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The effect of rock decompaction on the interaction of movement zones in underground mining

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A B S T R A C T

An increased interest in scientific applications for underground mining, mainly to extend the productive life of open pit mines such as Chuquicamata in Chile, has motivated a growing effort to model experimental and theoretically phenomena found in these mines as well as the processes involved in their operation. There is a general consensus that contamination as a result of dilution, a critical problem found in the operation of underground mines, might be reduced by an adequate design of draw point grids and the appropriate handling of them. This requires understanding of the flow of rock fragments and the evolution of the movement zone created by the interaction of multiple draw points. In this paper, we present a theoretical study focused on determining the movement zone created by the interaction of two neighboring draw points operating in alternate mode that simulate those found in a sub-level caving mine. We employ a modified 2D kinematic model that includes a dilation front and assumes that rocks are restricted to move only along streamlines so that we may determine the modification of an isolated movement zone that results from the extraction of material from a neighboring draw point. The volume of extracted material required to initiate the interaction and the location where it occurs are predicted in terms of the material's previously extracted volume, diffusion coefficient, density variations, and extraction rate. The results show that the top surface of the previously isolated movement zone is modified in order to permit the surface to reach greater heights and displace its maximum position closer to the operating draw point. We also find that the regions outside of the operating draw point's isolated movement zone are affected by the interaction and this is confirmed by the deflection of tracer lines. This could have significant negative effects in underground mining operations because dilution, initially located out of range of an operating draw point, might be carried to either the neighboring draw points or the operating draw point's opening, consequently increasing pollution. The results presented can be extrapolated to 3D systems and generalized to other type of flows described by more complex models than a kinematic model.

1. Introduction

Underground mining is under serious consideration to replace the longly, exploited open pit mine. Chilean mining company Codelco plans to transform Chuquicamata, a milestone as one of the biggest open pit copper mines, into an underground mine over the next few years. However, underground mines require a considerable initial investment and have inherent risks. Within the techniques applied in underground mining is sub-level caving, a method that employs a lattice of draw points built below the ore. The extraction of material from these points induces a downwards motion and creates a flow of broken rocks. One of the main concerns in underground mining is dilution, the contamination of minerals by useless material. Draw points contaminated by dilution must be shutdown, incrementing the mining operating cost. In the mining community, it is thought that an adequate distribution of draw points and good handling of the material inside the mine might prevent or reduce the draw point pollution. Therefore, a thorough understanding and characterization of the flow created by multiple draw points is required [1–6]. Despite the complexity found in underground mines, the main features of the flow of broken rocks during the extraction process have been described by simple models based on empirical observations [3,5] and hypotheses that produce inaccurate predictions [2]. More recently, kinematic and plasticity models have been introduced to describe these flows in a more grounded way [7–9]. Although these models are different in nature, it has been shown that the main features of the flow can be reproduced regardless of the model employed [7]. In a previous article, we studied the

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movement zone that resulted from the interaction of multiple draw points operating simultaneously [10]. We found that the interaction of draw points breaks the symmetry of the movement zone, increasing its height within the interaction region. However, for this study the draw points operate in alternate mode, meaning that the material is extracted by a single draw point at a time. Here we present a theoretical study based on a modified 2D kinematic model that includes a dilation front and considers two draw points operating in alternate mode in order to simulate those found in a sub-level caving mine. It is important to mention that the results shown below can be generalized to three dimensions and that they can be derived for flows arising in more complex geometries with the help of numerical methods. Here we limit the study to present the simplest case which illustrates the general rules. In Section 2 we show the basics of 2D kinematic model and dilation front. Section 3 describes the interaction of two draw points operating in alternate mode. In Section 4 we briefly discuss the effects introduced by models that reproduce the isolated movement zone more accurately and in Section 5, we summarize the results.

