetric water content once the rainfall began. Three types of soil temperature behavior were observed: 1) a steep rise, 2) a gradual rise, and 3) a negligible change. The relationship between the elapsed time from the start of rainfall to the start of soil temperature rise and volumetric water content rise implies that soil temperature monitoring using high-resolution sensors is a viable way to detect general volumetric water content behavior due to rainfall infiltration during various rainfall events. These results also indicate that soil temperature monitoring has the potential to improve the understanding of soil water behavior in a slope, which is dependent on rainwater infiltration.

1. Introduction

Heavy rainfall is one of the most common causes of landslides and debris flows. Sassa et al. (2009) analyzed 102 studies presented in "Landslides," which is an international journal, from 2005 to 2009 and reported that more than half of the studies that investigated the causes of landslides found that they were triggered by rainfall. Caine (1980) proposed a global rainfall intensity–duration (ID) threshold for the occurrence of shallow landslides and debris flows using the duration and intensity data on 73 rainfall events. Guzzetti et al. (2008) updated the work of Caine (1980) using 2626 rainfall events and established a new global rainfall ID threshold. Ponziani et al. (2012) investigated the relationships between rainfall thresholds and soil moisture, which were estimated based on the actual landslide events for hydrogeological risk prevention efforts. Brocca et al. (2012) investigated that the correlation between a rainfall, soil moisture and landslide movement by using recorded movements of a rock slope and applied satellite data as soil moisture indicators. This study indicated the potential use of satellite-derived soil moisture information for the prevention of landslides. The rainwater infiltration process depends on the distributions of soil moisture and soil suction. Slope failures tend to occur because of heavy rainfall, which increases soil moisture and helps to reduce the soil suction stress on a slope (e.g., Lu and Likos, 2006; Yeh et al., 2008). Despite earlier studies, the relationship between rainfall and the occurrence of shallow landslides is still not sufficiently clear. Techniques for predicting and monitoring soil water movement are required worldwide for the prevention of slope disasters such as slope failures, landslides, and debris flows.

Geophysical exploration techniques offer an effective way to monitor the soil moisture in a slope (e.g., Komata, 2005; Suzuki and Higashi, 2001). Bichler et al. (2004) investigated the ground under landslides through geophysical exploration techniques involving the use of electrical resistivity data as well as the reflection and refraction of seismic waves. There have also been many studies that monitored soil moisture using various sensors buried in the subsurface. To determine an early warning method for landslides, Chae and Kim (2012) performed real-time monitoring of rainfall and the volumetric water content gradient for soil on natural terrain in Korea. Corominas et al. (2005) evaluated the Vallcebre landslide in Spain, where the rainfall, groundwater levels, and ground displacement at the site have been monitored since 1996. Landslide displacements and velocities were predicted by solving the momentum equation with a viscous term. The study found good agreement between the computed and observed

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displacements, and the results suggest that predictions of displacement from changes in groundwater levels are feasible. Bittelli et al. (2012) tested the slope stability model of Lu and Godt (2008) for clay soils by using the observational results from a field monitoring survey. Their measurements of soil water content and matric suction proved fundamental to the slope stability analysis. Thus, measurement and monitoring of soil water content are regarded as vital for predicting and understanding landslides and slope failures. However, accurate predictions of slope failures using soil moisture monitoring are still difficult to achieve. Moreover, to predict the exact position of a slope failure, slope measurements over a wide spatial scale are required; this is because shallow landslides and slope failures often occur in unspecified areas (Kato, 2010). Improved spatial and temporal accuracy of soil moisture sensing data may contribute to the prevention of slope failures.

Many previous studies have conducted sensing and measurements of the spatial and temporal soil moisture distribution and behavior in shallow surfaces. A recent special issue of "The Journal of Hydrology" focuses on the determination of soil moisture at different spatial scales (Corradini, 2014). In regard to the measurement techniques, Dobriyal et al. (2012) reviews the various soil moisture methods in detail and discusses the advantages and disadvantages of each method. Remote sensing can be used to estimate soil moisture over large areas, but the results are less accurate and expensive. Moreover, field-based methods such as time domain reflectometry, the capacitance sensor method, and so on have limited spatial application and can also be expensive. Ojha et al. (2014) also pointed out that field-based measurements are expensive, time consuming, and only provide information at a few select points, and they went on to develop reference scaling curves in order to assist in the generation of surface soil moisture for any unmeasured location. For accurate estimation of the spatial soil moisture distribution, improvements in previous methods, the development of new methods, and the combined use of multiple methods would be beneficial.

