Seismic slope stability analysis of soil-rock-mixture using the coupled 2D DDA-SPH method

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Introduction

Earthquake-induced landslide is one of the significant secondary hazards of an earthquake. 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. Soil-rock mixture (SRM), which is mainly composed of rock blocks and fine soil, is widely distributed over nature, especially in mountainous areas. It is necessary to study the mechanical behaviors of SRM for the prediction and mitigation of landslide disasters, however, which is still a challenging issue. In previous studies, due to its heterogeneity and complex physical and mechanical properties, this geomaterial was commonly simplified as a uniform media without considering the influence of rocks. In this study, the 2D coupled DDA-SPH method is used for the applications of stability analysis of SRM slopes under seismic loading. To investigate the influence of rock on the stability of the slope, an SRM slope model and a homogenous soil slope model, where the slopes are both inclined at 26.57°, are analyzed in this study Through these numerical simulations, some conclusions and suggestions can be reached.

Numerical Method

DDA is a powerful numerical method proposed by Shi, which can be applied to analyze the movement and deformation of blocks in condition of both static and dynamic. Recently, numerous studies have shown that DDA is a powerful method in simulation of rigid blocks.

In SPH method, the continuum media can be discretized into a set of particles carrying physical properties of material and moving with the material velocity computed according to the governing equations. The interaction between particles is calculated by a kernel function. Through kernel and approximation functions, the governing equations and the constitutive equation become a set of ordinary differential equations that only rely on the variable of time. The fundamental principle of the strength reduction method is to gradually reduce the shear strength of material until the failure occurs to the slope.

In the coupled 2D DDA-SPH method adopted by Peng et al.[1,2], the SPH particles are employed to simulate the mechanical behaviors of soil, and DDA blocks are employed to model rocks and structures, viewed as moving boundaries for SPH particles. A penalty method is employed to calculate the interaction force between the SPH particles and the DDA blocks. As shown in **Fig. 1**,when a SPH particle approaching an edge of DDA blocks, regarding as a vertex-to-edge contact since the volume of SPH particles is much smaller than that of DDA blocks, repulsive forces of equal magnitude but in opposite directions will be applied to the contacted SPH particles and DDA blocks.

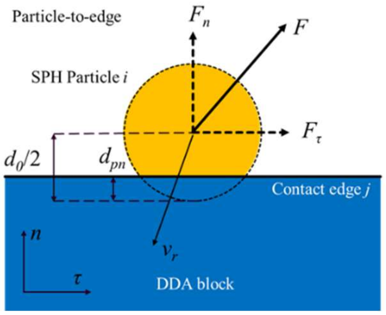

Fig. 1 Schematic view of the particle-to-block contact force.

In the past several decades, a lot of technique have been proposed and implemented in the numerical methods to calculate safety factor of the slope. Among them, the shear strength reduction technique is widely used for slope stability analysis in the finite element method. The fundamental principle of the strength reduction method is to gradually reduce the shear strength of material until the failure occurs to the slope. To determine the state of instability, the failure critical criterion is crucial. Recently, the failure critical criterion based on the distribution of plastic zones, abbreviated as DPZ criterion, is widely used in some FEM based research of slope stability analysis. When the plastic zone whether the plastic zone of the slope is in state of transfixion and formed a continuous plastic zone, the slope can be considered as unstable. In this research, the DPZ failure criterion will be employed for slope stability analysis.

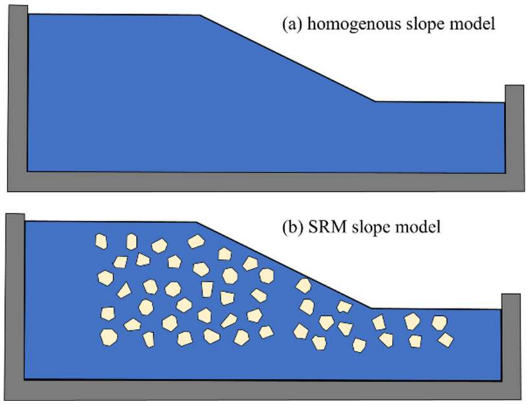

Fig. 2 Geometry of Homogenous slope and SRM slope.

