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# Numerical study on dynamic behavior of slope models including weak layers from deformation to failure using material point method

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**Abstract**

This paper describes numerical studies on the dynamic behavior of experimental slope models, including various inclined weak layers. These studies were conducted by simulation of shaking table tests using the material point method (MPM), which allows seamless treatment of various considerations, from elastic behavior to discontinuous collapse behavior of slopes, on the basis of an elasto-plastic constitutive law. The simulation results showed that the failure modes, progressive deformation and downward sliding of the numerical slope models, which were similar to that observed in the shaking table tests, can be obtained using the numerical method. In addition, sensitivity analyses of the numerical models used in this study were performed to determine the effects of mesh size, number of particles per cell (PPC) and damping constants on the simulation results. The results of these analyses indicated the use of fine meshes and high damping constants seems to produce sensible results and reduce numerical noises, respectively.


*Keywords:* Earthquake induced slope failure; Shaking table test; Material point method

## 1. Introduction

To ensure seismic safety of nuclear power plants in Japan, careful consideration should be made of their safety preparedness regulations against slope failures. Currently, slope safety is mostly evaluated by limit-equilibrium analysis conducted using methods such as Fellenius, Bishop, Spencer, Janbu, and Morgenstern-Price, or by finite element method (FEM) analysis (The Japan Electric Association, 1987), which focuses on slope stability before failure. However, particularly since the 2011 Tohoku earthquake, it is necessary to improve methods of evaluating the safety of slopes in the vicinity of nuclear power plants and to evaluate slope's dynamic behavior from deformation to failure to assess residual risk after failure during unexpectedly large earthquakes. In addition, the importance of top-slope stability has become critical because these areas are often installation locations for mobile equipment, such as emergency power supplies, to prevent or mitigate severe accidents at nuclear power plants. Thus, it is important to conduct a review of the current evaluation method, which focuses on dynamic behavior of slopes from deformation to failure with a view to improve it.

The current numerical methods of evaluating slopes, including the FEM, have difficulties in solving large deformation problems because of excessive mesh distortions.

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This inhibits the development of numerical methods that focus on dynamic behavior of slopes from deformation to failure. To overcome such challenges, several mesh-free methods, such as smoothed particle hydrodynamics (SPH, Gingold and Monaghan, 1977; Lucy, 1977), element-free Galerkin method (EFGM, Belytschko et al., 1994), moving particle semi-implicit method (MPS, Koshizuka and Oka, 1996) and material point method (MPM, Sulsky et al., 1994, 1995), have been applied to slope failure problems. These methods allow for seamless treatment of considerations ranging from elastic to discontinuous collapse behavior of slopes based on a constitutive law, which is able to address the slope failure problems that are inherent in models simulating large deformation and complicated elasto-plasticity. In this study, the MPM was highlighted as the preferred numerical method for analysis because the MPM offers many attractive features for dealing with slope failure problems over other mesh-free methods, which will be explained in Section 2.

However, it is necessary to verify the MPM's compatibility with the experimental results of the slope failure problems in order to confirm the MPM's applicability to numerical analysis of earthquake induced slope failure. One of the most advantageous features of the MPM is the ability to be capable of seamless treatment of different slope failure process, ranging from elastic to discontinuous collapse. Some studies have already investigated the application of the MPM to the slope failure problems, comparing numerical to experimental results (e.g., Kiriyama, 2012, 2014; Ceccato et al., 2014; Bandara and Soga, 2015; Soga et al., 2016). However, these studies have mainly focused on reproducing slope configurations after failure and large deformation. Few studies have performed comparisons between numerical and experimental results focusing on reproducing the slope failure process from elastic to discontinuous collapse, although this is one of the most advantageous features of the MPM. Therefore, this study emphasizes reproduction of the dynamic behavior of an experimental slope model from elastic deformation to failure state.

The subject of the MPM simulation is a shaking table test performed by Shinoda et al. (2015), with experimental slope models that include a weak layer. The shaking table tests focused on dynamic behavior of the experimental slope models during shaking, ranging from deformation to failure. The experimental slope models had a weak layer in which soil strength was lower than other layers. In addition, the test included various types of experimental slope models with the weak layers at different inclines, which was valuable to show the influences of layer angle and the strength of the weak layers on the landslide mass above the weak layer, which exhibited large deformation (Shinoda et al., 2015).

Hence, this study has focused on comparison between simulation and experimental results regarding displacement and response acceleration of the landslide mass above the weak layer. Each layer of the various experimental slope models was modeled on the MPM by clusters of Lagrangian particles. Stress-strain relation of a material specimen in the weak layer during tri-axial compression and cyclic tri-axial tests was modeled by an elasto-plasticity model including super/subloading yield surfaces. Simulations were performed using the numerical slope models and input waves measured from the shaking table tests. In addition, sensitivity analyses of the numerical models used in this study were carried out to examine the effects of mesh size, the number of Particles Per Cell (PPC) and damping constants on simulation results. Finally, applicability of the MPM to simulations of earthquake induced slope failure was discussed.

## 2. Advantage of material point method in slope failure problems

### 2.1. Advantage of mesh-free methods in slope failure problems

This study aimed to critically review the evaluation method, which focused on dynamic behavior of slopes from deformation to failure. As mentioned at Section 1, numerical methods such as the FEM have difficulties in solving large deformation problems because of excessive mesh distortion. Numerical methods with a discontinuum model such as the DEM can estimate the large deformation and discontinuous collapse behavior, which make it preferable over methods such as the FEM to examine large slope deformations. However, selection of discontinuum model parameters for input, such as spring and dashpot constants, is a crucial step. Moreover, modeling requires real problems to be idealized to fit constraints imposed by factors such as available material models and computer capacity.

On the other hand, several mesh-free methods such as the SPH, EFGM, MPS, and MPM, which were mentioned in Section 1, have been applied to slope failure problems to overcome the issues of numerical methods such as the FEM and DEM (e.g., SPH, Maeda et al., 2006; Bui et al., 2007, 2008, 2011a, 2011b; EFGM, Sato and Matsumaru, 2006; MPS, Yoshida, 2011; MPM, Wieckowski et al., 1999; Konagai and Johansson, 2001; Wieckowski, 2004; Andersen and Andersen, 2010; Abe et al., 2007, 2010, 2012, 2013, 2014, 2015; Higo et al., 2010, 2014, 2015; Beuth et al., 2011; Zabala and Alonso, 2011; Kiriyama, 2012, 2014; Ceccato et al., 2014; Yerro et al., 2015a, 2015b; Bandara and Soga, 2015; Soga et al., 2016). The slopes can be modeled using mesh-free methods by clusters of Lagrangian particles, which eliminates the problem of mesh distortion in large deformation problems.

Fig. 1 is an image of the scope of application of the mesh-free methods, FEM and DEM, at analyzing soil stress–strain relations. The mesh-free methods are capable of addressing large strains which cause changes in the effective stresses, material properties, and geometry, which cause slope failure. Deformation of the soil becomes dis-