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Technical Note

Experimental quantification of hang-up for block caving applications

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1. Introduction

Currently, the most economical underground mining method applied to large, deep, massive deposits is block caving. Although the method was first applied in caveable deposits, due to its advantages, block caving became interesting in hard rock mining. The method consists of rock fragmentation being induced through the caving process with material loaded at drawpoints that are constructed below the caved area. Various feasibility studies of block caving operations indicate that coarse fragmentation and interrupted caving are the main risks that can make the method unfeasible, especially in hard rock and poorly jointed deposits. Operationally, one of the most challenging aspects is the handling of oversized rocks, which have a high impact on the production rate of a drawpoint. According to Laubscher,[1] the main parameters affecting the draw rate are fragmentation, methods of draw, percent of hang-ups and secondary breakage. Therefore, practical hang-up estimation would assist in production planning and scheduling as well as equipment selection for the mitigation of hang-ups. Thus, the prediction of the hang-up frequency for a given geotechnical design or environment is a key to determining the production rate of a caving operation.[2]

A hang-up is an interlocking arch of fragments that lies across the top of the drawpoint blocking the flow of the material. There are multiple parameters that influence hangs-up. Kvapil[3] listed thirteen parameters that influence hang-up occurrence: particle size distribution, max size (d_{100}), shape of fragments, surface roughness and friction between particles, fragment strength, presence of fine material and moisture content, compressibility and compaction, extraction point geometry, magnitude, distribution and direction of external loads and extraction rate. However, there is a need to quantify the influence of these parameters on hang-up frequency. In general, hang-up frequency could be defined as the number of tonnes of material extracted from one drawpoint between interruptions of the flow. Hang-up frequency usually increases during the extraction of a drawpoint due to the decrease in the percentage of coarse fragments in relation to the secondary fragmentation.[1]

To-date, attempts have been made to quantify hang-up frequency for coarse, caved rock through the collection of data from mines, controlled experiments and numerical modelling,[2–13] mine data has been extensively used to predict hang-up frequency.[4–7] Hadjgeorgiou,[8] who summarised experiments and numerical modelling under low confined conditions, showed the influence of the ratio of the particle size to the ore pass diameter on flow conditions. Orellana[9] quantified the hang-up frequency in a physical model for different types of granular material showing the influence of density, strength, friction proprieties and shape of the fragments on hang-up frequency. However, the results obtained during low confined experimental conditions could not emulate the overload of the in-situ column of caved ore, which induces fragmentation and compaction. Recently, the results of the confined flow experiments using a circular exit point with vertical

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pressures from 1 to 6 MPa demonstrated that the mean vertical pressure and the fragment size influence the flowability and hang-up frequency.[2,10,11] The applicability of these latest experimental results to material flow at the full-size caveing mines is not clear as the influence of the geometry of the drawbell and type of loading machine was not investigated.

There are two numerical models that are being used to predict hang-up frequency and secondary fragmentation: Block Cave Fragmentation (BCF) and Core2Frag.[12,13] BCF proposes two options to estimate the hang-up frequency: Ore Pass Rules and Robin Kear Rules. Core2Frag hang-up module likewise considers a different Robin Kear Rule-Based Approach and uses secondary fragmentation as an input.[13] Both Ore Pass and Robin Kear rules consider the geometry of the fragments and drawbell and define the hang up probability according to rule based methods.[12] Ngidi and Pretorius (2010) showed that these predictions understated the total number of hang-ups and overestimated the secondary fragmentation.[6] Besides, both rules have the deficiency of considering the role of vertical pressure, moisture and fine material on hang-up frequency. While useful, rules-based methods to predict hang-ups require further development to be considered a validated approach.

