京都大学	博士（工学）	氏名	Sanchitha Hema Sharendra Jayakody
論文題目	Hydro-Mechanical Analysis of Unsaturated Slopes Subjected to Rainfall and Groundwater Flow （降雨と地下水を考慮した不飽和斜面の水・土連成解析）		

Landslides are one of the most pervasive natural hazards on the planet. Each year, these landslides impose not only billions of dollars in economic losses but also a priceless socio-economic impact. The inevitable climate change and global warming will change the precipitation patterns in many parts of the world with a rising tendency in the intensity of rainfall, which will instigate landslides to occur. It is a known fact that intense and/or prolonged rainfall is the major source of external triggering factors that induce catastrophic landslides on partially saturated slopes. Loss of matric suction with rainfall infiltration and saturation-dependent shear strength reduction has been identified as the common triggering mechanism in rain-induced landslides.

Landslide early warning systems have been developed over the last few decades to manage catastrophic events to some extent. These systems are usually implemented based on the actual rain gauge readings or forecasted rainfall and the correlations generated from past events. There is a significant probability of false predictions in landslide early warning due to the reliance only on intra-day rainfall when there are many uncertainties involved in hydraulic regimes. Therefore, this research has the prime objectives of understanding the effect of different hydraulic perturbations such as antecedent rainfall patterns and integrated effect of rainfall and groundwater flow on landslide initiation.

Chapter 2 reviews the background knowledge of rain-induced landslides. It includes fundamentals of unsaturated soil mechanics, and the review was extended up to transient water flow through unsaturated soil, constitutive models, and finite element modeling for hydromechanical analysis of rain-induced slope failures in unsaturated soils. This section provides the background needed for geotechnical centrifuge modeling on simulating landslides while understanding the research problems related to hydraulic perturbations on landslide initiation.

Chapter 3 discusses an often overlooked and crucial factor on landslide initiation, i.e., the effect of intermittent behavior of antecedent rainfall which may influence the temporal prediction of landslide initiation. Therefore, in this study, it was hypothesized that not only cumulative rainfall but also antecedent intermittent rainfall patterns have an impact on the initiation and temporal predictability of shallow slope failures. This hypothesis was tested experimentally using centrifuge model testing at the centrifuge

facility at DPRI, Kyoto University. The scattered behavior of antecedent rainfall was idealized as rainfall with a uniform gap, a decreasing gap, and an increasing gap when it reaches a landslide-triggering continuous rainfall event. The validation of the observations and behavior of the physical model results was conducted employing three-phase coupled hydromechanical finite element modeling, using van-Genuchten model to simulate water retention behavior and extended modified cam-clay model to simulate mechanical behavior of unsaturated soils. It was found that rainfall patterns directly impact temporal predictions of landslides in addition to cumulative rainfall since the failure occurred in the precedence of decreasing gap, uniform gap, and increasing gap. Furthermore, numerical analysis showed that there could be a critical gap value among successive rainfall events that determines whether to incorporate the effect of preceding rainfall events, which is especially important in practical application.

Chapter 4 examines the slope behavior under the integrated effects of groundwater flow and rainfall which has been hardly investigated. The effect of hydrogeology on the distribution of porewater pressure in the soil mass is greater if there is a pre-existing groundwater flow and with the presence of bedrock with fissures and fractures. To accomplish this objective, a new high-tech centrifuge chamber was developed, which successively enabled the simulation of groundwater flow and rainfall simultaneously and autonomously. In this study, not only the impact of different groundwater levels but also the effect of surcharge in groundwater flow were assessed. The results obtained from the physical modeling were compared and validated using hydromechanical finite element modeling. Experimental results and subsequent numerical analysis facilitated showing the influence of groundwater flow as an additional hydraulic regime on landslide initiation in both a qualitative and quantitative manner. It showed that integrated conditions are much more vulnerable to failure initiation, which eventually resulted in an accelerated and voluminous landslide. The study identified that even under low infiltration, the effect of groundwater flow is significant, implying the need to focus on regional hydrogeology to minimize uncertainties in landslide early warnings.

Chapter 5 summarizes not only the results and discussions carried out through the research project but also limitations of both experimental setup and numerical modeling. Furthermore, it investigates the future prospective such as, the steps to be taken to implement a simplified, yet more accurate landslide early warning predictions by incorporating the research outcomes.

氏　名	Sanchitha Hema Sharendra Jayakody

本論文は、斜面崩壊の早期予測において重要となる降雨や地下水位などの水理条件が、斜面崩壊に与える影響を模型実験や数値解析を用いて評価することを目的としたものである。特にこれまであまり検討がなされていない断続的な先行降雨パターンや地下水位と降雨の組合せに着目し、これらが降雨時に発生する斜面崩壊に与える影響を検討している。

まず、断続的な先行降雨が後の降雨時の斜面崩壊に与える影響を検討するために、遠心模型実験と数値解析を実施した。不透水傾斜基盤上の不飽和マサ土の斜面を対象として、３パターンの断続的な先行降雨とその後の降雨時の挙動について検討した。３パターンの先行降雨では全雨量と時間は一定として、３つの断続的な降雨が異なる時間間隔、すなわち時間間隔が均等なパターン、時間間隔が徐々に減少するパターン、時間間隔が徐々に増加するパターンを考慮した。この結果、時間間隔が徐々に減少するパターンでは、斜面内の間隙水圧の上昇が他のパターンより大きくなり、斜面崩壊が早く発生することがわかった。また、土・水・空気三相多孔質体理論と不飽和土に拡張した修正カムクレイモデルを用いた有限要素解析は上記の遠心模型実験の結果を定量的に再現している。数値解析により先行降雨の間隔を変えたパラメトリックスタディを実施して、斜面崩壊に影響する先行降雨の時間間隔の限界値の存在を示した。

次に地下水位の変化が降雨時の斜面崩壊に与える影響を検討した。遠心模型実験における地下水位を制御するため、斜面上流側の水供給タンクと下流から上流に水を循環させるポンプを備えた実験土槽を新たに開発し、遠心場において地下水位と降雨を同時に制御できるシステムを構築した。不透水傾斜基盤上の不飽和マサ土の斜面を対象として、定常的な地下水位だけでなく、降雨とともに時間的に変化する地下水位など様々な降雨と地下水位の組合せを検討した。この結果、地下水位の変化が降雨時の破壊挙動に影響し、地下水位によって降雨時の間隙水圧応答が早くなり、斜面崩壊の範囲も拡大することがわかった。この結果は上記の有限要素解析でも確認されており、降雨が少ない場合でも地下水位の影響が大きいこと、初期地下水位が低い場合は降雨中の地下水位の上昇の影響が大きいことを示した。

以上のように、本論文は断続的な先行降雨パターンや地下水位と降雨の組合せに着目し、これらが降雨時に発生する斜面崩壊に与える影響を定量的に検討したものであり、今後の斜面防災において有益な知見を与えるものとして、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和５年８月２日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。

なお、本論文は、京都大学学位規程第１４条第２項に該当するものと判断し、公表に際しては、当該論文の全文に代えてその内容を要約したものとすることを認める。

要旨公開可能日：　令和５年１０月１日以降