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The relationship between the slope angle and the landslide size derived from limit equilibrium simulations

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ABSTRACT

Katz et al. (2014) carried out a study of controls on the size and geometry of landslides using two-dimensional discrete element numerical simulations. One of their conclusions is that in addition to the peak strength of the slope material, the initial slope angle is another factor that controls the amount of material available for landslides, thus the size, of the resultant landslide. It means that in steeper slopes, more material disintegrates for a given material strength, and consequently the produced landslide is larger. However, in our studies based on limit equilibrium simulations, the sliding mass volume decreases with the increasing slope angle for a given material strength, just contrary to the result of Katz et al. One possible explanation is that when the slope angle in our model increases, the geometry of the potential critical slip surface changes, leading to a decrease of the amount of material available for potential sliding that compensates the increasing gravity effect owing to the enlargement of the slope angle. It suggests that there exist different controls of the slope angle on the landslide size for given material strength.

1. Introduction

Katz et al. (2014) carried out a study of controls on the size and geometry of landslides through two-dimensional discrete element numerical simulations. They hypothesized that the observed global characteristic landslide size is a result of the limited thickness of disintegrated and weathered material that exists on hillslopes. They also suggested that the primary controls on the landslide geometry could be proved to be the residual friction angle of the slope material and the original slope angle. Moreover, they observed that the initial slope angle is an additional factor that controls the amount of material available for landsliding, thus the size of the resultant landslide. In steeper slopes, more material disintegrates for a given material strength, and thus the resultant landslide size is larger. However, in our studies based on limit equilibrium simulations, the sliding mass volume decreases with the increasing slope angle, just contrary to the result of Katz et al. (2014). In this brief comment paper, we present our work on this subject and attempt to explain the difference between our results and that of Katz et al. (2014).

2. Methods

We performed two-dimensional slope stability calculations using the general limit equilibrium (GLE) method incorporated in the software SLOPE/W of GeoStudio for stability analysis of slopes. The initial code of this software was developed by D.G. Fredlund at the University of Saskatchewan and has been on the market since 1977 (Fredlund, 1974; Fredlund and Krahn, 1977; GEO-SLOPE International Ltd., 2010).

The GLE formulation satisfies two equations of factor of safety (*Fs*) (*Fs* is the ratio between the total available shear strength along the slip surface and the summation of the gravitational driving forces) and allows for a range of interslice shear-normal force assumptions, showing its advantages in the limit equilibrium analysis (Fellenius, 1936; Janbu, 1954; Bishop, 1955; Morgenstern and Price, 1965; Fredlund, 1974; Fredlund and Krahn, 1977; GEO-SLOPE International Ltd., 2010). The GLE method can be applied to any kinematically admissible slip surface shape (GEO-SLOPE International Ltd., 2010), which makes it more flexible and practical.

The SLOPE/W software provides some options to locate the position of the critical slip surface within the slope body. Finding the critical slip surface involves a trial procedure (Janbu, 1954;Bishop, 1955; Morgenstern and Price, 1965). This is repeated for many possible slip surfaces, and at the end, the trial slip surface with the lowest *Fs* is considered as the governing or critical slip surface. From previous work,

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the option Auto-Locate in this software can lead to a reasonable result (GEO-SLOPE International Ltd., 2010). So we used the Auto-Locate option to search for the critical slip surface instead of specifying a slip surface. This is more reasonable because the slip surfaces are usually undetected in many cases in reality.

To study the relationship between the slope angle and the sliding mass volume, we constructed a two-dimensional homogeneous slope model (Fig. 1). In this model, the slope height (H), slope angle (α) and slope base length (L) are the parameters to determine the geometry of the slope. The height of the slope was set to be 80 m, which was a constant value. Meanwhile, the slope angle α was adjusted by changing the horizontal distance L (i.e., $\tan\alpha = H/L$).

In the GLE factors of safety equations, the material strength parameters are important for the equilibrium, which are characterized by material cohesion (c) and internal friction angle (φ). In addition, material unit weight (γ) here is used to determine the sliding mass weight or gravitational force.

The slope material parameters for the simulation are listed in Table 1, which are close to the Katz et al. (2014) model.

During simulations, the slope height H was kept the same, while the right end of the slope base was moved from 210 to 60 m by an interval of 10 m for each step, which means that the length of the slope base as well as the slope angle were reduced step by step.

With these conditions, slope stability calculations were performed by analyzing, for each slope base length, 2000 slip surfaces to determine the one with the minimum *Fs*. Thus the potential slip surface within the slope body, which was initially a curved shape, was determined, and the corresponding sliding mass volume for each step was calculated.

