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Numerical Investigation of the Effect of Rolling Friction on Landslides by DEM

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Abstract - This study aims to analyse the effect of the rolling friction between soil particles on landslides by using the discrete element method (DEM). The landslide profile obtained numerically was compared with that from the experiment under similar conditions to validate the models used in the work. Five slope models with different values of coefficient of rolling friction were simulated by DEM to observe the landslide profile after the landslides. The results show that the increase in the coefficient of the rolling friction can change the shape of the accumulation area after the landslides and contribute to the increase of the landslide angle and the volume of soil particles remaining in the model. The main reasons for the influence are that the rolling friction can hinder the relative rotational motion between soil particles, and then resist the relative movements of the particles in contact during the landslides.

***Keywords*:** Landslide, Numerical simulation, Discrete element method, Coefficient of rolling friction, Soil particles

1. Introduction

Landslides frequently occur and always have detrimental effects. As a result, research on landslides has become increasingly important [1]. In general, the landslide process has four stages, i.e., slope damage, body mass fracture, debris fragmentation and block movement, which are not continuous [2]. The discrete element method (DEM), as one of the most widely used methods for particle systems, is an appropriate approach to consider this discontinuous situation.

Extensive simulations based on DEM have demonstrated that frictions, including sliding friction and rolling friction between particles, play an important role in controlling the behaviour of particles. For example, the increase of the sliding friction between mineral particles can produce more collisions, resulting in total collision energy between these particles rising in the milling of particles [3]. Rolling friction plays a key role in the formation of a stable sandpile, and the increase in the coefficient of rolling friction can cause an increase in the angle of repose of the pile [4]. Numerical simulations have also indicated that the sliding friction affects landslides. Lu et al. [5] restored a real case of landslide and found that the landslide range shrank with the increase of sliding friction and the landslide was essentially in a stable state when the sliding friction reached a critical value. In a landslide case where the river channels were temporarily blocked, the research by Guo et al. [6] discovered that the increase in the sliding friction during the landslide could reduce the collision stress between particles, resulting in an inertial flow dominated by collisions between particles, the phenomenon of landslide would gradually convert to the debris flow. However, to our knowledge, there are no studies conducted on the impact of rolling friction on landslides; nevertheless, rolling friction has been shown to be significant in some circumstances, particularly when the flow behaviour of particles shifts from static to flow or vice versa [7].

On the basis of the background, this study aims to analyse the effect of rolling friction between soil particles on a landslide using DEM. A comparison between the results of simulations and experiments was first conducted to validate the applicability of models used in the system. The effects of rolling friction on the landslide angle and profile and the remaining particles in the model during the landslide were then examined in detail.

2. Simulation method and conditions

In this study, EDEM software based on the DEM was used to simulate the flow of soil particles during landslides. In the DEM, the translational and rotational motions of every single particle in a considered system are described by Newton's laws of motion. For simplicity, our present study was limited to systems only composed of dry spherical particles. The Hertz-Mindlin (no-slip) contact model, as the default model in EDEM, was employed to describe the interactions between the dry soil particles. The torque acting on a particle includes two parts. One is contributed by tangential contact forces. Another, often referred to as the rolling friction, generally stems from the asymmetry of the normal traction distribution on the contact area between particles. It provides a resistance to relative rolling motion between particles. The details of the method and force models can be seen elsewhere [7].

Figure 1 shows the slope model considered in this work. Viewed from the side, the shape of this slope model consists of a rectangle foundation part (platform zone) and a right-angled trapezoid part (landslide zone). The model consists of 6 acrylic sheets with a thickness of 6 mm. The internal dimensions of the model are: 500 mm bottom length, 270 mm total height and 170 mm top width. The platform zone has the top length of 150 mm and the height of 90 mm. The original angle of the slope is 45^o . Because of the limitations of the computational capacity of computers when using the DEM, it is impossible to completely restore the real size of soil particles. Thus, the size of soil particles needs to be enlarged in the simulations. In this study, soil particles with a radius of 3.5 mm were selected. The other parameters used in the simulations are shown in Table 1. There were three steps involved in creating a landslide in the slope model. The slope model was first turned upside down, then its bottom plate was taken off, and finally soil particles were inserted through the bottom to fill the slope model. The slope model was sealed on its bottom in the following step, after which it was set back upright. Under the influence of gravity, the particles settled to the bottom and became stable. The plates on the top, slope, and platform zone of the model were finally removed to allow particles to slide under gravity. This work concentrated on the influence of the coefficient of rolling friction (μ_r) on landslides. Five slope models with different values of μ_r were simulated. In these simulations, only the value of μ_r was changed and other parameters were kept the same. During a simulation, the fixed time step was set as 3×10^{-5} s and the total simulation time was 30 s.

