Simulation of the run-out and mobilized volume of a 3D rock slope failure using the Material Point Method (MPM)

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ABSTRACT: Global and large failures are now the reality of some mines. The risk management process and monitoring system are approaches used to mitigate the problem. However, they cannot avoid the problem when the slope fell or is in a continuum deformation process. Considering slopes in a deformation process, it's important to know well the limits of the affected area and the mobilized volume for an optimal risk management approach. Runout numerical studies can predict and estimate the limits of the failed material in case of a slope failure. One of the numerical methods suitable for run-out simulation with large deformations is the Material Point Method (MPM). It is a hybrid numerical method that combines the advantages of Lagrangian and Eulerian approaches to simulate continuum mechanics processes with large deformations and displacements. This paper presents the results of a simulation of a large open pit in Brazil using the MPM method.

Keywords: open pit, slope failure, material point method, large deformations.

1 INTRODUCTION

In this article, we present the result, in 3D and using the Material Point Method, of a numerical analysis of the run-out process of a massive, highly heterogeneous, failed slope. It is located in the Gongo Soco Pit (VALE S.A., Minas Gerais, Brazil). The objective is to quantitatively describe the movement of the failed mass during the run-out process and to quantify the mobilized volume. Firstly, we provide a revision of the numerical method for large deformation problems. Secondly, we define the basic ideas behind the MPM. After that, we give the description of the analyzed case and the results. Finally, we present the conclusions.

2 NUMERICAL METHODS FOR ANALYZING LARGE DEFORMATION PROBLEMS

The numerical methods frequently used for stability and collapse analysis of structures involving geomaterials through a continuous approach are the Finite Element Method (FEM) and the Finite

Difference Method (FDM). Although these methods allow estimating and quantifying with a certain approximation the stability of the slope in the condition of imminent failure, drawbacks related to the mesh distortion are observed during the evaluation of the post-collapse state, particularly during the runout of the failed mass, thus requiring the use of re-meshing techniques that introduce additional errors in the numerical solution and mainly an excessive computational cost. In recent decades, various numerical methods have been developed to allow large deformations in the simulation of geomechanical materials (Soga *et al*. 2018). Within these methods, those without meshes and those based on particles, have been continuously developed and applied to various geomechanical problems with large deformations. In particular, the Material Point Method (Sulsky *et al*. 1994) is a highly relevant method for computational geomechanics involving large deformations. The MPM has been used to study and reproduce various failure modes in slopes (shallow, intermediate, deep, and progressive) with large deformations and with spatial variation of material properties (Liu *et al*. 2019). It has also been used in problems with complex constitutive models with rheology transition (Shi *et al*. 2017). The effect of water has also been considered in the study of fully coupled problems when evaluating the extent of slope mass during the run-out under saturated (Troncone *et al*. 2019) and unsaturated (Liu *et al*. 2020) conditions. Due to its dynamic nature, MPM allows the study of slope failure processes under seismic action and its effect on existing infrastructures (Nguyen *et al*. 2022), as well as runout processes as a consequence of slope excavations (Troncone *et al*. 2022). The MPM has proven to be very useful when combined with other methods for slope studies with a multiscale approach (Wang *et al*. 2022) and for the discrete representation of blocks inside the slopes (Zhao *et al*. 2022).

3 THE MATERIAL POINT METHOD

The material point method, or MPM, is a hybrid Lagrangian-Eulerian method that allows the simulation of continuum mechanics processes of large strains and displacements without drawbacks associated with the distortion of the computational mesh. In the MPM, the material domain to be simulated is discretized into a set of material points (also called particles) that can move freely within a (fixed) Eulerian computational mesh, where the equations of motion are solved. The material points concentrate all the variables of interest during the simulation, such as stress, pore pressure, temperature, etc., and give the method the Lagrangian characteristic. In an MPM computational loop, all material point variables are computed at the nodes of the computational mesh by using interpolation functions, and then the equation of motion is solved at the nodes. The obtained nodal solution is interpolated again for the particles, whose positions are updated, and all nodal variables are discarded. The MPM allows the solution of the motion equation of the continuum mechanics using nodes of an Eulerian computational mesh to perform the integration and using Lagrangean material points to store all properties. The discrete form of the motion equation at the mesh node is (Equation 1):

