熊本地震により亀裂が形成された斜面の土壌水文応答
Soil-water responses of a hillslope with fissures formed by the Kumamoto earthquake

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1. INTRODUCTION

Fissures are one of the major earthquake-induced topographic changes observed around the world. Fissures are defined as ground surface deformations, which are typically observed in convex topography and/or around ridgelines (Owen et al., 2008). Hart et al. (1990) found that fissures < 0.8 m wide concentrated on ridgelines after the 1989 Loma Prieta earthquake, San Francisco, USA. Mean fissure width and depth formed along a ridgeline during the 2016 Kumamoto earthquake were 1.4 m and 0.4 m, respectively; length-based density was 0.42 m/m^2 (Arata et al., 2020).

Hillslopes affected by fissures are usually assumed to be unstable because slope stability may decrease due to changes in topography and physical conditions (Marc et al., 2015). Because fissures formed at a slip surface similar to landslide surfaces during the Kumamoto earthquake (Arata et al., 2020), soil blocks between fissures may be unstable during subsequent rainfall. Based on numerical simulation, Chen et al. (2020) showed that fissure formation reduced tensile strength at the top of hillslopes after the 2008 Wenchuan earthquake, China. Furthermore, disruption of soil blocks by fissure formation may provide paths for preferential flow during rainfall and could induce the rapid development of perched water tables (Sidle et al., 2018).

Despite the likely instability of fissure-affected hillslopes, soil-water response, which is essential for evaluating the stability of slope with fissures (e.g. Sidle and Ochiai, 2006), has not been investigated thoroughly. Therefore, the objectives of this study are: (1) to investigate soil-water responses within fissures to rainfall inputs; and (2) to examine characteristics of soil water responses in various soil layers. Findings of this study will provide a basis for assessing slope failure risk of earthquake-affected areas and support for sustainable resource management (UNISDR, 2017).

2. METHODOLOGY

This study was conducted in a 6 × 20 m plot with 10º gradient located at the Aso central volcanic cones. Seven fissures (0.3 to 0.8 m in depth and 0.4 to 2.2 m in opening width) formed parallel to the ridgeline. Soil blocks remained with intact vegetation (*Miscanthus sinensis*) between fissures, while mineral soils were exposed within fissures. Mean annual precipitation and temperature around the study site are 2990 mm and 13 °C, respectively.

We monitored changes in soil pressure heads using tensiometers (Daiki and EMJ) and soil volumetric water contents using soil moisture sensors (TDR, Daiki) at various depths within fissures and between fissures. These sensors were installed at depths of approximately 0.4, 0.8, 1.1, and 1.3 m below the original ground surface. These depths correspond to shallow andisol (the 1st andisol), shallow tephra (the 1st tephra), deep andsiol (the 2nd andisol), and deep tephra (the 2nd tephra), respectively (Arata et al., 2020), while shallow soil layers were absence within fissures. When tensiometers and TDRs were measured at the same soil depths, we could develop *in-situ* soil water retention curves to examine soil water responses in the soil layers. Both sensors were calibrated after monitoring. Rainfall was monitored using a 0.2-mm tipping bucket rain gauge (Onset) located at the ridgeline within the plot. All data were collected at 10 min intervals during a 1-year period from Apr. 28, 2018 to May 16, 2019. For analysis of storm events, a single rainfall event was defined as having an interval of at least 6 h with no rainfall.

3. RESULTS

3.1 Soil-water responses within fissures

Pressure heads along the ridgeline responded to rainfall inputs. In the same soil layer, response of pressure head to rainfall within fissures was generally more rapid compared to the response between fissures. For instance, in the storm on Aug. 30 and 31, 2018 with 22.6 mm/h and 3.1 mm 7-day antecedent precipitation index (Event 1: Fig. 1), pressure head at the 2nd andisol layer within the fissure responded abruptly 2 h after the rainfall, while response

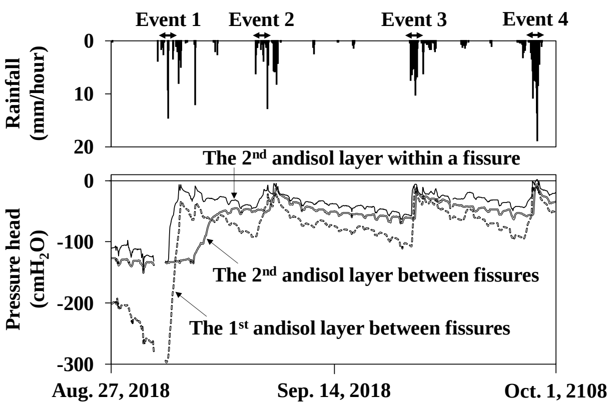

Figure 1. Pressure head responses within a fissure and between fissures.

