Study of rainfall-induced landslide: a review

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Abstract. Rainfall-induced landslides pose a substantial risk to people and infrastructure. For this reason, there have been numerous studies to understand the landslide mechanism. Most of them were performed on the numerical analysis and laboratory experiment. This paper presents a review of existing research on field hydrological condition of soil slopes leading to the initiation of rainfall-induced landslide. Existing methods to study field hydrological response of slopes are first reviewed, emphasizing their limitations and suitability of application. The typical hydrological response profiles in the slope are then discussed. Subsequently, some significant findings on hydrological condition leading to rainfall-induced landslides are summarized and discussed. Finally, several research topics are recommended for future study.

1. Introduction
Landslides are very commonly occurred during a long period of heavy rainfall and occur every year in many parts of the world, especially in environments that provide a prolonged and intense rainfall, steep slopes, sparse vegetation and an abundant source of incoherent fine-grained soils, including colluvium and residual soils. These landslides are common sights in tropical countries, and in some cases, in temperate regions where residual soil prevails. In a tropical country like Indonesia, most landslides occur annually between December and March, in which period the frequency and intensity of rainfall is higher than any other months.

Worldwide, rainfall-induced landslides have claimed untold numbers of human lives and have caused economic losses every year. In Indonesia, for example, during the ten years, the landslide events have resulted, either directly or indirectly, in more than 537 deaths and economic losses at about US$ 10 million annually. For this reason, these landslides have been the subject of numerous studies in order to understand the hydrologic condition of failure initiation or mechanism of the failures, and to develop a system for predicting the occurrence of failures. Studies on landslides have involved a multi-disciplinary field of soil mechanics and hydrology. The study requires good knowledge of not only strength properties of the soil, but also hydrologic behaviour of the soil governed by the soil seepage properties.

This paper aims to present the current state of-the-art hydrological approach for landslide investigation, mainly considering the technological and methodological development of this approach. In particular, this study presents the existing methods to study field hydrological response of slopes are first reviewed, emphasizing their limitations and suitability of application. The typical hydrological response profiles in the slope are then discussed. Subsequently, some significant findings on hydrological condition leading to rainfall-induced landslides are summarized and discussed. Finally, several research topics are recommended for future study.
2. Monitoring methods of hydrological response of slope

Recently, in an effort to develop a landslide early warning system, a number of studies have focused on monitoring the hydrologic response of a soil slope under the effect of infiltration. Most of these commonly involved monitoring the presence of groundwater table and soil suctions within the slope. However, all the preceding methods for in situ monitoring still evidently show some limitations, as indicated herein.

2.1 Monitoring of piezometric water pressures

The fluctuation of groundwater level and piezometric water pressures are typically monitored by open standpipe piezometers [1-2]. Although these instruments give reliable data, they have some limitations regarding their performance [3]. They have the potential of hydrodynamic time lag in response to changes of groundwater pressure. During rainfall periods, they will not show any response until the free surface rises above the elevation of the screen. Such response will obviously hinder the prediction of the occurrence of a particular event. The quality of filter screens against the potential for clogging also affects their performance. Thus, monitoring piezometer pore-pressures are limited to deep landslides. Huang et al [4] used Fibre Bragg grating piezometer array to study the piezometric pore pressure in a deep landslide in Taiwan.

2.2 Monitoring soil suction

Recently, in attempts to develop a predictive warning system for rainfall-induced slope failures, a number of studies have focused on monitoring the hydrologic response of a soil slope under the effect of infiltration. Most of these involved the monitoring of pore-water pressures in saturated and unsaturated conditions using jet fill tensiometers [5-16]. Although tensiometers have been proven effective to directly measure the absolute soil suction and to indicate the direction of suction change, these instruments still have some limitations regarding their performance. The standard tensiometers, like vacuum gauge types, are subject to failure at soil suctions higher than 100 kPa. Springman et al [8] suggest an alternative method for measuring suction that should be applied in the top soil zones as the soil suction may be higher than 100 kPa. The reliability of tensiometer depends on the contact between the soil and ceramic tip and the quality of the sealing material [3]. They also lack in response to time and accuracy [5]. Consequently, they require careful installation and regular maintenance when used for a long-term measurement activity [5-6]. These drawbacks obviously hinder the prediction of a particular failure hazard, and thus, there is a need for a reliable and effective approach to measure the hydrologic condition during rainwater infiltration for the purpose of predicting the occurrence of slope failures. Concern also exists on the reliability of indirect methods for measuring soil suctions. Harrison and Blight [16] used a number of indirect and direct soil suction measuring devices for long-term in-situ soil suction measurements, and found none of the devices recorded comparable suctions. From the results of this study, they concluded that there is not yet a method available for reliably measuring soil suction magnitude in-situ.