The loading of the time-dependent acceleration is widely used by many researchers to conduct earthquake analysis. In this study, the input of seismic loading is accomplished by adding the acceleration of seismic loading to the base block. To investigate the influence of rock on the stability of slope, a SRM slope model and a homogenous soil slope model, where the slopes are both inclined at 26.57°, are analyzed in this study, see **Fig. 2**. These models are analyzed under a seismic loading based on the data from the 2018 Hokkaido Eastern Iburi earthquake (HKD126 Station). The interface friction angle ϕ_{cf} between particles and blocks is equal to the friction angle of soil. The number of edges of each rock is 4-7. The other parameters are listed in **Table. 1**. The size of rock blocks is featured by the equivalent radius, that is, the radius of a circle having the same area. The rock content of the SRM slope model is 20%. Notably, the rock content (RC) is calculated by the proportion of the area of the rocks.

Table 1 Material parameters of the SRM slope model

DDA block	Density(kg/m^3)	Poisson's ratio	Young's modulus(GPa)	Maximum displacement ratio	Spring stiffness (GPa)
	2300	0.2	10	0.001	20
SPH particle	Density(kg/m^3)	Poisson's ratio	Young's modulus(MPa)	Initial friction angle of particles (°)	Initial cohesion (kPa)
	2000	0.3	100	20	10

Simulation Results

The safety factor of the SRM slope model calculated from the DDA-SPH method is 0.995 while that of the homogenous soil slope model is 1.125. The safety factor in the simulation of SRM slope under seismic loading is smaller than that of homogenous slope. This suggests that rocks in SRM slope can decrease the seismic slope stability compared to homogenous slope. This phenomenon can be attributed to the difference in physical property between soil and rock. **Fig. 3** shows the distribution of the local failure when the strength reduction faction (SRF) is 1.0. The failure at first occurs at the toe of slope in two models. However, the development of local failure in the SRM slope model is faster than that of the homogenous slope. Additionally, the development of local failure in the homogenous slope model is continuous while in the SRM slope, the local failure occurs in the contact area between rocks and soil in the slope and gradually connects into a line. Moreover, the local failure in the SRM slope model continues to develop after the seismic loading while the local failure in the homogenous slope model stops developing.

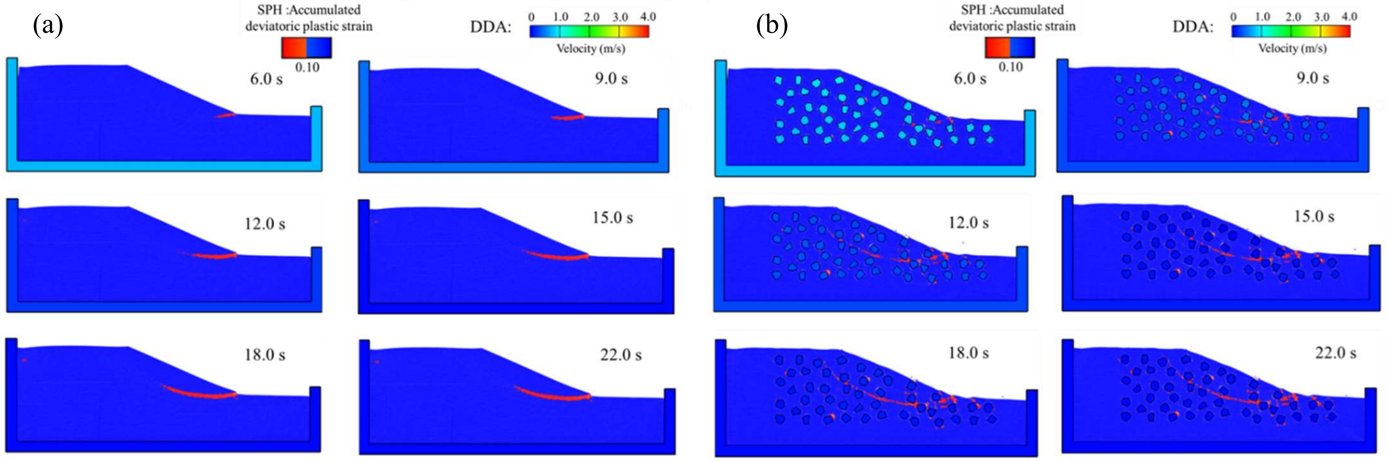

Fig. 3 local failure distributions in (a) homogenous soil slope model and (b) SRM slope model with SRF= 1.0.

Summary

1. The DDA-SPH coupled method was applied to the analysis of the SRM slope stability analysis considering seismic loading. To determine the safety factor, he failure critical criterion based on the distribution of plastic zones was employed in the presented method. The input of seismic loading was accomplished by adding the acceleration of seismic loading to the base block.
2. The safety factor in the simulation of SRM slope under seismic loading was smaller than that of homogenous slope. This suggested that rocks in SRM slope could decrease the seismic slope stability compared to homogenous slope. This phenomenon could be attributed to the difference in physical property between soil and rock.

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