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Characterization of the groundwater response to rainfall on a hillslope with fractured bedrock by creep deformation and its implication for the generation of deep-seated landslides on Mt. Wanitsuka, Kyushu Island

Cristobal Padilla [a,*], Yuichi Onda [a], Tomoyuki Iida [a], Shinya Takahashi [a], Taro Uchida [b]

[a] Graduate School of Life and Environmental Science, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8572, Japan
[b] Research Center for Disaster Risk Management, National Institute for Land and Infrastructure Management, 1 Asahi, Tsukuba 305-0804, Japan

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ABSTRACT

In this study, the hydrogeological response of a hillslope affected by gravitational deformation was analyzed based on the data obtained for two observation boreholes: a 10-m borehole representing a relatively superficial section of the hillslope dominated by soil and old landslide deposits and a 40-m borehole representing the bedrock aquifer. For this analysis, the precipitation events in the area, groundwater levels of the two boreholes, electrical conductivity and isotopic concentration (oxygen and hydrogen) of the groundwater in the boreholes and rainfall samples were measured. Derived from the rainfall data, the antecedent precipitation index (*API*) with a 6-h half-life offers a good correlation with the peaks in the groundwater levels in the bedrock aquifer. The characteristics of the groundwater response suggest the existence of a single structure in the bedrock that controls the response of the hillslope. The structure serves as a conduit, which rapidly drives the rainfall water (recharge) into the bedrock. Evidently, this process is unrelated to the superficial section represented by the observations in the 10-m borehole. The structure is associated with an area of high hydraulic conductivity in the bedrock caused by the gravitational deformation in the hillslope. The strong control of this structure in the hillslope's hydrogeological response makes it responsible for the hillslope's stability during high-precipitation events. This information is highly relevant to areas featuring the generation of several deep-seated landslides under heavy-rain conditions.

1. Introduction

The hydrogeological response of hillslopes to rainfall events has been studied for a long time. The main objective of these studies is to define the slope runoff or the conditions for slope failure and landslide generation (Wilson and Dietrich, 1987; Yano, 1990; Montgomery et al., 1997; Guglielmi et al., 2005). To develop simple, low-cost methodologies to study the response of slopes, several conceptual models using rainfall data were developed to interpret the infiltration rates and water contents of the soil (Kohler and Lindsey, 1951; Sugawara et al., 1984; Jain, 1993). These methods have been used to model the runoff generation or analyze the slope deformation processes originating in the superficial sections of hillslopes, such as shallow landslides or, in some cases, debris flows (Yano, 1990; Gabet et al., 2004; Onda et al., 2006a; Saito et al., 2010; Routte et al., 2011). The superficial areas of a hillslope are commonly dominated by soil cover or materials that can generally be modeled as homogeneous and isotropic media in terms of their hydraulic response. Although many studies focus on the analysis of the deposit cover in the hillslopes, recent studies indicate the importance of the bedrock groundwater characteristics in the hillslope response and processes originating in and below the surface (Mathewson et al., 1990; Tsujimura et al., 1999; Uchida et al., 2003; Furuya et al., 2006; Onda et al., 2006b; Jitousono et al., 2008). When deeper processes involving fractured bedrock are analyzed, such as deep-seated landslides, the use of simple methodologies to model the hydrogeological response of the hillslopes becomes difficult (Onda et al., 2003; Zang et al., 2005).

The anisotropies observed in fractured media can generate complex patterns of groundwater flow requiring the construction of observation boreholes. Observation boreholes permit the identification of special characteristics of the groundwater flow or the calibration of simplified models that can be used under certain conditions (Jiao et al., 2005; Zang et al., 2005; Rodhe and Bockgard, 2006; Banks et al., 2009; Peng et al., 2010; Kosugi et al., 2011). Some studies have correlated the groundwater behavior and slope processes using data from observation boreholes (Okunishi and Nakagawa, 1977; Wilson and Dietrich, 1987; Peng et al., 2010; Kosugi et al., 2011). Okunishi and Nakagawa (1977) carried out a complete analysis and modeling of the groundwater and

* Corresponding author. Tel.: +81 29 853 6886.
E-mail address: cristobal30364@ies.life.tsukuba.ac.jp (C. Padilla).

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spring discharge in a hillslope affected by a large-scale landslide. In that study, the structures in the bedrock that define special patterns in the groundwater flow were found to be related to the occurrence of landslides.

The deformation processes in slopes can generate several structures on the bedrock that modify the original bedrock flow patterns. Additionally, gravitational deformations are considered to be precursors of catastrophic events, such as deep-seated landslides (Chigira and Kiho, 1994; Bisci et al., 1996; Petley et al., 2005; Tsou et al., 2011; Zarathe and Lebourg, 2012). The hydrogeological analysis of these processes and their interactions with rainfall improves the understanding of the deformation itself, hillslope failure conditions and the generation of deep-seated landslides. However, there is an absence of data demonstrating and supporting these interactions and their implications in the generation of catastrophic landslides events.