2.3. Measurement of soil moisture content

From a hillslope hydrology point of view, the hydrologic response of soil slopes to rainfall can also be described by using measurements of soil moisture content. The measurements of soil moisture content can come from a variety of sources, by indirect and direct measurements. The former utilizes soil suction measurements in conjunction with the moisture-retention characteristics of a soil to estimate the respective soil moisture content. While this method would offer a good approach to evaluate the importance of antecedent soil moisture content in controlling the hydrologic response of a soil slope to rainfall [5], the conversion of the tensiometer readings into soil moisture content is sensitive to the accuracy and reliability of soil suction measurements as well as the characteristics curves of the soil. The generalization of the characteristics curves and the negligence of hysteresis effect, for example,
can introduce large errors in estimating soil moisture content. Thus, there is a need to utilize a direct method for measuring soil moisture content.

In order to evaluate the application of soil moisture content sensor to monitor hydrological response of soil slopes to rainfall, Tohari et al [17] conducted a small-scale laboratory rainfall-induced landslide. Based on the experimental results, they show that ThetaProbe sensors are capable of indicating the landslide initiation. Other works also show similar findings [18-19]. However, field application of soil moisture content sensors to study the hydrological condition of landslide initiation requires the proper installation of the sensors. Tohari and Nishigaki [20] suggest that good care must be taken in the installation of moisture content sensors to prevent the presence of air pocket around the sensing rods and inclined installation can result in the soil mass around the sensing rods to reach a saturated condition.

3. Characteristics hydrological response of slopes to rainfall

Numerous studies have focused on the characterization of hydrologic response of a soil slope to rainfall through laboratory experiments and field measurements in effort to develop an earlier warning system. From the typical profiles of soil moisture content observed in a series of laboratory rainfall-induced landslide experiments, Tohari et al [17] showed that the hydrologic response of an initially dry soil slopes to the infiltration of rainwater is characterized by two stages of significant increase in volumetric moisture content associated with the advancing the unsaturated wetting front and the rise of groundwater level to the slope surface. In contrast, the hydrologic response of a wet, less permeable soil slope to rainfall only consist of one stage of increase in volumetric moisture content of the soil, corresponding to the advancement of a saturated wetting front from the slope surface. Also, longer durations of rainfall are required to develop the hydrologic condition leading to failure initiation in the less permeable soil slopes hence the hydrologic properties of the slope, such as antecedent soil moisture conditions and soil permeability, control the slope hydrologic response to rainfall.

Based on the pore-water pressure measurements in a series of laboratory flume experiment, Hakro and Harahap [19] suggest that the soil pore-water pressure will increase in three stages in response to rainwater infiltration. At the first stage, the pore-water pressure remains constant in response to the ingress of wetting front. The second stage is associated with the increase of water level in the slope by which the pore-water pressures increase sharply. The third stage is indicated by the gradual increase of pore-water pressure in the soil. However, the sharp increase in pore-water pressure may also result from the rapid movement of the slope. Thus, it is difficult to determine the critical pore-water pressure as a warning toward the initiation of landslide movement.

The current understanding of the hydrological response of the slope to rainfall infiltration has been also commonly gained from field measurement of soil pore-water pressures. The characteristics of hydrological responses of a hill slope to rainfall are typically site specific. From the pore-water pressure records obtained from a study of rain-induced debris flow, Johnson and Sitar [5] show that the hydrological responses of soil slope varied from site to site depending on the antecedent moisture condition. Under dry antecedent moisture condition, the shallower soil responds before those deeper within the soil column. However, in the presence of lateral source of moisture, the deeper part of soil profile may respond earlier than the intermediate soil. In response to rainfall, a soil profile with wet antecedent moisture has different hydrological responses. The shallow soil may have no pronounced pore pressure responses, whereas the deeper soils generally do. The wetter antecedent soil moisture condition of the shallower soil will cause the rainwater infiltration to be transmitted through the shallower soil within a soil profile. The response of deeper soils to rainfall may be characterized by a transient pore-water pressure response which generally shows the build-up of positive pore-water pressure in a certain time. From this study, they suggested that the continuous monitoring of pore-water pressure at multiple locations is required to assess transient and spatially variable responses of soil slope to rainfall in order to develop warning systems for rain-induced hill slope failures.

Measurement of soil pore-water pressure using tensiometer method in a steep tropical slope in Hawaii [6] shows that the shallow soils responded earlier than the deeper soils. The response was
characterized by the fastest rate of pressure change, the shortest peak duration, and the fastest decline. The advance of wetting front slowed with depth and the response was of lower magnitude and longer duration at a greater depth.