$$\dot{p}_{iI} = f_{iI}^{int} + f_{iI}^{ext} \tag{1}$$

were Equation 2 is the nodal momentum, Equation 3 is the nodal internal force, Equation 4 is the nodal external force, and Equation 5 is the nodal weighting function evaluated at the particle position and integrated over the particle domain. By choosing different characteristic functions χ_p and interpolation functions N_I, different weighting functions are obtained (Bardenhagen & Kober, 2004) (Zhang, *et al*., 2016). In this study, the step function is used as the characteristic function and linear interpolation functions are employed. Once the nodal acceleration is reached by using the motion equation, the position, and velocity of each particle are updated with the nodal values is given by Equations 6 and 7. Then, the deformation increment in each particle can be obtained by Equation 8. The particle stress increment is determined from the deformation increment $\Delta\epsilon_{ijp}$ by a constitutive relationship. The numerical implementation presented here was previously verified by Fernández (2020) with several 3D large deformation problems, and more recently, with a physical laboratory model (Fernández *et al*. 2021).

$$p_{iI} = \sum_{p} S_{Ip} p_{Ip} \quad (2)$$

$$f_{iI}^{int} = -\sum_{p} \sigma_{ijp} S_{Ip,j} V_p \quad (3)$$

$$f_{iI}^{ext} = \sum_{p} m_p \, S_{Ip} b_{ip} + \int_{\Gamma} \mathrm{t}_i N_I dA \quad (4)$$

$$S_{Ip} = 1/V_p \int_{\Omega_p \cap \Omega} \chi_p N_{Ip} \, dV \quad (5)$$

$$x_{ip}^{t+1} = x_{ip}^{t} + \sum_{I} \mathrm{p}_{iI}/m_I S_{Ip} \, \Delta t \quad (6)$$

$$v_{ip}^{t+\frac{1}{2}} = v_{ip}^{t-\frac{1}{2}} + \sum_{\mathrm{I}} \mathrm{f}_{iI}/m_I \, S_{Ip} \, \Delta t \quad (7)$$

$$\Delta\epsilon_{ijp} = \sum_{I} \frac{1}{2} \left(S_{Ip,j} v_{iI} + S_{Ip,i} v_{jI} \right) \Delta t \quad (8)$$

4 PROBLEM DESCRIPTION AND NUMERICAL MPM MODEL

The problem consists in simulating the runout process of a 3D high-heterogeneous rock slope failure, and quantifying the mobilized mass after the collapse while the failed mass interacts with the basal 3D topography. The MPM numerical model consists of a set of material points distributed inside a computational Eulerian mesh. The model consists of 3.6×10^6 material points and 1.1×10^6 computational nodes (see Figure 1). The failed mass is modeled with the Mohr-Coulomb elastoplastic constitutive model, and the basal materials as linear elastic behavior. An elastic stress distribution is considered the initial state of the model. The boundary conditions are fixed displacements at the bottom and allowed vertical displacements at the laterals. The interaction between the failed mass and the topography is modeled with Coulomb's frictional law, using a frictional parameter equal to 0.15. Table 1 presents the material parameters used in the simulation.

Table 1. Material parameters.

