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Discrete modeling of waste rock dumps stability under seismic loading

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Abstract. Copper mining produces significant amounts of associate waste, leading to the construction of huge mining waste dumps in the highly seismic zone of the Andes Mountains. To analyze the seismic stability of these deposits, it is necessary to characterize the mechanical properties of these materials in laboratory, which is quite difficult due to the large size of particles composing these structures. In this study, the global stability of mine waste dumps is analyzed by means of discrete element simulations. Three analogues upscaled particle size distributions were generated from the original PSD. The particles composing the dump were modeled using regular polygons. The modeled dumps were subject to a seismic loading by applying a velocity signal on the boundary walls, which was integrated directly from accelerometers database. The results show that failure in these structures is produced by infinite slope, for samples scaled by a factor until ten. This methodology is encouraging for the analysis of the global stability of mine waste dumps and for forecasting the runout distance after failure.

1 Introduction

The large open-pit copper mining in Chile involves the mobilization of huge amounts of waste rocks or mining ballasts, which have a poor or no mineral content and which must be removed to extract the mineral interest to be exploited. With the mining expansion projects it has been estimated that currently more than one Mton of waste to be stored, which will lead to the construction of Waste Rock Dumps (WRD) reaching 1,000 m high. Considering that the pits of the large mines are located in the Andes Mountains, these deposits are placed in reduced spaces with steep mountain topography. Therefore, unprecedented high-rise of WRDs must be designed in a seismically active country such as Chile.

Regarding the physical stability, a large percentage of failures in WRD reported internationally have occurred in coal mine waste dumps, although failures in other types have also been reported of mining dumps [1, 2]. According to the cadaster carried out by Golder Associate [3], up to the 1990s there had been 160 cases of failure in WRD. According to [2] a failure in a WRD corresponds to the uncontrolled or unforeseen release of the material beyond the limits of the deposit.

In a seismically active country such as Chile, earthquakes have generated in WRDs superficial faults in the slopes (figure 1), assimilated to an infinite slope, with sliding of the surface rocks that roll down the slope and accumulate at the foot of the dump. In many cases, surface tensile cracks and differential settlements are generated near the top or on the dump platforms. Considering that WRDs are usually built pouring the waste materials, the generated slopes present an equilibrium equivalent to the material angle of repose with slopes of 1:1.3. Under this scenario, the safety factor, in static conditions, near the surface of the slope is slightly higher than unity. Therefore, a small seismic event can disturb this near-limit stability condition, eventually generating a scenario of physical instability, affecting the operational safety of the structure. In the particular case of a WRD with a single slope, without intermediate berms, a local superficial instability may involve a large mass of waste materials and considerable energy that would induce a flow slide that would travel a great distance downwards the slope (run -out distance). This phenomenon would be associated with the eventual generation of static liquefaction in WRDs [4–6].

Figure 1. Infinite slope surface failure in a seismically induced mining waste dump.

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To analyze the different failure mechanisms, it is essential to have information regarding the foundation soil, the geotechnical characteristics of the waste deposited and the construction method used. Regarding the shear strength parameters, their determination is currently not trivial. The characterization of these materials in the laboratory is quite complex due to the large size of the particles. In this way, it is necessary to use large specimens to be able to characterize the shear resistance respecting the minimum representative elementary volume (REV) required.

One way around this problem is by using numerical simulation to analyze the global equilibrium of these structures. A current practice in geotechnical engineering is to analyze the slope stability using the Limite Equilibrium Method (LEM) to determine the safety factor and the localization of the slip failure. On the other hand the Finite Element Method (FEM) can be used to calculate the stresses that will generate the failure and also the strains for small displacements in the framework of continuum mechanics. However, these classical approaches do not allow us to know the behavior under large deformations, such as those that can occur during an earthquake, in order to identify the large displacements of structure particles. In this context, the discrete elements method can provide an answer to this problem. This method models the interactions of independent bodies to obtain the contact forces and displacements of each element. This approach has been used for the last 30 years to model similar problems such as rockfill dams, dry stone wall stability, etc. Nevertheless, the modeling of a mining waste dump is quite complex, due, on the one hand, to the important polydispersity of the particles that constitute it, with a particle size varying from 1 cm up to 1 m, and on the other hand to the large volume of the dump itself. This translates into the need to model millions of particles.

To tackle this issue, this work presents a simplified method to model the global behavior of the dump, based on the modeling of particles at the mesoscopic scale. First, section 1 will present the numerical procedure for modeling the dump, introducing the numerical method used in the simulations and the generation of the particles within the dump. Section 2 will address the analysis of the global stability of the dump, the modeling of the earthquake used in this study. Finally, section 3 will focus on the analysis of the dump global stability for different configurations.

2 Numerical procedures

2.1 Sample preparation

The numerical samples are composed of rigid polygons following an analogue size distribution, shifted from the original PSD of a WRD [7] displayed in Fig. 2. This scaling process is performed by applying a scale factor on the original particle sizes [8–12]. This numerical trick reduces the total number of particles in the sample and, consequently, the computational time in the simulations. Here, the used scaling factors were 20, 10, and 5 to generate samples composed of 2327, 10047 and 40113 particles respectively.