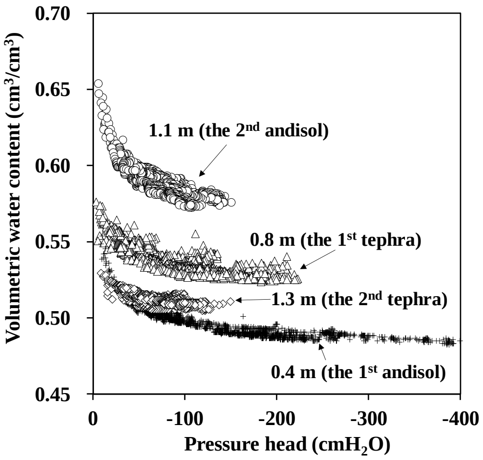

Figure 2. Soil water retention curves of andisol and tephra layers based on field monitoring.

between fissures was 49 h after the rainfall. During the subsequent storms (Events 2 to 4; Fig. 1) with increasing wetness, the time lag for pressure head responses to rainfall was shorter than during the first storm event. Furthermore, initial pressure heads in the 1st and 2nd andisol layers within the fissure and between fissures were nearly positive (≈ -100 and ≈ -50 cmH_2O, respectively) during the progressive storm events.

3.2 Water responses in soil layers

Volumetric water contents (VWC) monitored by TDR at the ridgeline differed depending on soil layers on Aug. 14, 2018 when no rainfall was observed for 9 days. The 1st andisol layer (0.4 m depth) had VWC of ≈ 0.49 cm^3/cm^3, whereas VWC at the 1st tephra layer (0.8 mdepth) was ≈ 0.53 cm^3/cm^3. The 2nd andisol layer (1.1 m depth) had higher VWC (≈ 0.58 cm^3/cm^3), while the 2nd tephra layer (1.3 m depth) had lower VWC (≈ 0.51 cm^3/cm^3).

In-situ soil water retention curves differed for each soil layer (Fig. 2). The 2nd andisol layer had distinctively higher water contents, and soil water was highly variable when pressure heads were greater than -30 cmH_2O. Furthermore, the 2nd andisol layer had consistently higher pressure heads of above -150 cmH_2O, whereas the pressure heads of the 1st andisol layer decreased below -200 cmH_2O.

4. DISCUSSION

Water in soil matrix behaved differently within the fissures compared to between the fissures. Within the fissures, because of the absence of surface soil layers (1st andisol and tephra), rainwater directly reached to the 2nd andisol layer and then infiltrated into the 2nd tephra layer. In contrast, rainwater between the fissures fell on the grass-covered soil surface and infiltrated through shallow to deep soils. Some of soil water in the 1st andisol layer between fissures could be transpired by silver grass. Consequently, soil-water responses within the fissures were much faster than those between the fissures, particularly when the soil matrix was relatively dry (Fig. 1). In contrast, during wet conditions, water from subsequent rainfalls (Events 2 to 4) rapidly propagated into deeper soils between the fissures, likely due to high hydraulic conductivity associated with relatively high initial pressure heads in the soil matrix (Torres et al., 1998) and arrived more rapidly at the 2nd andisol layer (Fig. 1).

Water that infiltrated into the 2nd andisol layer was retained longer based on the slow recession (Fig. 1) and slowly drained due to the high water holding capacity (Fig. 2). The low bulk density and high organic matter in the 2nd andisol layer (Arata et al., 2020) likely supported the storage of soil water. Other investigations have noted that aggregated soils with large pore volumes can store abundant soil water (Nanzyo, 1993; Nanzyo et al., 2002). Such attributes probably caused the high water retention capacity in the 2nd andisol layer at our site. Findings of this study showed that changes in processes of water propagation and duration of water storage in the different layers of the soil matrix affect the temporal availability of water in a specific soil layers (i.e., andisol) and possibly alter the stability of fissure-affected hillslopes.

5. REFERENCES

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