# A FEM-DEM framework for progressive modeling of landslides

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## ABSTRACT

In practical engineering, characteristics of landslides, such as slope stability and influence area, should be carefully studied to facilitate mitigation constructions in regions at risk of landslide hazards. Most mitigation projects in design adopted numerical analyses, specifically in conventional landslide studies; however, if only a single numerical method is used, limitations of only capturing certain characteristics of landslides would result. We establish an effective and practical framework, incorporating finite element method (FEM) and discrete element method (DEM), to quantitatively examine the pre- and post-failure states of progressive landslides essential to help mitigation projects in regions prone to landslide hazards. Two catastrophic landslides are presented to demonstrate the capability of the FEM-DEM framework on progressive landslide examinations, including the Aso-Bridge landslide (coseismic landslide) and the Yanchao landslide (rainfall-induced landslide), both in 2016. In addition, a simpler concept of substituting the FEM, utilizing a limit equilibrium method (LEM), in the pre-failure state of landslides is also introduced. We believe that the concept described in the study will be helpful for practical applications to mitigate landslide hazards.

**Keywords:** FEM-DEM framework; Earthquake-induced landslide; Rainfall-induced landslide; LEM

## 1 INTRODUCTION

Landslides, a devastating natural hazard, threaten human lives, properties, and environments. Various studies have shown that earthquake and rainfall are two main factors driving landslides (Keefer, 1984; Lin et al. 2006; Hung et al. 2018a, 2018b). To study landslide behaviors associated with earthquakes, Newmark's method, shaking table test, and numerical methods have been adopted in the convention. Newmark (1965) proposed a sliding block model, having a known yield or critical acceleration, to characterize the slope behavior and the accumulated displacement under seismic excitations. Wang and Lin (2011) used shaking table tests and seismic records to study the slope failure initiation. Mitani et al. (2013) utilized a FEM to investigate the amplification effects on a slope.

On the other hand, to investigate the behaviors of rainfall-induced landslide, rainfall threshold, physical model, and numerical simulations are typically involved. Guo et al. (2014) used a local intensity–duration relationship to propose a rainfall threshold of debris flows in the affected areas of the Wenchuan Earthquake. Lo and Weng (2015) performed a physical model test to identify the deformation and failure characteristics in cataclinal slopes during rainfall. Leshchinsky et al. (2015) utilized a FEM to describe the progressive movement of a shallow landslide under above-average rainfalls after its toe was excavated.

The Newmark's method could overestimate the critical acceleration and underestimate permanent displacement (Lin et al. 2018; Li et al. 2018); scaled slope model may be limited to idealized conditions and a smaller scale than actual events (Castelli et al. 2016; Hung et al. 2018c); rainfall thresholds cannot investigate the mechanism of the rainfall-induced landslide. Numerical methods such as FEM and DEM, if used separately may possess limitation of only capturing a certain characteristic of landslide behaviors (Hung et al. 2018c, 2018d). To overcome the limitations, multiple numerical models that account dynamic ground responses, nonlinear behaviors of soil, and soil water interactions, could be selected to cope with each method's limitation.

A FEM-DEM framework for progressive modeling of landslides are presented herein. Two case studies, involving earthquake- and rainfall-induced landslides, are demonstrated in hope to shed some lights on facilitating mitigation constructions.

## 2 FEM-DEM FRAMEWORK FOR PROGRESSIVE MODELING OF LANDSLIDES

Landslide is a phenomenon that occurs when a slope failure occurred due to weakened self-resistance of the materials subjected to earthquake or rainfall events. Clarifying of landslide behavior is a fundamental task for designing functional construction against landslide hazards. The progressive behavior of landslide is also important to understanding the response of a slope to earthquake and rainfall events. As shown in Fig. 1, a landslide activity can be decomposed into four stages:

deformation, failure, sliding, and deposition. In the pre-failure state (deformation and failure), the material of a slope experiences the reduction of effective shear strength at various depths within a slope and develops a shear surface before the sliding movement is initiated. On the other hand, in the post-failure state of landslides (sliding and deposition), the sliding mass moves along the failure surface toward downslope and causes damages to buildings and human lives. Because each stage involves different landslide characteristics, a single simulation of these phenomena would suffer majorly from the limitation of each method. To fill the gap, this study presents a framework, combining models of FEM and DEM, for quantitatively assessing critical issues on landslide hazards, including failure surface, initial failure time, impact force, and influence area (Fig. 1). The detailed methodologies of the FEM and DEM were described in the works of Hung et al. (2017, 2018c, 2018d). Combination of these two methods is based on the concept that the initial acceleration and the seepage force of the sliding mass at the initial failure state were estimated by the FEM and further linked to the DEM to reasonably reproduce the kinematic process of the sliding mass under the earthquake and rainfall conditions. Compared to the single usage of the two numerical approaches, the interplay of FEM and DEM can provide more realistic and considerate results on the kinematic process of sliding mass in the post-failure state. Applications of a combined FEM-DEM method for simulating landslides can also be found in Munjiza (2004), Mahabadi et al (2012), and Barla et al. (2012). The following case studies will highlight the proposed framework in practical applications.