In this context, the objective of this study is to analyze and characterize the hydrogeological response of a hillslope affected by gravitational deformation (creep deformation) with special focus on the bedrock groundwater response to rainfall inputs. This study was conducted in Mt. Wanitsuka, located in southern Kyushu Island, Japan. In this area, several deep-seated landslides were generated due to heavy-rain conditions caused by the passing of Typhoon No. 14 in 2005 (Taniguchi, 2008; Chigira, 2009). This event has motivated some studies to identify possible locations of landslide generation in the area. These studies describe several slopes in the zone that were affected by deep creep deformation prior to the occurrence of the landslides (Chigira, 2009; Akther et al., 2011; Uchida et al., 2011; Yokoyama et al., 2011). During the typhoon event, a cumulative rainfall of 1029 mm was measured over a period of 92 h. However, according to residents, the deep-seated landslides occurred 71 or 72 h after the rainfall began, which is coincident with the peak rainfall of 46 mm h^{-1}. The extremely short time between the rainfall peak and the occurrence of the deep-seated landslides, which is not common for this type of landslide, suggests that the hillslope in Mt. Wanitsuka features specific conditions that facilitate this phenomenon. The analysis of the hydrogeological responses of those hillslopes affected by gravitational deformation can reveal the mechanism that generates the catastrophic sliding and, thus, improve the deep-seated landslide forecasting models.

2. Study area

Mt. Wanitsuka is located approximately 18 km to the south of Miyazaki City in Kyushu Island (Fig. 1). This mountain is one of the tallest in the area, with an elevation of 1118 m asl (above sea level). The average annual precipitation in the area is 2669 mm (Japanese Meteorological Agency). Kyushu Island has a subtropical climate with year-round precipitation; however, as is the case for the rest of the Japanese archipelago, the main rainfall occurs during summer, from June to September, as part of the East Asian monsoon. In this period, the Japanese territory is also lashed by the passing of severe tropical cyclones or typhoons. Most of the heavy rainfall observed in Japan can be attributed to the passing of typhoons over the territory.

The studied hillslope is located in the Shirinashi River basin, a sub-basin of Byutano River with 15.2 km^2 of drainage area. It has a height

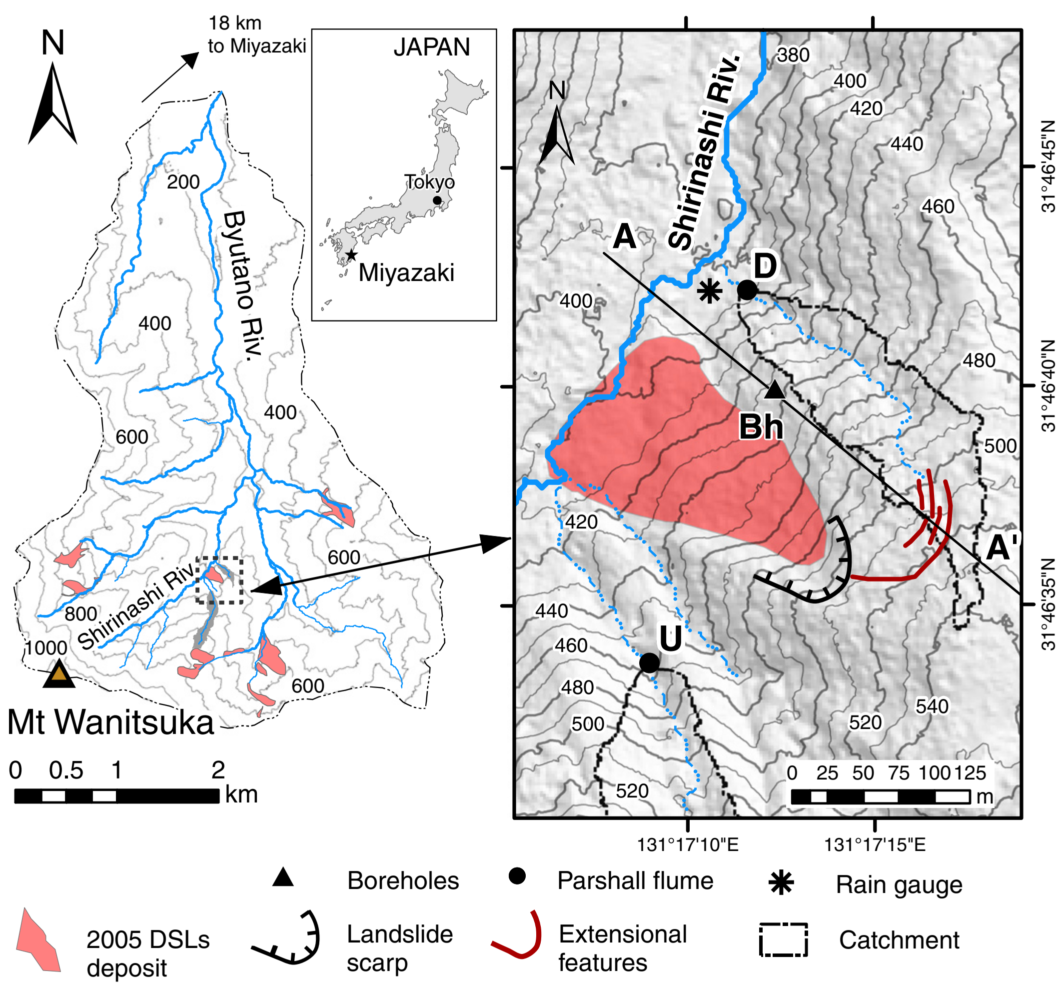

Fig. 1. Study area and instrument location. In red: areas where deep-seated lanslides (DSLs) ocurred in 2005 due to heavy rain conditions during the passing of Typhoon No14.