2. Kinematic model, dilation front and isolated movement zone

In recent articles we have shown that simple granular models such as 2D kinematic model could be considered as a starting point to study more complex situations like that observed in underground mining when sublevel caving technique is applied, see Refs. [7–10]. Although, these models do not consider effects like humidity or grains shape and roughness the resulting predictions are consistent with experimental measurements on scale models, see Ref. [10]. It is important to note that kinematic model is successful in describing the velocity distribution, represented by the streamlines, in a rectangular hopper under stationary conditions, when the material is in a loose packing state [11]. However, the agreement becomes poor if material is in a nearly compact state [12,13], because dilation takes place when densely packed granulate starts to flow. These finding have been recently confirmed by experimental results [14,15] showing that streamlines are correctly predicted by kinematic model in loose packing regime. Different approaches have been developed to modeling this type of granular flows, Mullins [16] modeled the granular flow as the upwards diffusion of voids and Litwiniszyn [17] considered the probability of motion of grains as a random process. Following similar ideas Nedderman and Tuzun [11] developed a model in which particles located immediately above the extraction orifice fall down, letting the particles in the upper layers slide into the vacant space. This model is based on the study of the trajectories of rock fragments, that is the geometrical study of the motion of rock fragments, and therefore does not require to make reference to the forces involved in the process in particular the gravity, i.e. is a pure kinematic model and is currently referred to as *the kinematic model*. If the sliding of particles in the upper layers is viewed as a quasi-stationary process, then it is expected that the horizontal velocity depends on the gradient of the vertical velocity. According to Nedderman and Tuzun [11] the simplest relationship that can be considered between vertical and horizontal velocities in a 2D system is $u_x = -D_P \partial u_z / \partial x$, where u_x and u_z are the horizontal and vertical velocities and D_P is a parameter representing the lateral mobility of grains called diffusion coefficient which has units of distance. Assuming constant density throughout the system and replacing the last expression into the stationary mass conservation equation $\partial u_x/\partial x + \partial u_z/\partial z = 0$ it is found a diffusion-like equation for the vertical velocity, $\partial u_z/\partial z = D_P \partial^2 u_z/\partial x^2$. A complete study of the diffusion equation including their solutions can be found in Ref. [18]. For simplicity we considered the solution of diffusion equation in the case of a narrow aperture, see Ref. [11]. Then, the vertical velocity is given by

$$u_z = \frac{dz}{dt} = -\frac{Q_0}{\sqrt{4\pi D_P z}} \exp\left(-\frac{[x-x_0]^2}{4D_P z}\right), \tag{1}$$

and the horizontal velocity is obtained from $u_x = -D_P \partial u_z/\partial x$, it reads

$$u_x = \frac{dx}{dt} = -\frac{Q_0}{\sqrt{4\pi D_P z}} \exp\left(-\frac{[x-x_0]^2}{4D_P z}\right)\left(\frac{x-x_0}{2z}\right), \tag{2}$$

where D_P is the diffusion coefficient, measured in meters, which magnitude is of the order of the size of a typical rock fragment, x_0 is the location of the center of the draw point and Q_0 is the sectional flow rate, i.e. the section of removed material per unit of time, measured in m^2/s. In three dimensional systems it corresponds to the flow rate or volume of removed material per unit of time, measured in m^3/s. The system of coordinates is shown in Fig. 1. Eqs. (1) and (2) represent the velocity field of steady flow of grains where dilation or local volume changes are negligible.

The position of grains or rock fragments in time is determined by the pathlines or trajectories. These pathlines are obtained by solving the differential Eqs. (1) and (2) simultaneously. In general, find the analytical solution to these equations is not possible when velocity components depend on time. However, as in our case, in a steady state the velocity components are independent of time and therefore the pathlines and streamlines coincide, then the trajectories are determined by introducing the streamlines equation into Eqs. (1) and (2) and integrating in time. The streamlines are calculated from the tangent condition $dz/dx = u_z/u_x$, it reads

$$\frac{dz}{dx} = \frac{z}{x-x_0}. \tag{3}$$

The solution to this equation is given by

$$z = c(x-x_0)^2. \tag{4}$$

This equation which represents the trajectory of rock fragments in a steady flow created by the extraction of material from a narrow draw

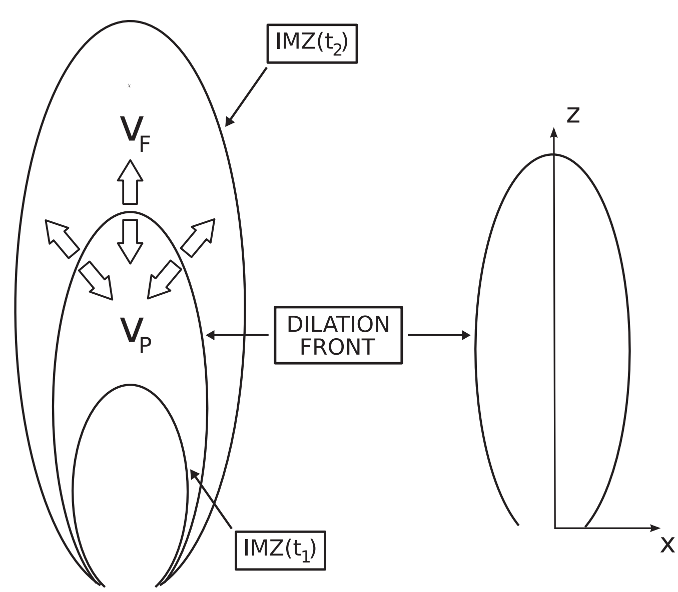

Fig. 1. A schematic illustration that shows the dilation front moving upwards with velocity v_F and the IMZ at two different times, t_1 and t_2. Behind the front, the rocks move downwards with velocity v_P while the rocks located ahead of the front remain static. At rightmost is shown the coordinate system.