Material Name	id	E (MPa)	ν	ρ(kg/m3	c (kPa)	φ (°)
Schist – Nova Lima Formation	1	24844	0,1	2000	70,0	23
Dolomitic Schist –Nova Lima	2	24844	0,1	2000	100,0	25
Quartzite – Moeda Formation	3	18886	0,1	2600	100,0	38
Phylites – Batatal Formation	4	17033	0,1	1800	20,0	28
Phylites transitional Unit –Batatal	5	17033	0,1	1800	20,0	28

BIF – Nova Lima Formation	6	24275	0,1	2900	350,0	36
Friable Dolomitic Itabirite –Cauê	7	24275	0,1	2000	80,0	38
Dolomitic Itabirite –Gandarela	8	24275	0,1	2100	27,5	41
Compact Itabirite – Cauê	9	24275	0,1	3000	250,0	40
Compact Hematite – Cauê	10	24275	0,1	3000	120,0	43
Talc Schist – Cauê Formation	11	24844	0,1	1800	40,0	25
Waste Pile	12	210	0,1	1800	5,0	26
Tertiary Formation	13	1440	0,2	2000	15	33,5
Dolomites – Gandarela Formation	14	33603	0,2	2503	27,5	41
Tailings	15	20	0,2	1660	0	31

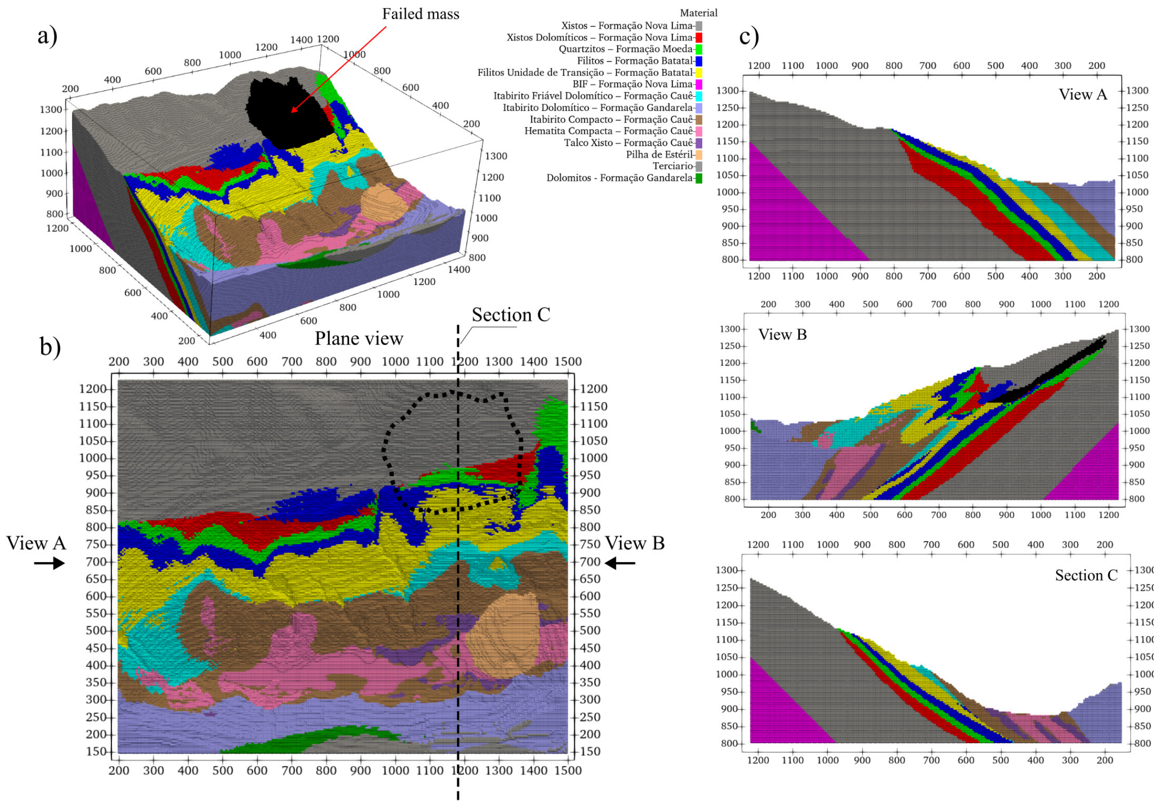

Figure 1. MPM numerical model. a) 3D view of Gongo Soco Pit and failed mass, b) plane view, and c) sectional view, showing the distribution of materials and the identification of the failed mass in black.

