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Probabilistic Analysis of Post-Failure Runout Behavior of Landslides

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Abstract: Landslide is one of the most significant geohazards all around the world, which may lead to destructive damage or risk to human life and infrastructures. The damage of a landslide can be determined by the deformation characteristics and the post-failure runout behavior. In general, the post-failure runout behavior is simulated with the numerical software such as particle flow code (PFC), the simulation results are greatly influenced by the micro-parameters (e.g., normal stiffness and tangential stiffness between the particles) adopted in the PFC models. However, the calibration of the micro-parameters in the PFC models is a great challenge and various uncertainties can be involved. The uncertainties in the micro-parameters could certainly lead to the uncertainty in the simulated runout behavior of the landslide; as a result, the potential damages of this landslide may not be accurately evaluated. In such a circumstance, this paper will present a probabilistic analysis of the runout behavior of landslides, in which the uncertainties of the micro-parameters adopted in the PFC models are explicitly considered. In this paper, the micro-parameters are simulated as discrete random variables and a Lagrangian interpolation is employed to sample the potential realizations of the micro-parameters; then, the generated micro-parameters are adopted as the inputs to the built PFC model of the landslide. With the results obtained from these PFC analyses, the distributions (i.e., histograms) of the runout distance and sliding duration of the sliding mass could be derived. The study results can aid in making an informed risk assessment of landslides.

Keywords: Landslide; Particle Flow Code (PFC); runout behavior; micro-parameters; Lagrangian interpolation.

1 Introduction

An accurate evaluation of the post-failure behavior of a landslide is of vital importance for the assessment of the potential geohazards induced by the landslide. For example, the damage or risk to human life and infrastructures is greatly affected by the runout behavior of the landslide (Viero et al. 2018; Paliaga et al. 2019). The runout behavior of the landslide could be studied with data-based empirical solutions, model tests or numerical simulations. In that strong assumptions were often adopted in the model derivation, the empirical solutions may only be applicable to some specified scenarios and the study results might be biased (Xiao et al. 2016; Gong et al. 2016). Even through the complex post-failure behaviors of the geomaterials within the landslide may be captured with the model tests, the model tests could be cost-inefficient (Cao et al. 2017). As an outcome, the numerical simulation might be the best solution (Zhong et al. 2017). Indeed, the numerical simulation of the post-failure behavior of landslides is gaining a world-wide popularity.

In the field of the numerical simulation of the post-failure behavior of landslides, various numerical methods such as the discrete element method (DEM), discontinuous deformation analysis (DDA), smoothed particle hydrodynamics (SPH) and particle flow code (PFC) can be available (Cundall 1971; Shi 1992; Gingold et al. 1977; Cundall et al. 1992). It is known that the input parameters adopted in these numerical methods are the micro-parameters of the geomaterials, not the macro-parameters such as the friction angle ($\phi$) and cohesion ($C$); however, most engineers are not familiar with these micro-parameters. Note that although the effectiveness of these numerical methods has been extensively validated in the literatures, quite little effort has been conducted on the determination of the micro-parameters. In that no explicit relationship could be established between the micro-parameters and the macro-parameters of the geomaterials, the input micro-parameters adopted in the numerical simulation could only be obtained through trial-and-error analysis (Cao et al. 2017). As an outcome, the accuracy of the study results, in terms of the post-failure runout behavior of the landslide, could be strongly dependent upon the experiences of the engineers and significant uncertainty can be involved.

This paper presents a probabilistic analysis of the post-failure runout behavior of landslides. In which, the micro-parameters adopted in the numerical simulation utilizing PFC are modelled as discrete random variables; then, the potential realizations of the micro-parameters are obtained with a Lagrangian interpolation that yields the true macro-parameters of the sliding geomaterials. The potential runout behaviors of the landslide are readily studied by taking these potential realizations of the micro-parameters as inputs to the built PFC model. Based
upon the study results of these potential realizations of the input micro-parameters, a probabilistic analysis of the runout behaviors for the landslide can be conducted.

The rest of this paper is organized as follows. First, the case history of Shenzhen 12·20 Landslide, which is taken as the illustrative example in this paper, is introduced. Second, the PFC model of Shenzhen Landslide is established, and the micro-parameters adopted in which are calibrated with traditional trial-and-error analysis. Third, the relationships between the micro-parameters and the macro-parameters are investigated, and the potential realizations of the input micro-parameters to the built PFC model are obtained. Fourth, the probabilistic analysis of the post-failure runout behavior of this landslide is presented. Finally, the concluding remarks are drawn based upon the results presented.

