MECHANISM OF LARGE-SCALE FLOWSLIDES DUE TO THE 2018 SULAWESI EARTHQUAKE, INDONESIA

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(2018 年インドネシアスラウェシ地震による大規模な流動化破壊の発生機構に関する研究)

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論　文　内　容　の　要　旨

The 2018 Sulawesi earthquake triggered massive flowslides at four key locations Balaroa, Petobo, Jono Oge, and Sibalaya, in the Palu Valley of the Central Sulawesi Province, Indonesia, engulfing localities and killing thousands of people. Ground displacement was observed up to a distance of a few hundred meters to a few kilometers at a rapid pace during the sliding. The terrain where these flowslides occurred had a very gentle gradient of less than 5% on average. In addition to it, the flowslides triggered 1-2 minutes after the earthquake ceased to happen.

Multiple hypothesis have been proposed by researchers on the exact cause of such massive landslides, one of them is the water film formation due to liquefaction under the low permeable cap layers, while the other is due to probable rupture of an underground aquifer, supplying additional water to the already liquified surface layer, sustaining the flow for long-distance and duration. Alternatively, the existence of a shallow water table beside the seepage from unlined irrigation canal destabilizing the already metastable alluvial fans was also proposed. However, there were no flowslides observed in other locations in Palu despite meeting the alternative conditions, therefore this hypothesis alone cannot be implied. Furthermore, for the formation of water film in a large area, the cap layers need to be continuous, which may or may not be realistically possible. Therefore, it is necessary to clarify the mechanism of such long-distance flowslides in gently sloping ground based on the field data, laboratory tests, and numerical simulations of those.

The purpose of this study is to 1) identify the site conditions which might have significantly contributed to the triggering of the flowslide, (2) simulate the site heterogeneities through experimental studies and, (3) to numerically elucidate the forces generated in the soil profile and which could have led to the flow failure.

To realize the stated objectives, field investigations of the flowslide areas are performed, involving quadcopter survey, portable dynamic cone penetration testing (PDCPT), disturbed and undisturbed soil sampling and recording soil profiles through trenching to assess the in-situ ground condition and perform soil classification. The site heterogeneities are then simulated experimentally through 1D soil column tests with varying cap layer configurations. 1g shaking table tests are performed to evaluate the soil particle movement during failure. Later, numerical simulations are carried out to simulate the 1D experimental models and determine the forces and stresses generated in the soil model and qualitative evaluation of the flow side mechanism are made clear.

The trench surveys confirmed the presence of multiple fine silt and clay layers between coarse sandy or gravelly layers, which were classified as most liquefiable based on the N values obtained from PDCPT tests and grain size classification. These fine layers could have acted as a capillary barrier against

the upward flowing pore water leading to the formation of water films. Through the experimental model tests, it was observed that, the permeability and plasticity of cap layer wielded significant influence on the dissipation of excess pore water pressure and the soil settlement duration. In the numerical studies, formation of a localized low confinement and high shear strain zone below the cap layers was observed, which signal soil dilation at that elevation. From the observations made through this research, it can be concluded that the low permeable plastic cap layers tend to form a slip surface with high hydraulic gradient, which may lead to flowslide.

This thesis is organized into 6 chapters. The contents of each chapter are summarized as follows:

Chapter 1 highlights the background of the 2018 Sulawesi earthquake and the geodynamics of the Palu valley. Past research published related to this earthquake and flowslides on gentle ground is highlighted and the necessity for a better understanding of the failure mechanism in multi-cap layer environment is discussed. Finally, the objectives and originality of the research are introduced.

Chapter 2 presents the findings of the site investigations carried out at the flowslide locations. Multiple cap layers in the form of fine silt or clay layers in between coarse sandy layers were present, although the particle size and characteristics of the cap layers varied from each trench. The samples from the fine soil layers were classified as most liquefiable, while those from gravely layers had a high potential of liquefaction with fines content more than 10%. Furthermore, with low bearing strength at shallow depth and high-water table, these layers were most likely to have liquefied during the earthquake and led to formation of water film below the cap layers.

Chapter 3 discusses the limitations of the past centrifuge and 1g shaking table test studies performed on the influence of cap layers under dynamic loading. It proposes an alternative method involving the use of particle image velocimetry (PIV) in 1g shaking table tests to evaluate the trend of particle movement during a flowslide which has not been clarified yet. It is observed that, the cap layer influences the particle movement during the slope failure along with the duration of initiation of failure.

Chapter 4 describes the existing research on the one-dimensional soil column experiments with cap layer and presents new modifications confirming to the heterogeneities observed in field. A one-dimensional soil column with single and double cap layer configuration is imparted with a shock load and the trend in excess pore pressure dissipation, soil settlement, and formation of water film are studied. The effect of the presence of a cap layer with different permeability is also evaluated. It was found that the number and permeability of cap layers significantly influenced the magnitude and dissipation time of the excess pore water pressure from the underlying layers along with the soil settlement.

Chapter 5 describes the existing research on the numerical simulation of soil strata with single cap layers and their limitations. New modifications relating to the field observations are implied in the proposed models with multiple cap layers and cap layers with different permeability. 1D site response analysis of these soil models is carried out using a coupled solid-fluid computational porous soil model. The results of the parametric study were evaluated by examining the pattern of excess pore water pressure buildup and dissipation, along with shear strain and confinement stress developed in the soil profile to determine the zone of probable failure. Through the simulations, it was observed that very low confinement and high strain zone is developed at the cap layer interface which signals a zone of failure.

Chapter 6 concludes the results and achievements of the research and sheds light on future research.