TITLE:

Evaluation of seepage and deformation of unsaturated slopes during post-shaking rainfall(Abstract_要旨)

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CITATION:

Xu, Jiawei. Evaluation of seepage and deformation of unsaturated slopes during post-shaking rainfall. 京都大学, 2021, 博士(工学)

ISSUE DATE:

2021-09-24

URL:

https://doi.org/10.14989/doctor.k23485

RIGHT:

学位規則第9条第2項により要約公開; 許諾条件により要約は2022-08-24に公開

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論文題目	Evaluation of seepage and deformation of unsaturated slopes during post-shaking rainfall （地震後の降雨における不飽和斜面の浸透・変形の評価）		

（論文内容の要旨）

This study sets out with the aims of evaluating the effect of earthquake on seepage and deformation of slopes subject to the rainfall after earthquake and examining the impact of different factors such earthquake intensity and rainfall intensity on the response of slopes to rainfall. Centrifuge model tests and numerical simulations were performed. There are six chapters in total in the thesis.

Chapter 1 presents the introduction. Prior studies have implied the importance of earthquake on the slope behavior during the post-earthquake rainfall, but little was found in the literature on the quantitative assessment of the effect of earthquake on slope response to the subsequent rainfall, and the impact of rainfall on both stability and failure patterns of slopes that have been subject to pre-rainfall earthquakes has not been explicitly investigated yet. This study was carried out to evaluate the importance of earthquake on the behavior of slopes during the post-earthquake rainfall and examine the impact of earthquake and rainfall on landslide occurrence and kinematics during rainfall.

Chapter 2 presents the review of current literature related to the response of slopes to shaking and rainfall, the application of inflight rainfall simulator to modeling of slopes under different conditions, and the stability of slopes with cracks during rainfall. The current studies of slope behavior during rainfall have provided great assistance in the understanding of failure mechanism of slope failure under different conditions, but the consideration of pre-rainfall shaking is lacking. As to the studies of seismic slope behavior, studies were also concentrated on the stability and failure of slopes subject to seismic loading, with no consideration of the impact of the following rainfall. Despite the investigation of stability of slopes with cracks under rainfall, the modeling of cracks was still too simplified and did not reflect the generation of cracks. Apart from that, the discussion was mainly centered on the slope stability and the studies of deformation of slope with cracks were insufficient.

Chapter 3 presents laboratory test results, including sieve analysis, soil compaction, monotonic triaxial test results, cyclic triaxial test results, soil-water characteristic curve (SWCC), and hydraulic conductivity.

Chapter 4 presents results and discussions of the centrifuge modeling of the response of unsaturated slope subject to shaking and rainfall. The experiments revealed that, once shaking caused cracks on the slope shoulder, the behavior and failure of the slope under rainfall became different and was related to rainfall intensity. The effect of preferential flow due to

cracks was more significant during rainfall with a higher intensity and heavy rainfall accelerated the failure of the crack-containing slope, leading to a fast and massive landslide. In addition, for the slopes containing shaking-induced cracks, even though being under the same rainfall, they were different in the deformation magnitude. The slope that experienced larger antecedent shaking had more deformation during rainfall and the previous shaking-induced slope deformation decided the slip surface location. Finally, the velocity of rainfall-caused landslide could be greatly influenced only because of the prior shaking event. Despite a low intensity, the rainfall could still lead to an instant landslide once the slope has encountered more intense antecedent shaking.

Chapter 5 presents results and discussions of the numerical modeling of the response of unsaturated slope subject to shaking and rainfall. First, slope deformation caused by shaking was largely reproduced in the numerical simulation. Then, a permeability-deformation model was proposed for the simulation of post-shaking seepage and deformation analysis. The simulation result showed that the proposed method was applicable to the seepage and deformation simulations of slopes subject to post-shaking rainfall and the failure features of slope during post-shaking rainfall was confirmed to be different from that of the slope during only rainfall, due to the impact of shaking. In addition, soil displacement and the pore water pressure response were well reproduced by the simulations. Finally, the proposed method was found to have good performance once applied to more complex conditions where slopes were subject to rainfall, shaking, and rainfall.

Chapter 6 presents the summary, which consists of conclusions, future work, and application in disaster prevention.

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（論文審査の結果の要旨）

本論文は、地震後の降雨に対する不飽和斜面の浸透・変形挙動を評価することを目的としたものである。地震によって斜面にクラック等の変状が発生し、その後の降雨によってその変状が拡大する事例が報告されている。これまで降雨や地震が斜面挙動に与える影響は検討されているが、地震後の降雨を扱った研究はほとんどない。そこで、本研究では遠心模型実験や数値解析を用いて、降雨前の地震の強さや降雨強度が不飽和斜面の挙動に与える影響を調べた。得られた主な成果は次の通りである。

１．遠心模型実験では、傾斜基盤上の不飽和斜面の小型模型を用いた。遠心場において、振動台により斜面を加振した後、新たに開発した降雨発生装置を用いて斜面に降雨を与えた。実験では、加振加速度、降雨量、加振前の条件を変えて、降雨時の不飽和斜面の変形を観察した。実験の結果、加振によるクラックは法肩近くで発生し、そのクラックの存在は後の降雨時の挙動に影響し、地震後の降雨による変形は降雨強度と加振強度の両方の影響を受けることがわかった。降雨強度が大きい場合、クラックの存在による優先的な地下水流れの影響が顕著となり、揺れによるクラックに沿った斜面の崩壊を加速させることがわかった。一方、降雨強度が小さい場合、加振の影響は比較的小さかった。さらに、異なる加振強度で同じ降雨量を与えた場合、降雨時の変形挙動は事前の加振強度に応じて変化し、加振強度が大きい場合では降雨時の変形速度が大きくなることがわかった。

２．数値解析では、土・水・空気連成の多孔質体理論と弾塑性モデルを用いた有限要素解析を実施した。はじめに降雨時および加振時のみの模型実験を再現し、解析は実験で得られた斜面の浸透・変形挙動をよく再現した。次に加振による土の物性の変化を再現するために、地震後のひずみに依存した透水係数モデルを新たに提案し、降雨時の浸透解析に組み込んだ。また、地表面付近のクラックによる透水係数の変化も考慮した。解析は実験での斜面内の間隙水圧応答を再現し、加振の有無による降雨時の斜面の浸透・変形挙動の違いを再現した。

以上のように、本論文は降雨時の不飽和斜面の浸透・変形挙動に対して降雨前の地震の影響を実験的・解析的に評価したものであり、今後の斜面防災に対して有益な知見を与えるものと評価でき、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３年８月６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。