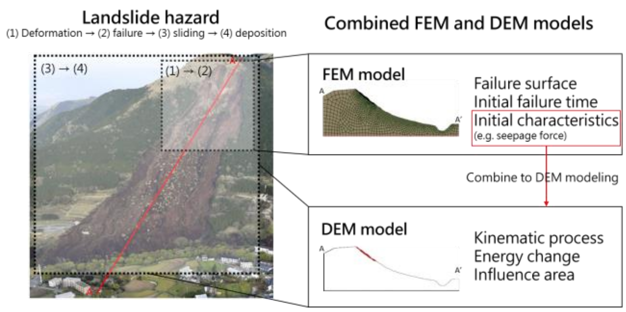


Fig. 1. FEM-DEM framework: progressive landslide modeling.

## 3 RESULTS

### 3.1 Earthquake-induced landslide: Case of the 2016 Aso-Bridge landslide

In 2016, earthquakes occurred in the Kumamoto City and triggered the Aso-Bridge landslide, located nearby in the western caldera of Aso Volcano. The sliding mass blocked the Aso-Bridge for about 200 m with an estimated volume of about 8700 m$^3$. Weathered volcanic cohesive soil, which is porous, loose, and has low cohesion, are distributed in the landslide area (Song et al. 2017; Hung et al. 2017, 2018c). Based on the high-resolution terrain data, the regional terrain gradually becomes gentle from northwest to southeast, and the elevation ranges between 350 m and 720 m (a.s.l.). The average of the upper slope inclined with the angle of approximately 33° and the slope gradient is 13° in the lower slope. In order to understand the dynamic behavior of the slope subjected to the 2016 Kumamoto earthquake, this study applied the framework to conduct the numerical investigation for Aso-Bridge landslide. The seismic record used in the simulations was processed from the nearest station (OHDU) with the strongest shaking of 15-40 s. The detailed parameters and boundary conditions of both numerical models can be found in Hung et al. (2017, 2018c). In Fig. 2a, during the pre-failure state, the deformation displacement increased with time. The rapid change of slope displacement (RCSD), which was proposed to precisely define the initial time of the landslide, was verified at the time of 5.6 s (Fig. 3). After the initiation time was determined, the initial condition at failure can be obtained and then applied to the DEM model. Figures 2b-2c show the kinematic process of the Aso-Bridge landslide in the post-failure state. By the 11 s, acceleration and disintegration were observed due to the steepness of the slope. By the 18th second, the sliding mass reached a gentle slope with a deceleration motion. By the 21 s, the sliding mass reaches the riverbank and collided with the opposite riverbank. The whole event was close to the end at 38 s.

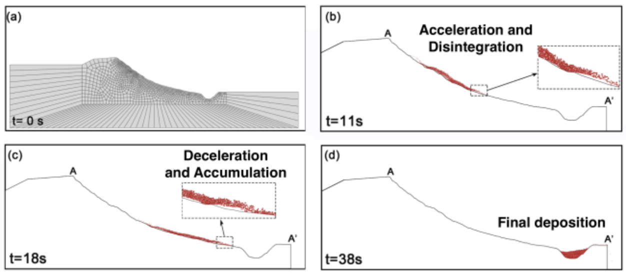


Fig. 2. Results of the 2016 Aso-Bridge landslide.

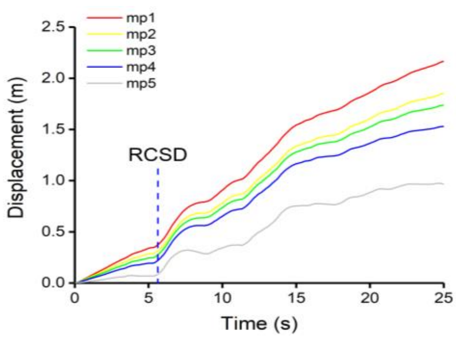


Fig. 3. RCSD of the 2016 Aso-Bridge landslide modeling.