5 RESULTS

Figure 2 shows the evolution of the failed slope mass during the runout. At $t = 0s$ the mass is in its initial position. At $t = 0s$ the mass is in its initial position. Until $t = 40s$, the mass moves approximately $208m$, to $t = 60s$, about $401m$, and by $t = 120s$ nearly to $600.1m$, reaching the final position. Analysis of the displacements field suggests that the most mobilized material is located mainly in the central part and at the foot of the failed mass. The large deformation simulation allows us to estimate the main movement of the failed mass, and this information can be used in a posterior risk management analysis. The displacement field clearly shows a first generalized translational movement of the mass from the initial position, followed by deformations and displacements mainly located in the central region and at the foot of the slope. The evolution of the mass contours suggests that the mass presents a significant movement between the times $t = 0s$ and $t = 60s$, until reaching a state of low variability between the times $t = 80s$, $t = 100s$, and $t = 120s$.

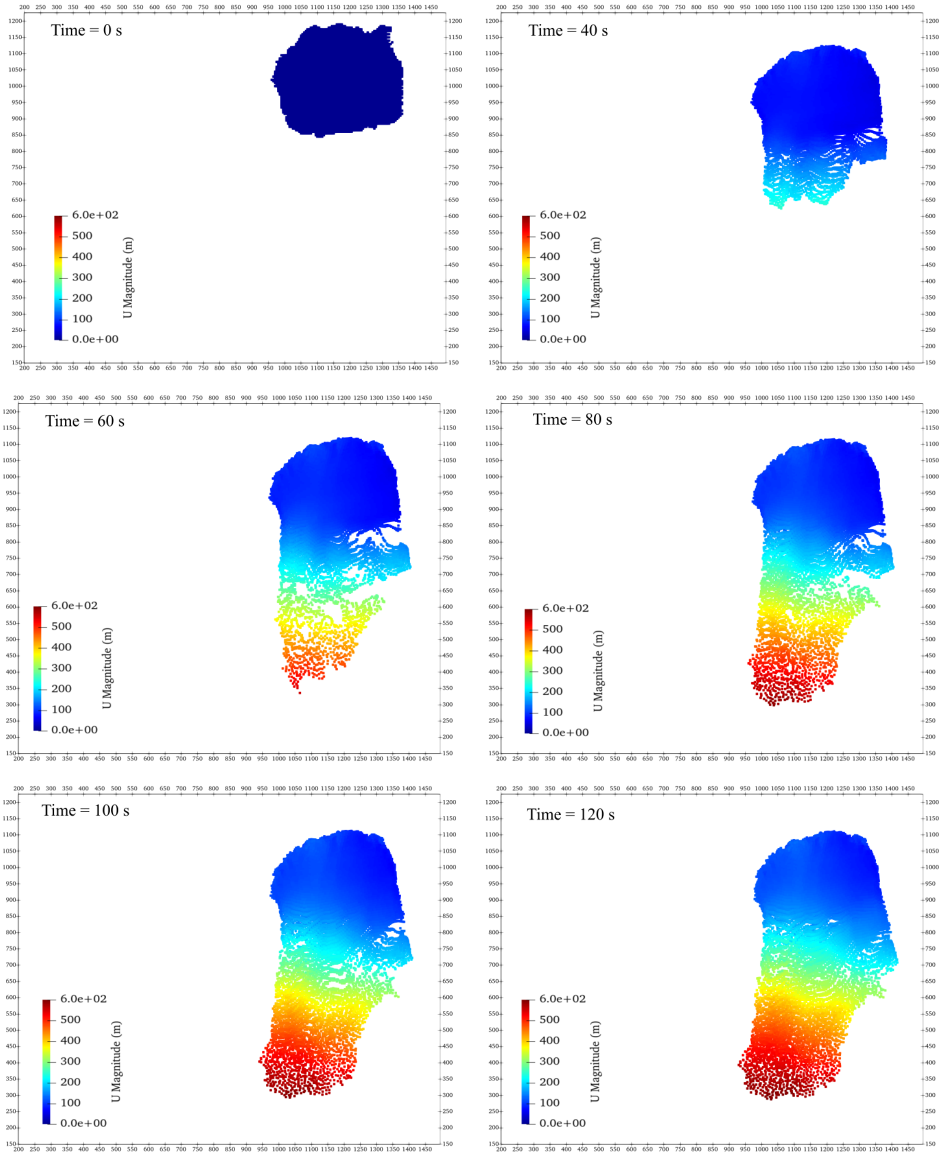

Figure 2. Evolution of the failed mass displacements during the runout.