Tohari [15] studied the hydrological response of a residual soil slope in Java, Indonesia using some jet-fill tensiometers. The records of a long time measurement of pore-water pressures show that the increase of pore-water pressure of shallow soil layers was commonly faster in response to rainfall infiltration due to low antecedent moisture condition. However, the hydrological response of the shallower soil was less sustained than that of deeper soil in the same soil profile. The additional sources of moisture within the deeper part of soil profile was considered being responsible for such a hydrological response of the residual soil slope.

Using soil moisture content sensors, Tohari et al [20] compared the hydrological responses of two cut-slope sites of decomposed granite in Okayama, Japan. In both sites, the response of the shallow soils was earlier than the deeper ones. However, the soil moisture records of stable slope (site #1) show that the deeper soils showed no moisture responses to rainfall, meanwhile the deeper soil in failed slope (site #2) responded to the infiltration. This suggests that, in addition to vertical infiltration, a lateral source of moisture contributed to the deeper part of the soil profile in site #2.

4. Factors controlling hydrological response of slopes to rainfall

Field soil moisture and pore-water pressure profiles generally shows the partial or complete disappearance of matric suction at shallow depths associated with infiltration of rainwater during heavy rainfall. Subsequently, a perched water table or transient positive pore-water pressure would develop in the shallow soil. It is typically observed that significant build up in positive pressure heads is generated in an area low on the slope [2,5]. However, the mechanism of pore-water pressure generation is site-specific; it differs from site to site depending on the site hydrology, rainfall pattern, topography, and soil properties [5-6,15].

The previous studies of in-situ hydrological response of a hillslope to a rainfall indicated that the site hydrology was complex, and showed variation in response over very short distances. Some factors influencing the specific hydrological response are to include the type of ground cover, high permeable zone and an additional source of moistures within the soil profile.

The ground cover generally controls the high antecedent moisture condition of shallow soils by preventing the loss of soil moisture by evaporation. This antecedent moisture condition will result in rapid increase of soil moisture or pore-water pressure of the shallow soil that can lead to saturation and shallow failure. However, some vegetation, such as bamboo, may also introduce a low moisture condition of soils near the ground surface. Thus, the types of ground cover seem to introduce different antecedent moisture condition that will control types of landslide.

The presence of the ground cracks in the slope surface can cause the rain infiltration to advance further into deeper soils. This will introduce more dominant and more significant hydrologic responses of the deeper soils than that of shallow soils within a soil profile. This hydrological response of deeper soils may result in the rise of water table.

Fast response of deeper soils within a soil profile indicates that the flow condition within the deeper soil profile appears not only to be characterized by the vertical infiltration alone but also by additional through and side-flow. The contribution of the through and side-flow facilitated by the presence of provides a preferential path for moisture movement associated with the presence of highly permeable zone within the deeper soil and the additional source of moisture within the soil profile. This through- and side-flow may have contributed to the development of a water table within the slope that can, subsequently, induce the initiation of a slope failure during or just after rain [26].

Based on the above discussion, the spatial and transient variation of responses over short distance across and along the slope cannot be explained by conceptual hydrological model [5, 6, 15, 20]. The presence of highly permeable zone due to fractures within the soil profile and the additional lateral source of moisture also influence soil response to a saturation process. Thus, it is clearly appropriate to
have the knowledge of specific hydrological responses of a soil slope to rainfall to develop a better understanding of the mechanism controlling the initiation of landslides.

5. Conclusions
Previous laboratory and field studies of the hydrological response of soil slopes lead us to have a better understanding on the hydrological condition leading to landslide initiation. While most of studies have focused on the measurement of pore-water pressure response, some other studies have also shown that measurement of soil moisture content can also improve the understanding of the hydrological response of a soil slope to rainfall infiltration.
Based on the results of previous studies, however, further researches with the following objectives are recommended:

- Different types of soil moisture sensors to measure pore-water pressures or moisture contents are available. However, they all have some drawbacks in the field application to study the hydrological response of a thick soil profile. Thus, future research should be focused on evaluation of different types of soil moisture sensors to obtain the most applicable sensors for a long-term field measurement and monitoring of hydrological response of soil slopes in order to establish an effective landslide warning system.
- Most of previous studies focused on evaluation of sub-surface factors controlling the hydrological responses of soil slopes. Thus, it is appropriate to study the effect of different type of vegetation and geomorphological factors on the hydrological response of different type of soil slopes. The outcome of the study can be used to establish an appropriate mitigation of landslide hazard.
- Results of field measurement of the hydrological response of soil slopes indicate that hillslope hydrology is very complex and the use of simplified model of hydrology cannot explain the transient and spatial variation of responses of the hillslope to rainfall. Thus, future research with the objective to produce a model of the hillslope hydrology that incorporates a specific hydrological response is encouraging. Therefore, the model can be used to make an accurate spatial and temporal prediction of landslide hazard in a hillslope.

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