### 2.2 Rainfall-induced landslide: Case of the 2016 Yanchao landslide

On September 28, 2016, due to the torrential rainfall carried by Typhoon Megi, a catastrophic landslide occurred in a mudstone slope in the Yanchao district of Kaohsiung city, Taiwan. The 2016 Yanchao landslide heavily damaged a building and displaced it about 13 m. Three people were killed in this event, which is the deadliest landslide in mudstone slopes that have occurred in recent Taiwan history. Based on the post-disaster terrain data, the source area of the landslide has a steep slope with the gradient of 27°and the slope angles is gentler in the lower slope (≈ 15°). Different from the earthquake-induced landslide, which the acceleration by the shake wave influences the landslide behavior, the soil-water interaction was an important factor for the rainfall-induced landslide. Hence, this study applied the representative rainfall record to consider the water infiltration at the pre-failure state of the landslide in the FEM model. The detailed parameters and boundary conditions of both numerical models can be found in Hung et al. (2018d). Figure 4a shows the variation of saturation and pore water pressure within the slope during Typhoon Megi. After 28 hours, the negative pore water pressure almost dissipates in the lower slope, leading to the shear strength decreased and the following instability of the slope. In addition, through the displacement-time curve, the RCSD was observed at the time of 28 hr, demonstrating the initial failure time of the 2016 Yanchao landslide (Fig. 5). The seepage force, which was estimated from the FEM model, was further applied to the sliding mass in the DEM model (Hung et al., 2018d). Figures 4b-4c show the kinematic process of the sliding mass in the post-failure state. By the 6th second, the sliding mass had almost blocked the industrial road. By the 16the second, the sliding mass arrived at the building and began to push the building toward the downward slope. Finally, the building was moved approximately 13m when the sliding mass was settled. The case study demonstrates that the proposed framework is valid to provide useful information for evaluating the landslide event that lack of witness and field monitoring devices.

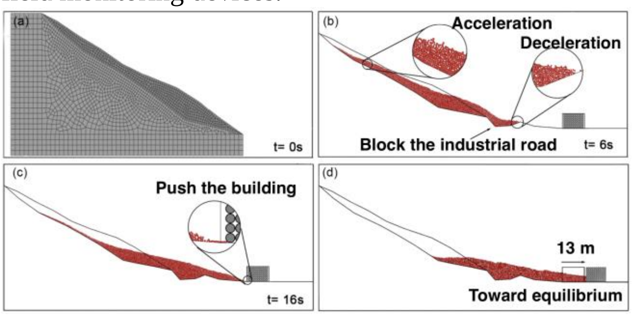


Fig. 4. Results of the 2016 Yanchao landslide modeling.

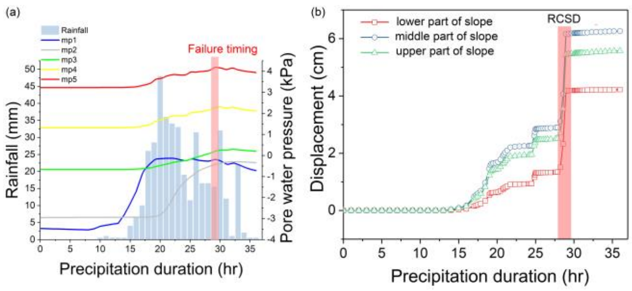


Fig. 5. Failure timing and RCSD of the 2016 Yanchao landslide modeling.

## 4 DISCUSSION

The use of numerical methods has recently become a rather powerful tool in landslide modeling; however, due to the complicated of landslide behaviors, the application of a single numerical model cannot possibly solve the modeling of landslide problem in complete. This study employed a framework combining FEM and DEM to examine two recent landslides triggered by rainfall and earthquake (Hung et al., 2017, 2018c, 2018d). For the mitigation design of landslide hazards, an effective strategy depends heavily on the understanding of the stability of a slope, revealing by the factor of safety (FOS) of possible slip surfaces in the simulation. Compared to Hung et al. (2018d), who used FEM simulation to combine with DEM model for the case of the 2016 Yanchao landslide, a limit equilibrium method (LEM) analysis may substitute the FEM analysis in the pre-failure state. LEM is quick and relatively easy for practicing engineers. By determining a representative cross-section of the selected slope, the numerical simulation can provide reliable information for hazard mitigation including the slip surface and FOS under different scenarios. In addition, with the high-resolution topographic data obtained by new technologies, the selection of representative cross-section in the landslide modeling can be considerably helpful. On the other hand, in the practical design, the impact region of a landslide is usually evaluated through empirical equations or expertise. The application of the DEM model can provide useful information, such as the energy change of sliding mass, impact force and influence area, on the slopes with high failure potentials to design an effective protective construction. Notably, results of landslide modeling could not interpret the mechanisms of a landslide event alone but need to be put together with the results of field investigations or in-situ monitoring data to elaborate landslide behavior.

## 5 CONCLUSION

In this study, we present a FEM-DEM framework for ascertaining the validity of landslide modeling and mitigation constructions in regions prone to landslide hazards. Application of the framework was demonstrated via interpretations of two recent catastrophic landslides occurred in 2016, in which, one was induced by earthquake and the other one by rainfall. The results showed that FEM modeling is a satisfactory approach for evaluating the landslide behaviors in the pre-failure state. The simulated circular failure surfaces agreed well with the post-disaster topographical data in the two cases. With the RCSD, the initiation time of the slope failure can be extracted. The initial landslide characteristics, such as the acceleration and the seepage force, can also be estimated by the FEM. The DEM model can reproduce the energy evaluation during the landslide as well as the information regarding the potential influence areas for future hazard mitigation. Based on the presented concept, an advanced numerical model that considers the hydrogeological characteristics and the preferential water infiltration path may be helpful to facilitate related mitigation constructions.

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