To generate each sample, an initial generation of disks is performed. A dense sample is generated inside a box of 66 m height and 86 m width, based on the minimization of the gravity potential. Then, each disk is replaced by a circumscribed pentagon (see Fig. 3a), to model an angular shape representative of a rock crushed aggregate. Other regular or irregular polygonal shapes are able to be modeled using this approach. These polygons are deposited by gravity, where the particle-particle and particle-wall friction are set to 0.1 to ensure a dense deposited sample, with a particle density of 2650 kg.m^{-3} (see Fig. 3b). For the sake of simplicity, in this study it was chosen to work with a simplified geometry of WRDs in 2D. The cross-section of the dump is trapezoidal, with a height of 50 m, a top width of 20 m and a slope of 37°, which is the angle of repose resulting from the depositing process of the mining waste from the transport roads. The deposited particles where their barycenters are outside this cross-section are removed. Finally, the particle-friction for all contacts is set to 0.84, which is a typical value for crushed stones [13]. The porosity of the obtained sample is equal to 0.36. For the boundary conditions, the box is replaced by a lateral and a bottom wall. Figure 3c displays a numerical sample obtained using this preparation protocol.

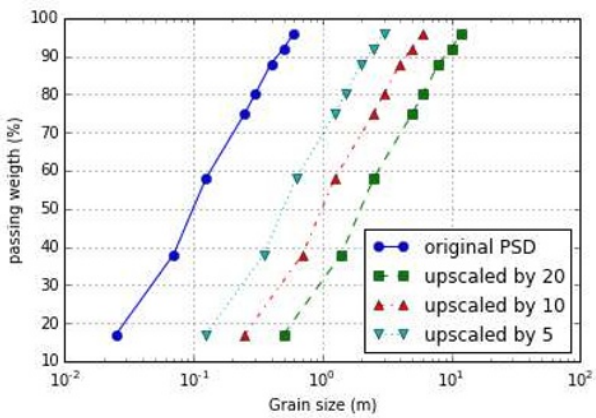

Figure 2. Original PSD for waste rock material and the analogue scaled size distributions.

2.2 Contact Dynamics method

All the simulations were conducted using the LMGC90 software, which is dedicated to multiple physics simulation of discrete material and structures [14] based on the Contact Dynamics (CD) method [15–17]. The CD method is a particle-based approach for the numerical simulation of non-smooth granular dynamics. The non-smoothness refers to various degrees of discontinuity in the velocities and contact forces arising in a system composed of rigid particles [18, 19]. The complementarity condition in the expression of the unilateral contact interactions and Coulomb friction law is the principal difference between the CD method and classic DEM. This for-

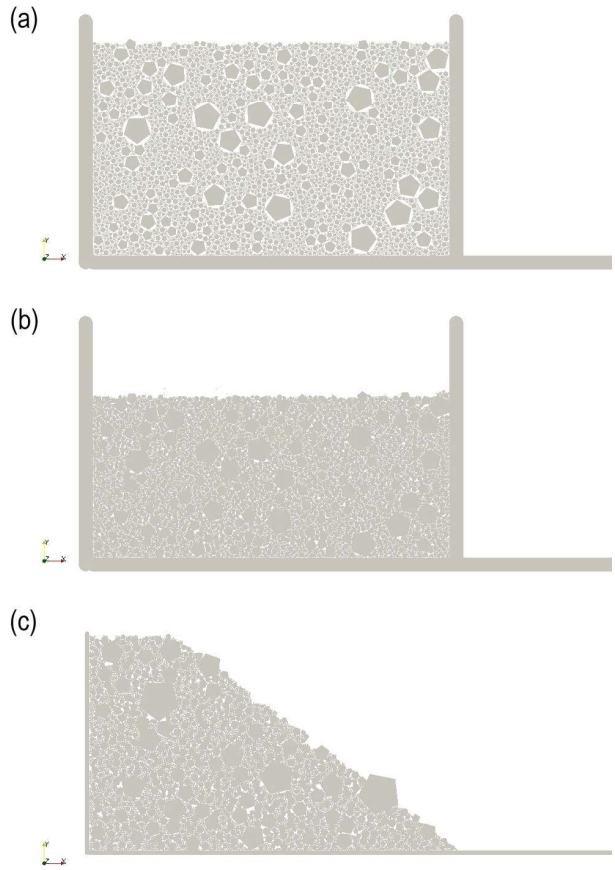

Figure 3. Preparation process at different stages: (a) Initial generation of the numerical sample, (b) Sample after the deposit by gravity, (c) Resulting numerical sample after removing particles outside the dump cross-section

mulation guarantees the non-interpenetration criterion between particles, avoiding the use of regularized laws used in explicit methods. The contact dynamics method cannot properly models features as the effect of wave propagation in the material, where shocks are perfectly plastic. This assumption could affect the particles mobilization due to the important attenuation of the seismic wave between the boundary conditions and the free surface of the particles.