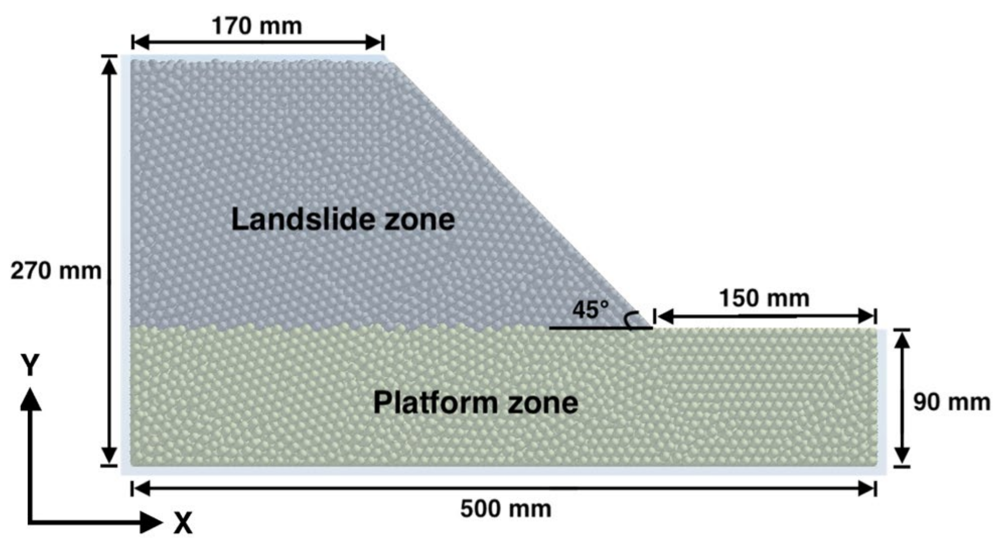


Fig. 1: Dimensions of the slope model and

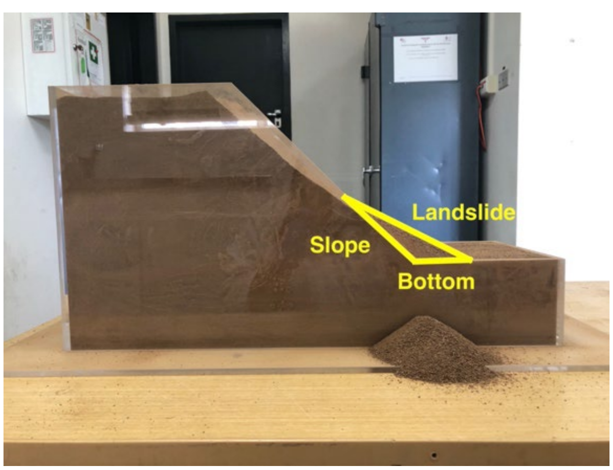
Table 1. Material properties and parameters of the basic model

Items	Value
Poisson's ratio (soil)	0.42
Solids density (soil) (kg/m^3)	1,322
Shear Modulus (soil) (GPa)	0.0098
Poisson's ratio (acrylic sheet)	0.38
Solids density (acrylic sheet) (kg/m^3)	1,180
Coefficient of restitution (soil-soil)	0.5
Coefficient of static friction (soil-soil)	0.6
Coefficient of rolling friction (soil-soil)	0.03
Coefficient of restitution (soil-acrylic)	0.45
Coefficient of static friction (soil-acrylic)	0.45
Coefficient of rolling friction (soil-acrylic)	0.002

