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論文内容の要旨

Earthquake-induced landslides are widely recognized as destructive secondary geological hazards in mountainous regions. They may involve small or large volumes of soil, rock or both, and could develop into debris flows or avalanches characterized by high mobility and long runout distances. In particular, tephra-mantled terrains in the vicinity of active volcanic centers are highly susceptible to catastrophic, regionally distributed landslide clusters, owing to the presence of fully saturated and highly weathered pyroclastic fall deposits. Therefore, understanding the material properties that govern the slope instability in such environments is crucial for effective hazard assessment and mitigation.

Building on the susceptibility of tephra-mantled terrains to earthquake-induced slope failures, halloysite-rich deposits within the sliding layers have been identified as a key material factor controlling slope instability. This is because the formation of halloysite during the weathering induces structural, hydrologic, and mechanical alterations that significantly weaken the slope stability. Moreover, the morphology of halloysite, including spherical and other distinctive habits, has been reported to be closely related to the mechanical behavior of halloysite-bearing pyroclastic fall deposits in volcanic terrains. These morphological characteristics strongly influence water retention capacity, soil structure, and shear resistance, thereby enhancing the susceptibility of tephra-mantled slopes to failure during earthquake shaking.

A representative example of such halloysite-bearing slope failures is provided by the 2018 Hokkaido Eastern Iburi Earthquake. This event triggered numerous landslides, most of which were shallow debris slides, with only two identified as deep-seated landslides. Previous studies indicated that the predominant controlling factor in these slope failures was the widespread occurrence of halloysite within pyroclastic fall deposits.

However, the specific morphology of halloysite present in these deposits and its role in controlling slope instability have not yet been clarified.

To address this knowledge gap, the comprehensive physical, mechanical, and mineralogical analyses were conducted on landslide materials collected from the affected areas. Accordingly, this study presents a detailed characterization of weathered Ta-d pumice (tephra derived from Tarumae volcano) from the Asahi and Uryu landslides triggered by the 2018 Hokkaido Eastern Iburi Earthquake. The yellowish-brown Ta-d pumice exhibited low dry density and high natural water content. Laboratory examinations included grain-size distribution analysis, Atterberg limits, and one-dimensional consolidation tests and static triaxial compression tests conducted on undisturbed and reconstituted samples. In addition, X-ray diffraction (XRD) examination and scanning electron microscopy (SEM) analysis were carried out to identify the clay mineral and to examine its micromorphology.

Laboratory results indicated that the weathered Ta-d pumices had liquid limit values of 89.34% and 61.76%, plasticity index values of 24.13% and 17.52%, and permeability value of about 4×10^{-7} cm/s, as well as peak effective cohesion of 11.2 and 5.8 kPa and peak effective internal friction of 20.8° and 23.1°, respectively. XRD analyses showed that halloysite is the dominant clay mineral in all samples, and SEM observations revealed that it dominantly occurs in “crinkly halloysite” habits. This morphology is associated with the spherical halloysite that can facilitate saturation of the slip layer and a critical reduction in shear resistance.

On the other hand, beyond understanding the material properties governing slope instability, predicting the potential occurrence and post-failure behavior of earthquake-induced landslides, particularly those characterized by rapid and long runout distances, has become increasingly important for landslide mitigation and disaster prevention. Quantitative hazard assessment of such landslides is essential for to predicting the spatial extent and characteristics of their motion. Given the complexity of complication of landslide movement processes, numerical simulation is commonly regarded as an effective method for conducting back analyses of post-failure motions.

Accordingly, this study reproduced the motion processes of two representative landslides using the LS-RAPID program. The Aso-Bridge landslide occurred on April 16, 2016, and was characterized by the rapid movement and a long runout distance. The Kataragai landslide occurred on April 9, 2018, and traveled with flow-like behavior. This work presented features and mechanical parameters of these two landslides by means of survey investigations and laboratory experiments. Pre-failure models of these two landslides were established, and their motion processes were simulated using the LS-PAPID program. Two indicators, consisting of the sliding speed and traveling morphology at different intervals, were employed to describe the motion processes. Results indicated that the resultant maximum sliding speeds of the Aso-Bridge and Kataragai landslides were approximately 297.1 m/s and 43.6 m/s, respectively, and that the post-failure morphologies were consistent with those observed in field investigations.

