パルス性地震動に着目した地震による斜面崩壊メカニズムの解明研究

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論 文 名：STUDY ON THE MECHANISM OF EARTHQUAKE-INDUCED LANDSLIDE FOCUSING ON THE PULSE-LIKE GROUND MOTIONS
(パルス性地震動に着目した地震による斜面崩壊メカニズムの解明研究)

区　　分：甲

論　文　内　容　の　要　旨

Earthquake-induced landslide is one of the significant secondary hazards of an earthquake. Even in a country like Japan, one of the advanced countries in earthquake disaster prevention, earthquake-induced landslides could still cause catastrophic disasters. For example, the 2016 Kumamoto earthquake (M7.3) and the 2018 Hokkaido Eastern Iburi earthquake (M6.5) induced landslides resulting in 15 victims and 39 victims separately, even though no victim resulted from building collapse due to the advance of quake-resistance technology of buildings. Thus, it is necessary and important to develop a more accurate prediction method on landslide-prone slopes based on the active fault information and potential earthquake magnitude. However, the mechanism of the earthquake-induced landslide has not been completely clarified up to now.

Slope stability is related to both the slope's inherent factors such as geological and physical properties and the external triggering forces from seismic waves. Up to now, the peak ground acceleration (PGA) of the seismic wave has been considered as earthquake triggering force of landslide. Thus, slope instability is related to PGA in some slope stability analysis methods such as the Pseudo-static analysis and landslide hazard mapping. However, by using PGA, it is impossible to explain the following two phenomena occurred during some earthquakes: (1) large-scale landslides occurred in the area with small PGA while no landslide in the area with large PGA; (2) one side slope collapsed while the opposite side slope back to back remain stable even though PGA is almost the same for the two slopes. In fact, it is believed that slope stability should also be affected by the energy of the seismic wave, which is not always proportional to PGA since seismic energy is related not only to the magnitude but also to the frequency of a seismic wave. Therefore, how to clarify the mechanism of earthquake-induced landslides from the view of seismic energy is very important in order to explain the above two phenomena.

This study aims to (1) clarify the mechanism of earthquake-induced landslides focusing on the pulse-like ground motion (PLGM) by using Discontinuous Deformation Analysis (DDA) simulation and (2) explain the above two phenomena. PLGM contains large seismic energy whatever PGA is in a seismic wave. DDA is a powerful numerical method for landslide simulation considering the dynamic behaviours of a rock mass system involving discontinuities. At first, the original DDA is improved so as to be used in slope stability analysis under seismic waves by modifying vertex-to-vertex contact processing and adding a unified tensile fracture criterion. Then, a method for evaluating the dynamic failure of the slope considering seismic energy is proposed in DDA. It is shown that a slope can collapse under a PLGM seismic wave with small PGA while it keeps stable under a large PGA seismic wave without PLGM. Thirdly, a case study on a landslide in the 2016 Kumamoto earthquake triggered by PLGM with a small PGA is performed to verify the proposed method. Finally, a possible mechanism of earthquake-induced landslides based on PLGM is clarified to explain the above mentioned two phenomena by investigating PLGM and PGA characteristics of various seismic waves and slope’s physical properties.

The contents of the thesis are organized as follows:

Chapter 1 introduces the background, scope and objectives of the research. Previous studies on the mechanism of landslides, analytic methods of earthquake-induced landslides, and studies on PLGM in the architecture field are reviewed and existing problems are briefly discussed.

Chapter 2 reviews the state-of-the-art of 2D DDA and numerical simulations for earthquake-induced landslides. The basic theory of DDA formulation and developments of the DDA program are introduced. The advantages of DDA application to numerical landslide simulation are reviewed. The problems of the original DDA are also clarified for improvement and extension in this study.

Chapter 3 improves DDA by modifying the vertex-to-vertex contact processing and incorporating a unified tensile fracture criterion for better slope stability analysis under seismic conditions. At first, a missing case of vertex-to-vertex contacts is found in the original DDA, which has no significant effect on general applications but the effect cannot be ignored on the landslide simulations under seismic waves. Thus, a new concept for vertex-to-vertex contact is introduced to enhance the contact detection algorithm. Then, a unified fracture criterion by combining shearing strength with tensile strength is incorporated into DDA to simulate the rock fracture behavior of various materials since only the Mohr-Coulomb criterion and maximum normal stress criterion are adopted in the original DDA, which can not be used to analyze the materials with correlation between shearing and tensile strengths. The accuracy of the improved DDA is validated by numerically reproducing several Brazil disc split tests, which are well used for verifying numerical methods. The simulated results agree well with those from experiment tests while no good results can be obtained by using the original DDA.

Chapter 4 proposes a method for slope stability analysis under earthquakes by considering the energy of seismic waves in DDA simulation. Earthquake-induced slope failure is related to not only PGA representing the maximum inertial force of a seismic wave but also seismic energy reflecting both amplitudes and frequencies. Although many PGA-based analytical methods have been developed, there is no energy-based slope stability analysis. For this reason, a dynamic failure method considering the effect of fatigue and cumulative damage of a seismic wave is proposed to analyze earthquake-induced slope failure by extending DDA as follows. 1) An effective-repeated loading (ERL) stress is defined based on slope's physically static strengths; 2) The cyclic number N of ERL accumulates as loading stress is larger than ERL stress in DDA simulation for the whole seismic wave. 3) Once the N reaches the critical number $N\mathrm{c}$, the slope failure occurs. A practical slope is modelled under two cases of seismic waves: large energy but small PGA (Case A: PLGM seismic wave) and large PGA but small energy (Case B: Non-PLGM seismic wave). The results show that the slope gets failure by using the energy-based DDA while keeps stable by using the original PGA-based DDA for Case A; but the results are inversed for Case B, which are also in agreement with seismic response analysis of SDOF system. Thus, the accuracy and effectiveness of the proposed energy-based DDA are validated and the energy of seismic waves is a key triggering factor in slope stability analysis under earthquakes.

Chapter 5 clarifies the mechanism of earthquake-induced landslides focusing on PLGM by explaining the two phenomena. A PLGM seismic wave contains a large velocity pulse waveform which is of large seismic energy. PLGM is usually caused by the so-called forward directivity effect in the near-fault area. PLGM seismic waves are identified at 3 K-NET observation sites in the Aso area where large-scale landslides occurred. Non-PLGM seismic waves with PGA>600 gal are also recorded at other 2 K-NET observation sites in the around areas where no landslide occurs. A DDA slope model is analyzed by using the energy-based method under the all 5 seismic waves. The results show that the slope gets failure under the 3 PLGM waves with small PGA but keeps stable under the 2 Non-PLGM waves with larger PGA. Thus, PLGM is one of key factors of triggering landslides in the near-fault area. In order to explain the second phenomenon, a symmetrical DDA model of two back-to-back slopes is analyzed. The results show that one slope can get failure while the other side slope keeps stable. The aspect of the failure slope is the same as direction of the PLGM velocity pulse but it is inversed for the case of shear failure dominated. Therefore, it is shown that the seismic energy from PLGM is the major triggering factor of earthquake-induced landslides in near-fault areas. It should be paid more attention to PLGM in the possible forward directivity effect area near seismic fault in predicting landslide-prone slopes.

Chapter 6 summarizes the conclusions of the study and proposes recommendations for future research.