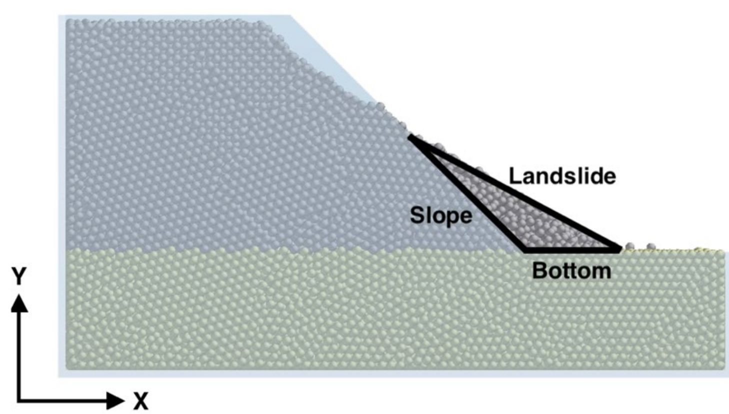
Physical experiments have also been conducted to validate the simulation modelling. The dimensions of the model used in the experiments were the same as those in the simulations. Soils with diameters less than 1.18 mm were the main experimental material and the density of soil particles was tested as 1322.0 kg/m^3. In order to ensure that the soil particles used in the experiments were dry enough, they were dried in the oven at 106^o for 24 hours before filling the slope model.

3. Results and discussion

Figure 2 shows the profiles of landslides in the experiment and the numerical simulation after the landslide occurred. Due to the site restrictions during the experimental operation, the left side view after the landslide could not be completely presented in 2D form, which made the shape of the accumulation area in the experiment look smaller than that in the numerical simulation. However, in the actual situation, the shape of the accumulation area after the landslide in the numerical simulation was consistent with that in the experiment, both appearing as triangles. In the experiment, the angle of the landslide was measured as 26.25°, which is close to the landslide angle of 26.37° in the simulation. The results indicate that the model used in the simulation can be used to simulate the systems considered.



(a)



(b)

Fig. 2: Profiles after the landslide occurred: (a) experiment and (b) numerical simulation.

Figure 3 shows the landslide angles and profiles in the left side view after the landslide when μ_r is 0.005, 0.01, 0.03, 0.05 and 0.1. With the increase of μ_r, the landslide angle rises linearly. Higher μ_r could lead to more soil particles in the top part of the slope model moving down and less particles in the accumulation area formed at the corner of the slope surface of the landslide zone and the top surface of the platform zone. In addition, rolling friction can affect the shape of the accumulation area after the landslide. Whenμ_r increases, the shape of the landslide edge gradually transits from an convex curve to a straight line, the length of the bottom edge decreases, and the length of the slope edge increases. When landslide occurs, some particles in the top part of the model move down under gravity. These particles would contact of other particles in static state. Higher rolling friction can generate larger resistance to the relative movement of the in contact. Thus, the particles are harder to move. This is the reason why less particles in the top part move down for a higher μ_r . Similar reason can be used to explain the effect of rolling friction on the bottom edge of the accumulation area. When the particles in the top part move to the bottom of the landslide zone, they would contact the static particles on the surface of the platform zone. Due to the influence of rolling friction, the particles can stop after moving a distance. Larger μ_r would cause a shorter distance (i.e., a smaller length of the bottom edge), and then a larger landslide angle.