3 WRD stability under seismic loading

3.1 Acceleration signals

In the aim to perform the modeling campaign for WRDs under seismic loading, accelerometer records from the National Seismological Center of the Universidad de Chile were used (http://evtdb.csn.uchile.cl/). The acceleration signals were filtered and converted into velocity signals by means of numerical integration to be charged directly into the LMGC90 software. The CD method can handle directly applied forces and velocities on rigid bodies.

To analyze the mechanical stability of WRD composed of different analogue PSD, a seismic record was employed to analyze the effect of earthquake magnitude on the dump stability. Table 1 displays the information for the simulated earthquake. Figure 4 shows the original acceleration employed to assess the velocity signal after the numerical integration.

Table 1. Date and location of the seismic event used in this study.

Date	2015/09/16
Latitude	-31.55
Longitude	-71.86
Depth (Km)	11
Magnitude	8.4

The velocity signal is applied directly on the left and bottom walls of the numerical sample (see Fig. 3c), following the X-axis. For all simulations, the time step was set to 1×10^{-2}s, where 30,000 time steps were needed to apply the entire velocity signal for the seismic loading.

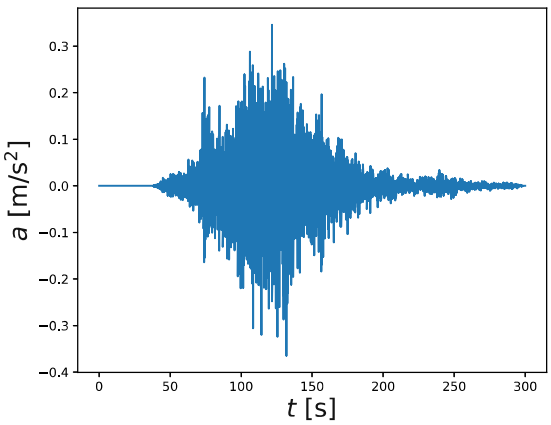

Figure 4. Original acceleration signal from the accelerometer database.

3.2 Global stability

During the seismic loading, a large number of particles are subject to the movement induced by the earthquake. This movement is concentrated in the area near the slope. This mechanism induces an infinite slope failure in the dump. The particles placed on the free surface of the slope are subject to zero confinement and can move freely. Figures 5a and 5b shows this kind of failure for samples with a PSD upscaled 20 and 5 times respectively. At the end of the simulation, it is possible to identify the particles falling down the slope. For samples where the particle size were scaled 5 times, the quantity of displaced material is much more important, where the failure mechanism is more like a slope failure. On the contrary, for samples with finer analogue PSD, it is possible to identify an infinite slope failure. The difference between these failure mechanisms is linked to the grain-size effect for coarse samples, inducing a slip failure localization. In samples with a PSD scaled below 10 times, the effect of the influence of particle size

on the failure mechanism disappears. The global stability of the dump is ensured because the peak acceleration induced by the earthquake about 0.35 m.s^2 is too low to trigger the overall flow of the material (vibration intensity $\Gamma << 1$).

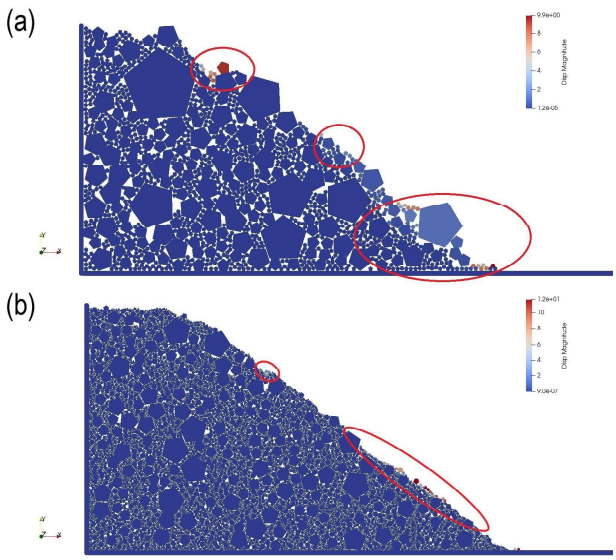

Figure 5. Zoom on particles displacement at the end of the seismic loading : (a) Numerical sample upscaled 20 times. (b) Numerical sample upscaled 5 times.

4 Concluding remarks

This work presents the numerical simulation of an earthquake for mining waste dumps using analogues PSD of the granular material composing the dump. The results show that the failure in these structures is produced by infinite slope, for samples with a PSD upscaled until ten times, which corroborates the type of failure observed in these structures at the full-scale, during the operational phase, under static and seismic conditions. For larger scaling factors, the coarser PSD induces a localization of the slip failure.

This preliminary work is encouraging as a first validation of the proposed approach for the analysis of the global stability of WRD. Nevertheless, at this stage, it is too early to employ directly the proposed methodology on actual WRDs. Further validations will be necessary to verify the performances of the model regarding the macroscopic properties for the upscaled materials and the effect of seismic wave propagation on particle mobilization. Future works on this subject will focus on the identification of runout distances, and the inter-layer mobilization, besides a more accurate model validation. Other topics will cover the 3D behavior of these structures, the modeling of particles with a more realistic shape of the deposited material and the effect of material segregation on mechanical stability.

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