In this paper, the results of the experiments using a scaled, confined physical model to investigate the flow mechanisms during ore extraction in block caving method are described. The experiments were conducted using granular material, which was drawn from one or two drawpoints of the same drawbell. Hang-up frequency and height of hang-ups were quantified for different mean vertical pressures while extracting from one or two drawpoints. In addition, the influence of fragmentation and moisture on hang-up occurrence was also analysed, thus showing the importance of considering confined conditions on hang-up occurrence.

2. Similitude analyses

The use of scaled models for engineering applications requires a provision for the conditions of similitude that depend on the problem to be solved. Castro[14] proposed six criteria to achieve kinematic similitude in a large physical model to study free flow in granular materials for block caving. The conditions of kinematic similitude include: geometrical similitude (shape and size of particles, geometry of drawpoints), friction angle (residual friction angle and boundary friction angle), bulk density (related to size distribution), and time (draw rate). However, dynamic similitude refers to the scaling of the most important forces within the model.

In the gravity flow of caved rock in block caving, the main forces are vertical pressures, friction and cohesion. In summary, a reduced system should preserve the geometry, velocities and the acting forces of the system under study (prototype). Table 1 lists the scale factors that need to be considered, which are scaled in accordance with the geometric scale factor ($1{:}\lambda_L$).

Table 1
Similitude analysis variables scaling parameters.

Variable	Scale factor
Length	λ_L
Area	λ_L^2
Volume	λ_L^3
Velocity	$\lambda_L^{1/2}$
Time	$\lambda_L^{1/2}$
Weight	λ_L^3
Density	1
Friction angle	1
Pressure	λ_L
Strength	λ_L

Applying the same material in the prototype and model would certify the resemblance of friction angle. While, according to dynamic similitude, the applied vertical pressure should be the same as material strength to observe fragmentation and compaction. Of course, there are distortions that are likely to occur due to the presence of spurious forces that may affect the scaled system.

In this research, a vertical pressure was applied through a cylindrical press during the flow experiments. The experiments showed the influence of the vertical pressure on fragmentation, compaction and hang up frequency. However, it should be noted that these experiments required a special setup, which may not be available to all physical modelers.

3. Definition model condition

The experimental model of confined flow was implemented in the laboratory to investigate the impact of mean vertical pressures, moisture and draw policies on hang-up occurrence. This model was represented by three main components. The first was a "physical model" which contained the steel-based container with granular material under high stress condition, including the drawbell located at the bottom of the model. The second part was the "loading system" which involved an LHD system to draw material at the drawpoints. Moreover, this model comprised a press as a "Hydraulic press machine" to apply the vertical pressure during the experiments.

3.1. Physical model

The physical model consisted of a steel cylinder, with a hydraulic press machine which was filled using broken rock (60 kg of crushed ore) (Fig. 1). Fuenzalida[10] introduced this geometrical model to analyse the effects of vertical pressures on gravity flow. However, the base of the Fuenzalida model consisted of a circular-shaped hole to draw material. In this research, for a practical application in cave mining, a drawbell was designed with a rectangular opening of 53 mm × 96 mm at the bottom of the model (Fig. 1b). The dimensions of the opening were defined to characterize the drawbell configuration for an LHD system.

The detailed geometry of the drawbell is displayed in Fig. 2, including two different sections of the physical model. The drawbell was located in the centre of the cylinder with rectangular openings for two drawpoints. This model enabled analysing the flowability of granular material subject to the interaction between two drawpoints. The interaction between drawbells was not in the scope of this research. Scaled and actual drawbell dimensions are indicated in Table 2.

3.2. Loading system

In this physical model, an extraction system was built to replicate the LHD extraction, as is the case of mine site conditions. The material extraction from the drawbell was carried out utilising two LHD systems (scaled from a bucket of 14 yd^3). The LHD extraction system was developed to replicate the draw system of the production level in a Block/Panel caving operation (see Fig. 3). The system had stepper and servo motors. The stepper motor provided horizontal movement of the extraction system and the servomotor controlled the bucket movement during loading and dumping of the fragmented material (between 50 and 60 g of material).

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