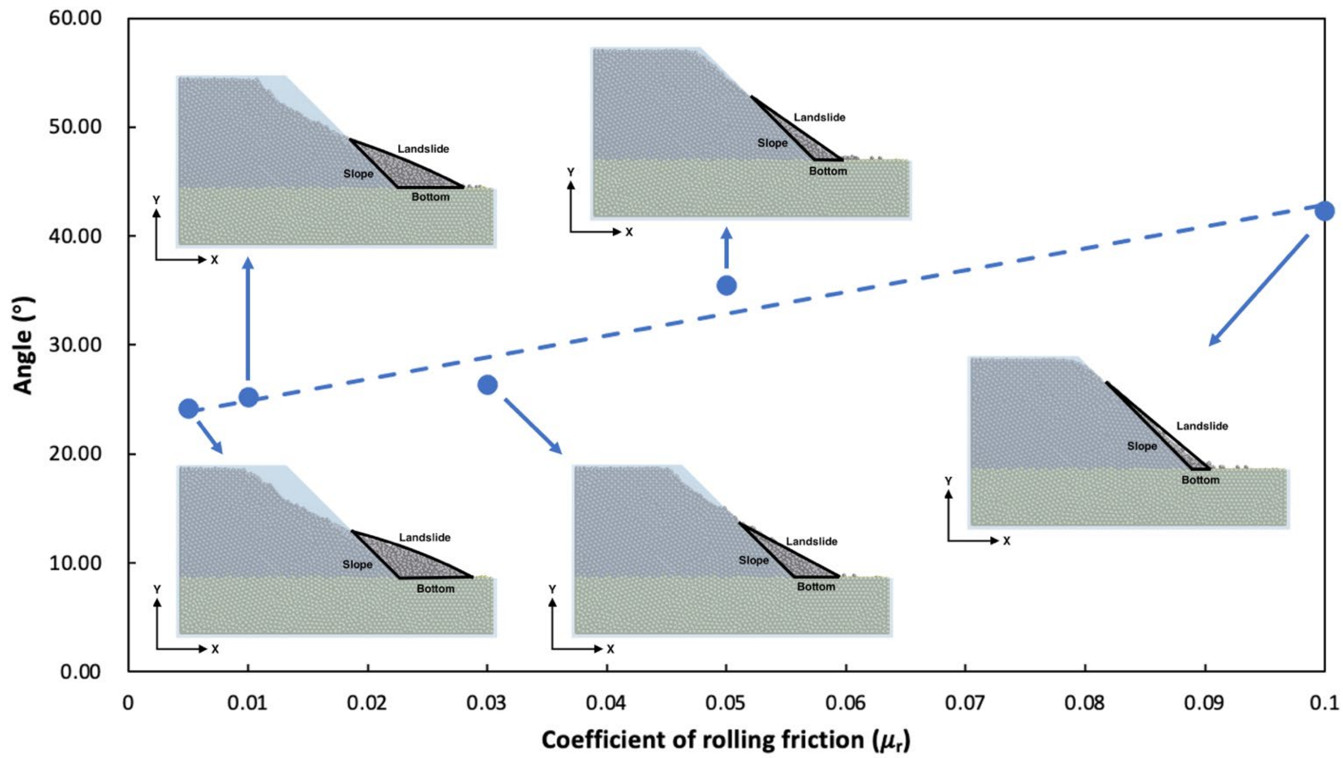


Fig. 3: Effect of μ_r on landslide angles in the left side view. The insets show the left side view of slope models with different values of μ_r after the landslide.

Figure 4 depicts the change in the remaining volume in the slope models during the landslide with different μ_r. For all μ_r except $\mu_r = 0.1$, the volume of the soil particles remaining in the slope model declined rapidly when the landslide started. This indicates that some particles slipped out of the slope mould under the action of gravity After a certain time, soil particles no longer moved out of the mould, and the volume of soil particles in the slope model remained unchanged. For $\mu_r = 0.1$, almost no particles moved out of the model. The rolling friction coefficient affects the time when the remaining volume started to change. In fact, the starting time is at 0.4 s to 6.2 s when μ_r is from 0.005 to 0.05. In addition, the growth of μ_r could contribute to the remaining volume of soil particles increasing logarithmically, as shown in the inset of the figure. Therefore, these phenomena further illustrate that rolling friction can hinder soil particles from generating motion. The rolling friction can not only delay the occurrence time of landslides but also reduce the volume of landslides. It would somehow contribute to an improvement in landslide stability.