Soil temperature measurements can serve as potential indicators of hydrological conditions. Wierenga et al. (1970) investigated soil temperature changes due to irrigation by warm or cold water. In order to clarify the effects of infiltrating meltwater on soil temperature, Taniguchi and Kayane (1986) performed numerical simulations of thermal and hydrological conditions during the snowmelt season in Nagaoka, Japan. Temperature changes due to rainwater infiltration have been studied over short periods in both the field and the laboratory. Onderka et al. (2013) calculated seepage velocity in a stream by a new processing technique that involved analyzing the temperature record measured in the streambed sediments by using wavelet analysis. Rutten et al. (2010) carried out soil temperature measurements and analyses to investigate the potential for using the distributed soil temperature and moisture observation data to quantify the spatial and temporal water and energy fluxes. In their study, they found that these measurements are useful for obtaining quantitative information on the energy balance at the shallow subsurface. Tyler et al. (2009) noted that Raman spectra distributed temperature sensing by fiber-optic cables is available for quantifying hydrological processes. Sakura (1984) made field observations of the rapid changes in soil temperature at 1 m depth during heavy rain. The conclusion of that study was that heat exchange between rainwater and soil particles occurs before the wetting front is formed. While importance of soil temperature in the study of soil moisture has been reported by previous studies, the relationships between rain intensities, soil moisture changes, and the properties of the subsurface of the slope are not well understood. Therefore, more data need to be acquired to generate better knowledge of heat and soil moisture transport in soil during rainfall.

Theoretical studies of heat and mass transport in the vadose zone have been developed from the work of Philip and De Vries (1957) who provided the theory of non-isothermal moisture behavior in porous media. Specifically, they introduced a new model of evaporation and condensation in porous media at micro scales and developed an enhancement factor for the flux equation of vapor in order to explain that the observed results of vapor in field experiments were greater than predictions by Fick's law. After that, many researchers addressed the problems associated with the enhancement factor (e.g., Cass et al., 1984; Sakai et al., 2009). The model and its formulation were also further developed in some studies. Smits et al. (2011) developed a numerical model to simulate coupled heat, water vapor, and liquid water flux in soil, and they compared the simulated results with the results of a laboratory experiment with a well-controlled thermal boundary condition. Grifoll et al. (2005) presented a model formulation of non-isothermal transport of water in unsaturated soil. The model was developed based on the work of Philip and De Vries (1957), and it consists of convective transport in the gas and liquid water phases, vapor dispersion, and liquid sensible heat dispersion without an applied enhancement factor. Bittelli et al. (2008) developed a fully coupled numerical model to solve equations for heat flux, liquid water, and vapor flux in the soil and at the soil–atmosphere interface, and the simulated results for soil temperature, heat flux, water content, and soil evaporation were in good agreement with the observed data. Soil temperature plays a key role in vapor transport and evaporation, therefore the developed model has been used for the evaluation of mass and heat flux between the soil surface and atmosphere in many studies, especially in agriculture and micrometeorology fields.

The present study focused on changes in the soil temperature as a rapid indicator for detecting changes in soil moisture, which may help to prevent slope disasters. Infiltration of rainwater changes the thermal conditions in the subsurface. The mechanisms of soil temperature change in saturated and unsaturated subsurface soil during rainwater infiltration include the following: 1) changes in thermal properties (the heat capacity and thermal conductivity) of bulk soil, 2) heat exchange between soil particles and rainwater during contact (bulk heat diffusion), and 3) heat advection with the infiltration. Measurement of soil temperature is considered to be one of the most effective methods for understanding soil water behavior. Moreover, some temperature sensors are more manageable and reasonable than other techniques. For example, fiber-optic cables can be used for estimations of hydrological processes (Selker et al., 2006; Tyler et al., 2009) and evaluations of shallow geothermal tests (e.g., Fujii et al., 2009).

Soil temperature measurements have the potential to improve the sensing of spatial and temporal soil moisture behavior associated with hydrological processes, as described above. However, it is actually unclear whether soil temperature sensing is useful for soil moisture monitoring in regard to the prevention of slope disasters. Measured data at field scales that represent soil temperature changes in a slope in response to various rainfall levels are crucial for evaluations of this potential technique. The purpose of this study was to obtain knowledge about 1) whether the effect of rainfall intensity on soil temperature changes can be measured at the field scale, 2) whether the soil temperature changes along with soil moisture, and if so, what is the nature of the relationship, and 3) how much sensitivity is required for measuring soil temperature in order to detect soil moisture movement and other indicators of potential slope failures. To accomplish this task, we collected measurements of soil temperature and volumetric water content in a slope of an embankment under four different rainfall intensities that were produced by a rainfall simulator. The results of the experiment were analyzed, and then we discuss the relationship between the behaviors of the soil water content and the soil temperature in regard to rainwater infiltration and the mechanisms that caused the changes in the soil temperature.

2. Methods

2.1. Experimental embankment

The experiments were performed using the experimental embankment located in the western portion of a large-scale rainfall simulator