3. Results

Totally, we obtained 17 simulation results. Limited by the space, here we only present five representative results for slope angles 23°, 33°, 45°, 53°, and 65° (Fig. 2). They indicate that the potential slip mass volume decreases with the increasing slope angle (Fig. 3). The potential sliding volume reaches the maximum value of 9097 m^3 when the slope has the minimum angle of 23° (corresponding to the right end of the slope base which is at the horizontal axis of 210 m, Fig. 2A), whereas the potential sliding mass volume decreases to the minimum value of 474 m^3 when the slope angle approaches 65° (the right end of the slope base is at the horizontal axis of around 58 m) (Fig. 2E). It seems that such a relationship is associated with the changes of geometry of the critical slip surface. For example, when the slope angle is 23°, the critical slip surface is a big curved plane (Fig. 2A). As the slope angle increases, the curvature and the length of this slip surface become smaller, thus leading to a decrease in the thickness as well as the volume of potential sliding material. When the slope angle is around 65°, the slip surface turns into a straight plane with a very small length, correspondingly the least volume of potential sliding material (Fig. 2E).

Table 1
Slope material strength parameters for simulation.[a]

c (MPa)	φ (°)	γ (kN m^{-3})
1.0	30	25.0

[a] c (MPa): cohesion; φ (°): internal friction angle; γ (kN m^{-3}): material unit weight.

4. Discussion

The limit equilibrium method of slices in SLOPE/W is based purely on the principle of statics, which says nothing about strains and displacements. The lack of a stress–strain constitutive relationship to ensure displacement compatibility creates many of the difficulties to obtain a converged solution under certain conditions (GEO-SLOPE International Ltd., 2010). For example, a steep slip surface makes it difficult to obtain a converged solution, which accounts for why the greatest slope angle is less than 70° in this simulation.

However, the limitations do not necessarily prevent using the method in practice; it has been widely applied in slope stability analysis, and the outcomes are versatile (Wilson and Keefer, 1985; Lam and Fredlund, 1993; Jibson et al., 2000; Miles and Keefer, 2001; Jibson and Michael, 2009; Frattini and Crosta, 2013; Chen et al., 2014). Comparing the simulation work of slope failure conducted by Katz et al. (2014) and this study, except for the different model sizes, we found that the obvious difference is the principles of simulation methods. Although it is difficult to explain in physical mechanism the reasons for such differences at present, we speculate that there may exist various controls of the slope angle on landslide size for given material strength. One possible explanation is that when the slope angle in our model increases, the amount of material for potential sliding also decreases, which compensates the increasing gravity effect due to the enlargement of the slope angle.

The purpose of our simulation was to find the possible critical slip surface within the slope body. So the processes leading to slope failure and the position where the failure starts are not the concern. In Katz et al.'s (2014) work, they indicated that the slope failure initiated at

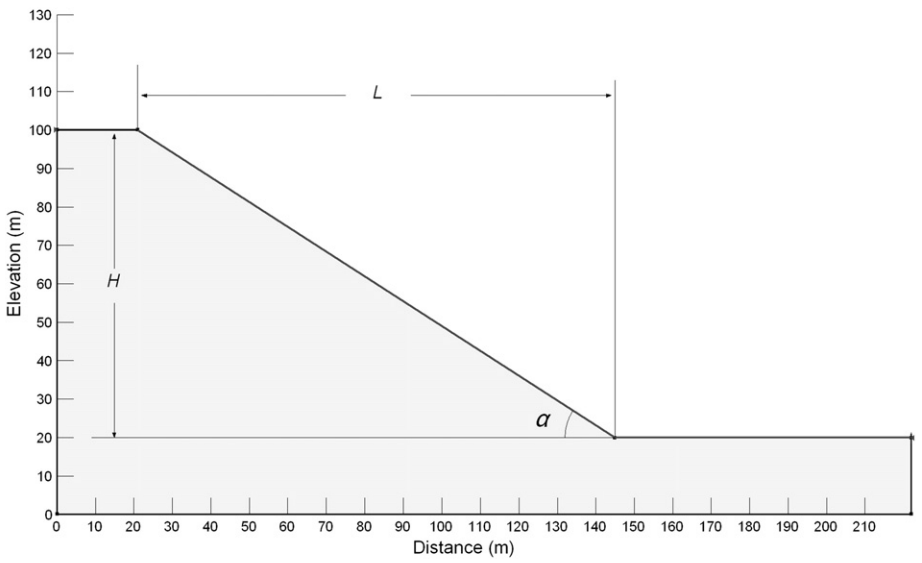

Fig. 1. Sketch of the model geometry. H: slope height. L: slope base length, which is the difference between the left end and the right end of the slope base. α: slope angle.