2 The Shenzhen 12·20 Landslide

On December 20th, 2015, a catastrophic landslide of a municipal solid landfill took place at Hongao landfill, Guangming new district, Shenzhen, China. This landslide suddenly collapsed and rushed down to the residential buildings and industrial zones, which caused a devastating catastrophe of 33 buildings’ destruction and 77 deaths. The maximum sliding distance, in terms of the distance measured from the trailing edge to the front edge of the landslide, is about 1100 m. The maximum width of the source area is about 400 m. The maximum width and the minimum width of the deposit area are around 625 m and 150 m, respectively (Ouyang et al. 2017; Zhu et al. 2018; Zhan et al. 2018; Wang et al. 2017). In that the runout behavior of this landslide has been extensively studied in the literature (Qiao et al. 2019; Yin et al. 2016) and lots of information regarding the runout behavior of this landslide could be available, this landslide is adopted herein as the illustrative example for the probabilistic analysis of the runout behavior of the landslide.

3 PFC Modelling of Shenzhen 12·20 Landslide

In this paper, the PFC is adopted as the solution model to study the post-failure runout behavior of this landslide, and the detailed PFC modelling of this landslide is presented below.

(a) PFC model of Shenzhen 12-20 Landslide.

(b) Forward calibration of the micro-parameters.

Figure 1. PFC modeling of the landslide and forward calibration of the micro-parameters.

3.1 Construction of the PFC model for Shenzhen 12·20 Landslide

In references to the field investigation of this landslide outlined in Yin et al. (2016), the geometry model of this PFC model can be determined: the length is 1400 m and the height is 240 m. The sliding mass in the PFC model is divided into two sub-regions according to the construction of this landfill: a front sub-region (see geomaterial II in Figure 1a) and a rear sub-region (see geomaterial I in Figure 1a). The sliding mass is then discretized into 13,088 particles and the radius of the discretized particles ranges from 0.4m to 0.8m; and, the linear model is adopted to simulate the interaction between the particles.

In the context of the selected linear model, three micro-parameters, in terms of the normal stiffness (kn), tangential stiffness (ks) and coefficient of friction (fric), are involved and which must be carefully determined for an effective PFC modelling. It should be noted that much less effort was carried out on the determination of the ball-ball contact parameters, compared to the determination of the ball-facet contact parameters (Boemer et al. 2017). Thus, the emphasis of this probabilistic analysis is upon the determination of the ball-ball contact micro-parameters mentioned above.
To obtain these three micro-parameters required in the PFC simulation of this landslide, a set of two-dimensional (2D) direct shear tests are conducted to calibrate the strength parameters of the sliding geomaterials; meanwhile, the stiffness parameters of the sliding geomaterials are verified with the aid of biaxial tests. The plots in Figure 1(b) indicate that a set of the macro-parameters may correspond to several realizations of the micro-parameters; however, the final deposits of this landslide derived from the PFC simulations, with these realizations of the micro-parameters as inputs, could be somehow different from the true deposit observed in the field investigation.

3.2 Calibration of the micro-parameters required in the PFC simulation

Indeed, the micro-parameters calibration process shown in Figure 1(b) may be called as the forward calibration: the calibration starts with the 2D direct shear tests and ends with the comparison of the final deposits of the landslide. It is found that the forward calibration could not be applicable to the PFC modelling of this landslide, as indicated by the mismatch between the true deposits and the simulated deposits.

Further, the backward calibration of the micro-parameters required in the PFC modelling is conducted: the calibration starts with the PFC simulation of the landslide and ends with the 2D direct shear tests. With the aid of a set of trial-and-error analysis, the micro-parameters that yield the true deposits of this landslide could be obtained, as shown in Figure 2(a). Take the obtained micro-parameters as inputs to the 2D direct shear tests, the macro strength parameters of the sliding geomaterials could be derived, as shown in Figure 2(b). Similarly, a significant difference can be identified between the true strength parameters and the simulated strength parameters. In other words, the backward calibration shown in Figure 2 may also not be applicable to the PFC modelling of this landslide.

As a matter of fact, the mismatch of the macro strength parameters (see Figure 2) and that of the macro runout behavior (see Figure 1b) always exist in the PFC modelling of the post-failure runout behavior of landslides. These kinds of mismatch are, indeed, attributed to the following aspects: 1. no explicit relationship is established between the micro-parameters and the macro-parameters; and 2. most engineers are not familiar with the micro-parameters, in comparison to the macro-parameters. As an outcome, these kinds of mismatch could lead to a significant uncertainty in the simulated runout behavior of the landslide.
4 Generation of Potential Realizations of the Micro-Parameters

In that the micro-parameters required in the PFC modelling cannot be derived with the traditional trial-and-error analysis, this paper presents a probabilistic analysis of the runout behavior of landslides, in which the uncertainties of the input micro-parameters in the PFC models are explicitly considered. Here, the micro-parameters are simulated as discrete random variables and a Lagrangian interpolation is employed to sample the potential realizations of the micro-parameters.

