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Experimental tests of slope failure due to rainfalls using 1g physical slope models

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Abstract

In order to mitigate the damage due to sediment disasters, knowledge about how slopes fail due to rainfall is indispensable. The main objectives of this paper were to investigate experimentally the effects of surface sand layer density and rainfall intensity on the slop failures due to rainfalls. We conducted a series of experimental tests using 1g physical slope models constructed of Kasumigaura sand and a silt soil named DL clay for the permeable residual surface layer and the firm rock foundation, respectively. A total of nine cases with different combinations of surface sand layer densities and rainfall intensities was tested. Two types of failure: surface slide failure and retrogressive failure, were observed depending on the rainfall intensity and the surface sand layer density. The following mechanism of failure was accounted. At first some sands, which contained a lot of accumulated rainwater, flowed out (flowslide) at the slope toes. The flow slides may be due to the reductions of effective stresses as a result. When a surface slide failure occurred, most of the PWP (pore water pressure) values were still negative but the whole sand layers were almost at the saturation condition. In the case of retrogressive failures, seepage surfaces rose up to higher positions and excess PWPs appeared under the seepage surfaces. This difference of generation mechanism of PWP values may be the deciding factor in the difference in the type of failure.

Keywords: Experimental model test; Slope failure; Rainfall; Unsaturated soils; Pore water pressures

1. Introduction

Devastating damage due to sediment disasters, such as slope failures and debris flows triggered by heavy rainfalls, is becoming a more pressing concern in Asia since the frequency of heavy rainfalls is becoming higher year by year (International Strategy for Disaster Reduction, 2009; Adikari and Yoshitani, 2009). According to the JMA (Japan Meteorological Agency, 2009), the mean annual events of rainfalls with an intensity of greater than 50 mm/h for every ten years in Japan are gradually increasing: at 160 in 1976–1987, 177 in 1988–1997 and 233 in 1998–2007. The major sediment disasters since 2003 in Japan are listed in Table 1. As can be seen, a significant number of people have lost their lives or have been listed as missing almost every year in Japan. The annual mean sediment damage over the last 10 years due to typhoons and heavy rainfalls comes up about US $ 100 million in Japan only (Kawagoe et al., 2014).

A reduction in shear strength with an increase in the water content of unsaturated soil is one of the main causes of slope failure due to rainfall (Kitamura and Sako, 2010; Rahardjo et al., 2005). Kohgo et al. (1993) proposed an elastoplastic model that can express the reduction in shear

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Table 1
Main sediment disasters in Japan in recent 10 years.

Year	Prefecture	Cause	Num. of Victims
2003	Kumamoto	SRF*	19
2004	Mie, Tokushima, Kanagawa, Ehime	Typhoon 21	17
2004	Nagano, Toyama, Gifu, Hyogo, Kyoto, Okayama, Kagawa, Ehime	Typhoon 23	27
2005	Kagoshima, Miyazaki, Oita, Tamaguchi	Typhoon 14	22
2006	Nagano etc.	Torrential rain	20
2009	Yamaguchi etc.	Torrential rain	21
2011	Wakayama etc.	Typhoon 12	62
2012	Kumamoto etc.	Torrential rain	23
2013	Tokyo etc.	Typhoon 26	40
2014	Hiroshima	Torrential rain	74

* Seasonal Rain Front.

strength with an increase in the water content. Observing the behavior and role of water as it infiltrates into the soil slope during the rainfall is the key to understand the mechanism of slope failures.

Field investigations of slope failures have been conducted by many researchers (e.g., Rahardjo et al., 2005; Orense et al., 2006) to develop warning procedures and measures to prevent damage (e.g., Aleotti, 2004; Kamide et al., 2010). It was found from the field investigations that most failed slopes had the following common features: the depths of failures were less than 2 m, the inclines of the slopes were 30–50 degrees, and the slopes consisted of permeable residual layers on relatively firm rock foundations.

Experimental tests using physical models have been also conducted to observe the slope failure mechanism, the behavior of pore water pressures (PWP) and the slope displacements. The flume tests for flowslide were conducted by Wang and Sassa, (2001), Okura et al. (2002), Olivares and Damiano, (2007) and Damiano and Olivares, (2010) to discuss the conditions required for flowslide to occur.

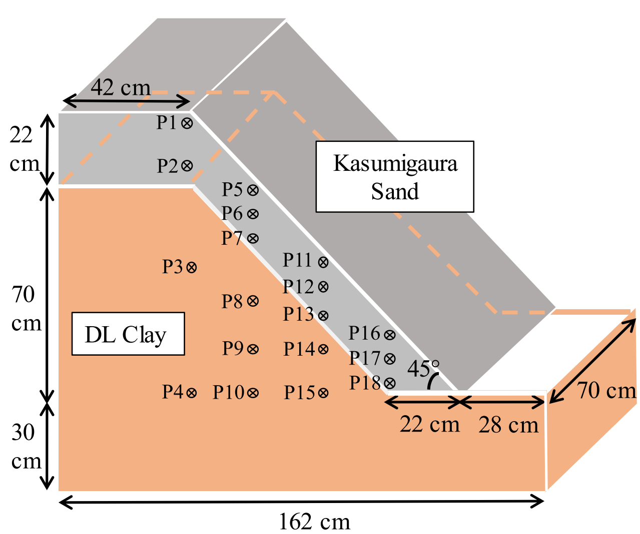

Fig. 1. Dimensions of model slope used and locations of ceramic cups installed into the model slope.

Experimental tests using slope models have also been conducted to investigate the failure mechanism. Yagi and Yatabe (1987), Eckersley (1990), Orense et al. (2004), Tohari et al. (2007), Kitamura et al. (2007) and Tokoro et al. (2012) carried out experimental tests using physical 1g slope models and Take et al. (2004), Kaneko et al. (2010) and Kohgo et al. (2011) conducted experimental tests using centrifuge slope models. Yagi and Yatabe (1987) observed the PWPs, the displacements, and the shear strains during the 1g slope failure experimental tests. It was found that the PWPs greatly affected the slope failures. Eckersley (1990) conducted experimental tests with the rising water levels in soil slopes and suggested that the excess PWPs in the shear zone were the key to the slope failure. Take et al. (2004) also investigated the effect of water level rising in centrifuge experimental tests and suggested that dense soil and loose soil have different failure mechanisms. Take and Beddoe (2014) discussed the initiation of the failure mechanism of the loose soil slope and the static liquefaction (liquefaction triggered from monotonic loading) played an important role to the initiation. Orense et al. (2004) inspected the effect of infiltrated water in a physical 1g slope model and found that the slope failure occurred at the toes of the slopes where the soil became nearly saturated. A similar result was obtained by Tohari et al. (2007) where the slope failure was initiated when the moisture content at the toe reached at saturation. Therefore, while the slope failure was induced by saturation at the toe, the majority of the sliding mass was still in an unsaturated condition.

Despite many previous efforts to reveal the mechanism of slope failure due to rainfall, it is still not sufficiently understood how the slopes fail due to rainfall. The main objectives of this study were therefore as follows: (1) to investigate experimentally the effect of rainfall intensity and the surface layer density on the slope failure, and (2) to clarify the behavior to the failures by monitoring both

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