The mobilized volume is a piece of relevant information resulting from the 3D continuum large deformation analysis. Figure 3 shows it obtained from the numerical model. The mobilized volume was measured by comparing the mass contour lines in the initial position and the deformed final configuration. For this scenario, it was estimated at $0.82 \times 10^6 m^3$. This analysis with large deformation allows us to estimate the mobilized volume accurately, by considering an elastoplastic constitutive model for the failed mass.

6 CONCLUSIONS

In this study, we numerically simulated the runout process of a rock slope inside an open pit. The failed mass was modeled as an elastoplastic continuum interacting with the topography in 3D. It was possible to consider the large deformations in the continuum due to the use of the material point method. The results showed that the failed mass has a first generalized translational movement from the initial position, followed by deformations and displacements mainly located in the central region and at the foot of the rock slope. In addition to the area affected during the runout, the volume mobilized was also estimated.

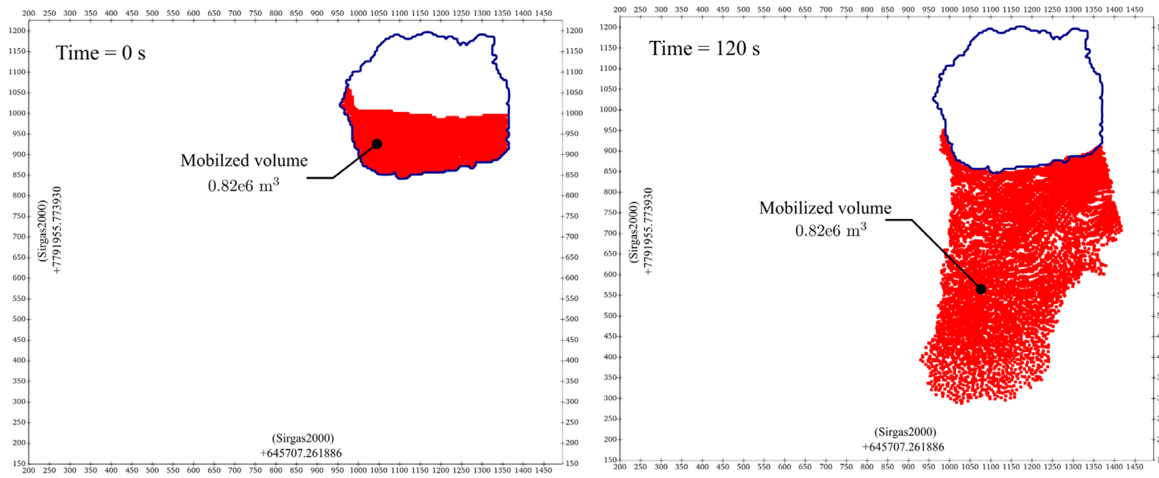

Figure 3. Mobilized volume.

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