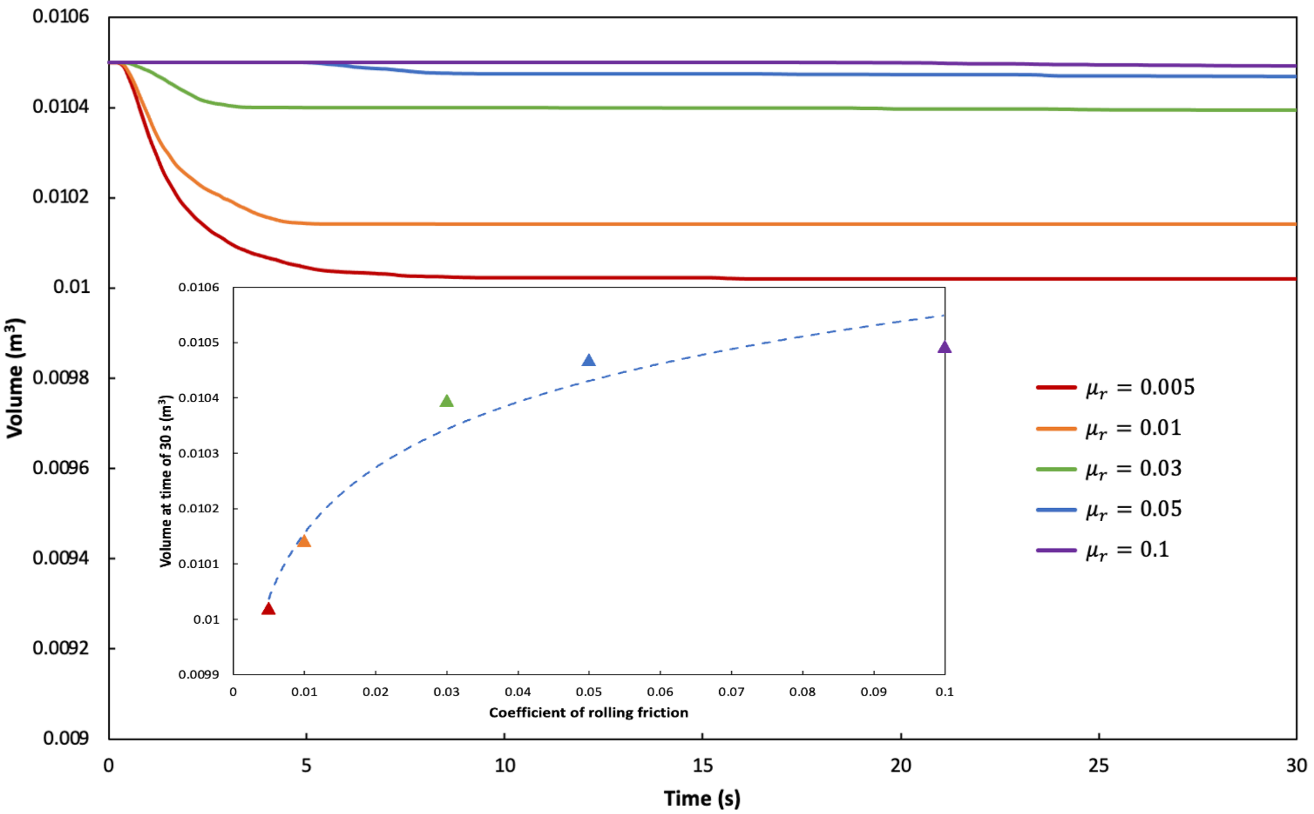


Fig. 4: Variation of the remaining volume of landslides during 30 s time. The inset shows the effect of μ_r on the volume at t = 30 s

4. Conclusion

In this study, DEM has been used to simulate landslides in a slope model. Five cases with different values of rolling friction coefficients have been considered to analyse the effect of rolling friction on landslides. The results can be summarised as follows.

1. Rolling friction has an important influence on the landslide angle and profile after the landslides. The increase of the rolling friction coefficient could cause the increase in the landslide angle and the length of the slope edge and the decrease in the length of the bottom edge of the accumulation area. The shape of the landslide edge would change from an upward convex curve to a straight line with the increase of the rolling friction. In addition, larger rolling friction coefficient can lead to more soil particles in the accumulation area and less soil particles moving down in the top part of the slope model. The main reason for these phenomena is that the rolling friction can hinder the relative rotation motion and then the translational motion of the particles in contact.
2. Rolling friction affects the number of the remaining particles in the model during and after the landslides. The larger rolling friction can cause longer delayed time when soil particles start to slide and can contribute to the smaller volume of the landslide, and thus playing a role in improving the stability of the slope.

This study indicates that rolling friction should be included when DEM is used to simulate landslides. It should be noted that the size of the model is much smaller than the real landslide, which may affect the results. How to select a suitable value of rolling friction coefficient for a real system is still an open question. To clarify the concerns, larger size of slope model and more rolling friction coefficients will be considered in our future work.

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