By integrating field investigations and laboratory testing, this study provides a comprehensive understanding of the role of material properties in controlling slope failure mechanisms of earthquake-induced landslides. Moreover, building on the understanding of failure mechanisms, this study reproduces landslide motion processes using numerical simulation. The findings not only advance fundamental knowledge of halloysite-rich pyroclastic fall deposits and their influence on landslide occurrence, but also offer valuable insights for quantitative hazard assessment, early warning, and slope mitigation strategies in seismically active or rainfall-prone volcanic regions. In particular, the results highlight the critical role of halloysite-bearing material behavior in governing both landslide failure.

論文審査結果の要旨

申請者の論文は，全 7 章から構成されている。第 1 章（Introduction）では，地震を引き金とする地すべりに関する研究の必要性および本研究の目的が述べられている。第 2 章では，先行研究のレビューを通じて課題の整理が行われている。特に，火山地帯では非火山地帯における地震に伴う地すべりと比較して，地すべり土塊の移動性が高いことが示され，軽石などの風化に伴って形成されるハロイサイトと呼ばれる粘土鉱物が地すべりの運動に大きく影響することが指摘されている。第 3 章では，本論文で採用した研究手法について述べられている。具体的には，現地調査（例：土質特性の原位置試験），室内実験（例：粒度分析および静的圧密非排水三軸圧縮試験），X 線粉末回折（XRD）および走査型電子顕微鏡（SEM）による鉱物学的分析，ならびに LS-PAPID プログラムを用いた地すべり運動過程の数値解析について解説している。第 4 章では，上記の土質試験および各種分析結果に基づき，変質したハロイサイト含有テフラの物理的・力学的・鉱物学的特性を示すとともに，降下火砕堆積物中における地震誘発地すべりの崩壊メカニズムについて議論を展開している。第 5 章では，地震誘発地すべりの高い移動性および長距離移動挙動を支配する原位置での力学特性に焦点を当て，急速な移動をもたらすメカニズムについて考察している。第 6 章では，近年発生した代表的な地震誘発地すべりの運動過程について，阿蘇大橋地すべりおよび島根県美郷町枦谷（かたらがい）で発生した地すべりを対象とし，現地調査および室内実験で得られたパラメータを基に，LS-RAPID 法によるシミュレーションを実施している。その結果に基づき，速度変化や運動特性などの動的挙動について議論し，両地すべりの運動像を評価している。第 7 章では，本論文の主要な成果を総括している。

本論文は，火山噴出物が厚く堆積した地域で発生した北海道胆振東部地震に伴う地すべりを主たる対象としている。野外調査，各種土質試験，XRD 分析，SEM によるすべり面周辺から採取した粘土試料の組織観察に基づき，クリンキー型の形態を有するハロイサイトを記載している。さらに，土質試験結果および粘土鉱物の詳細な組織観察に基づいて，その高い保水性および流動性について議論し，これらが地すべり発生に重要な役割を果たしたことを明らかにした。また，ハロイサイトの鉱物学的特性についても先行研究を踏まえた丁寧な考察がなされ，その地すべり発生における重要性を明確に論じた点は高く評価できる。日本国内では島根県を含め，火山噴出物が厚く堆積する地域が広く，緩傾斜地であっても地すべりのリスクが存在することを本研究は示している。こうした地域における地すべりリスク評価のために，粘土鉱物に関する詳細な解析が不可欠であることを強調するものである。さらに，阿蘇大橋地すべりおよび島根県美郷町枦谷地すべりの複雑な運動様式を解明するとともに，これらが相当な高速で移動した可能性を指摘した点は，火山噴出物分布地域における地すべり災害への警鐘となる成果である。

以上を総合的に判断すると，本論文は博士の学位を授与するにふさわしい内容を備えていると評価できる。