

PROBABILISTIC RISK ASSESSMENT FOR EARTHQUAKE- INDUCED SLOPE FAILURE USING GPU-ACCELERATED MATERIAL POINT METHOD

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論 文 名 : PROBABILISTIC RISK ASSESSMENT FOR EARTHQUAKE-
INDUCED SLOPE FAILURE USING GPU-ACCELERATED
MATERIAL POINT METHOD
(GPU 並列 MPM を用いた地震時斜面崩壊の確率的リスク評価)

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論 文 内 容 の 要 旨

Slope failure is one of the most destructive geological hazards. While conventional slope stability analyses focus on calculating the factor of safety for the slope, the large deformation analysis of collapsed slope provides a more accurate hazard assessment for downstream infrastructure and communities. The behavior of a post-failure slope is mainly controlled by the residual soil strength subjected to external forces such as rainfall and earthquake. Moreover, it is widely reported that soil properties of natural slope exhibit significant spatial variability due to natural geological processes. Therefore, it is important to introduce a probabilistic approach to evaluate the slope failure risk and its potential damage. From these background, this study aims to: (1) develop a large deformation slope analysis using a GPU-accelerated Material Point Method, (2) investigate the effects of seismic motion in conjunction with spatial variability of soil shear strength on slope failure mechanisms, and (3) propose a novel risk assessment framework that integrates collapsed slope kinematics with the resistance capacity of affected structures. The main contents of each chapter are summarized as follows:

Chapter 1 emphasizes that the post-failure large deformation plays a decisive role in determining the hazard potential of slope failure. It outlines the motivations and the primary research scopes of the dissertation.

Chapter 2 reviews the state of the art in probabilistic analysis of post-failure slopes, emphasizing the role of random field theory in representing spatial variability of soil shear strength. While prior studies have assumed gravity and rainfall as a triggering factor of slope failure, earthquake-induced slope failures under the effects of the spatial variability of soil shear strength remain insufficiently explored. The chapter also notes that conventional risk assessments for slope failure often use the runout extent of collapsed slope as a damage index, which overlooks the intensity of slope failure kinematic impacts and the resistance of affected structures.

Chapter 3 presents the development of a GPU-accelerated Random field Material Point Method (GPU-RMPM) for the efficient probabilistic analysis of post-failure slopes. In addition, a strain-softening constitutive model is adopted to introduce the shear strength degradation of collapsed slope in post-failure phase. The proposed method accelerates Monte Carlo simulation (MCS) significantly when there is spatial variability in soil shear strength. In single-layer slope, residual shear strength and the coefficient of variation are strong influence post-failure behaviors such as runout distance, influence range, and sliding volume. For two-layer slope, progressive failure yields a large hazard potential, increasing runout distance by over 27%,

while the failure probability increases about 3 times with increasing vertical correlation length. The GPU-RMPM achieves over 53 times speedup compared to CPU-based analysis, enabling large-scale MCSs of a large deformation analysis of collapsed slope.

Chapter 4 presents the probabilistic risk assessment of earthquake-induced slope failure. Parametric studies show that dilation angle and residual strength affect both failure initiation and post-failure deformation critically. From the result of MCSs on a two-layer slope with the spatial variability of soil shear strength, seismic motion significantly increases failure probability from 1.28% under static condition to 5.00% at the horizontal acceleration of 400 gal. When duration of seismic motion increase from 15 s to 30 s, the failure probability increases by 43% and the probability of progressive failure mode rises by 10%.

Chapter 5 proposes a novel probabilistic landslide risk assessment framework that integrates landslide kinetic energy (LKE) with structural resistance using GPU-RMPM. A LKE-based risk assessment could quantify the local impact energy of collapsed slope along the landslide path. Combined with structural resistance, the proposed assessment enables a precise location-specific risk classification. Based on the application of proposed risk assessment to the Aso Bridge landslide occurred in the 2016 Kumamoto earthquake in Japan, the failure probability of multiple structural components of Aso Bridge is estimated to be close to 100%, categorized as “extremely high risk”.

Chapter 6 concludes with the results of this dissertation and offers recommendations for future research directions.