4.1 Relationships between the micro-parameters and the macro-parameters

A parametric analysis is first conducted to obtain the potential ranges of these micro-parameters, and then an orthogonal experimental design is carried out to derive the potential combinations of these micro-parameters within the obtained ranges. Here, 116 potential combinations are obtained; however, the 2D biaxial numerical simulations indicate that only 52 combinations of these micro-parameters could yield the physically meaningful results. On the basis of the simulation results of 52 sets of 2D direct shear tests, the relationships between the micro-parameters and the macro-parameters of the geomaterials could be studied, as shown in Figure 3. Plotted in Figures 3(a-c) are the contours of the macro cohesion of the geomaterials under different combinations of the micro-parameters and the macro friction angle is set at 8.2°, and plotted in Figures 3(d-f) are the contours of the macro friction angle of the geomaterials under different combinations of the micro-parameters and the macro cohesion is set at 8.4 kPa. The plots in Figure 3 indicate that the relationships between the micro-parameters and the macro-parameters are fairly complicated, rather than the generally acknowledged monotonous relationships. For example, one set of the macro-parameters could correspond to various sets of the micro-parameters; and, one set of the micro-parameters can also correspond to various sets of the macro-parameters.

4.2 Potential realizations of the micro-parameters for the true macro-parameters

With the relationships between the macro-parameters and the micro-parameters shown in Figure 3, a Lagrangian interpolation is employed to sample the potential realizations of the micro-parameters that yield the true macro strength parameters of the sliding geomaterials. Here, the three micro-parameters required in the PFC modelling of this landslide are simulated as discrete random variables and the following two-step procedure is adopted to generate the potential realizations of the micro-parameters: 1. construct a 21 × 18 mesh grid of the micro-parameters (k_n/k_s); and 2. derive the potential value of the coefficient of friction (fric) at each mesh grid of (k_n/k_s, k_s) with the derived Lagrangian interpolation, as shown in Figure 4. It is found only 234 sets of the friction coefficients are within an effective range. Hence, the 234 potential realizations of the micro-parameters are studied in the probabilistic analysis (of the post-failure runout behavior of this landslide).

5 Probabilistic Analysis of the Post-Failure Runout Behavior

With the obtained 234 potential realizations of the micro-parameters as inputs to the built PFC model, the post-failure runout behavior of this landslide can readily be studied. The determination of the joint probability mass function of the micro-parameters is a significant challenge, and no reference could be available. For illustration purposes, in this probabilistic analysis, an assumption is made that each and every potential realization of the
micro-parameters could yield the equal probability mass function. Plotted in Figure 5 are the resulting 234 post-failure configurations of this landslide and the comparison with the analysis results in the previous literature (Ouyang et al. 2017; Zhu et al. 2018). As can be seen, the probabilistic analysis results, in terms of the resulting post-failure configurations, could bracket the true post-failure configuration effectively; and, the expected post-failure configuration, taken as the mean of the resulting 234 post-failure configurations, is quite close to the true post-failure configuration. Further, the 90% confidence intervals of the post-failure configuration can be derived. The post-failure configurations derived by SPH and Massflow are both in the 90% confidence intervals derived in this probabilistic analysis, and quite close to the expected configuration. And, the runout distance and height of the deposit in these studies are all consistent with the configuration obtained from the field investigation. Thus, the effectiveness of this probabilistic analysis is depicted. In comparison to the single post-failure configuration obtained with the deterministic analysis, the 90% confidence intervals of the post-failure configuration obtained from the probabilistic analysis could allow a more informed risk assessment of this landslide.

![Figure 4. Potential realizations of the micro-parameters yielding the true macro-parameters of sliding geomaterials.](image)

![Figure 5. Probabilistic analysis results of the post-failure configuration of the landslide.](image)

In that the potential consequence of a landslide is mainly influenced by the post-failure runout distance and sliding duration, which could capture the influencing range and destructive power, respectively (Scaringi et al. 2018), the histograms of these two terms are derived and plotted in Figure 6. Figure 6(a) demonstrates that the runout distance of this landslide tends to be uniformly distributed, which might be attributed to the assumption that each potential realization of the micro-parameters yields the equal probability mass function; whereas, Figure 6(b) indicates that the distribution of the sliding duration is quite skewed. On the basis of the histograms of the post-failure runout distance and sliding duration shown in Figure 6, the potential consequence and risk of the landslide can be assessed in a quantitative manner, as the uncertainty involved in this post-failure behavior analysis is explicitly considered. This is a significant superiority of the presented probabilistic analysis over the traditional deterministic analysis that is based upon the trial-and-error analysis.

6 Concluding Remarks

This paper presented a probabilistic analysis of post-failure runout behavior of landslides, in which the uncertainties of the micro-parameters adopted in the PFC models are explicitly considered. In comparison to the traditional deterministic analysis that is based upon the trial-and-error analysis, the micro-parameters required in the PFC modelling of the landslide are simulated as discrete random variables and a Lagrangian interpolation is adopted to sample the potential realizations of the micro-parameters. The effectiveness and superiority of the presented probabilistic analysis framework were illustrated through the case history of Shenzhen 12-20 Landslide. The probabilistic analysis results, in terms of the 90% confidence intervals of the post-failure configuration, the histogram of the runout distance and the histogram of the sliding duration, could allow for an informed and quantitative risk assessment of this landslide.

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Figure 6. Histograms of some features of the landslide.

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