The role of gravity flow in the design and planning of large sublevel stopes

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Synopsis

Sublevel stoping (SLS) is one of the oldest and most used methods for underground mining. It relies heavily on the use of drilling and blasting techniques to remove the rock, and gravity to transport the broken rock to drawpoints located at the base of the stope, with LHDs to transport material from the drawpoints. Current SLS operations are based on the assumption of stable geometry of the stope. Thus, the stope design includes the definition of the geometry according to the orebody shape and geomechanical constraints to avoid instability, which may cause excessive dilution. Under some circumstances, dilution could enter the stope due to geotechnical instability, especially when large stope geometries are used. A review of current design and planning practices for large SLS operations indicates that no consideration is given to the material flow and the mixing that occurs after blasting. Material flow could have a large impact on the mixing of ore when grades are heterogeneous in the stope. In this paper, we discuss the influence of gravity flow on the design and planning of large sublevel stopes with and without vertical dilution, based on laboratory experiments. The outcomes of this investigation are used to develop guidelines towards the design and planning of large SLS mines, which would complement the currently used geotechnical considerations.

Keywords
sublevel stoping, mine design, gravity flow, ore dilution.

Current design practices for sublevel stoping

Sublevel stoping (SLS) is a method that can be implemented as sublevel open stoping (SLOS) or vertical crater retreat (VCR). The optimal conditions for the application of SLS are related to the geometry and inclination of the orebody and the stability of the walls and pillars that form the stopes (good geotechnical condition). The stability of the stope, pillar, and walls is determined by the geotechnical characteristics of the hangingwall and footwall (Potvin *et al.*, 2001). SLS could be applied when the dip of the orebody is greater than 50°; this condition is based on the ability of the fragmented rock to flow due to gravity, when extracted at the production level (Pakalnis *et al.*, 2011).

The design of the sublevel stope includes the placement of the draw and the locations of the auxiliary and the drill levels. Figure 1 shows a schematic of the conceptual design of a large stope designed from level 1 to level 3. Note that the stope is defined as large when the height (H) and width (W) of the stope are greater than 30 m. In Figure 1, the dip of the footwall is 90° (vertical). The spacing of the sublevels (h_i) depends on several factors, including the orebody geometry, the drilling technology, and capital costs.

Figure 1 also includes a reference to a variation of ore grade with the stope height. The *in situ* grades are represented by horizontal layers G1, G2, and G3, where (G1>G2>G3). In current planning practices, ore grades are planned to be extracted in the order from G1 to G3 without considering the mixing that might occur during gravity flow. Figure 2 show a typical draw or production level layout for a large sublevel stope, where DD are drifts where a long drawbell is located, while PD is the production drift where, in general, mechanized equipment such as LHDs operates. In the case presented in Figure 2, drawbells are spaced at *Dd* metres while drawpoints are spaced at *Dpe* metres. Generally, for SLS, *Dpe* is approximately 15–18 m while Dd is 48 m (Contador *et al.*, 2001).

Figure 3 shows the application of SLS with the footwall inclined at an angle *a* and the hangingwall inclined at *b* degrees to the horizontal. In this case, the location of the drawpoints must be considered with respect to the maximum recovery of ore, especially if unplanned dilution can enter the stope due to instability. This is related to the gravity flow properties of fragmented rock.

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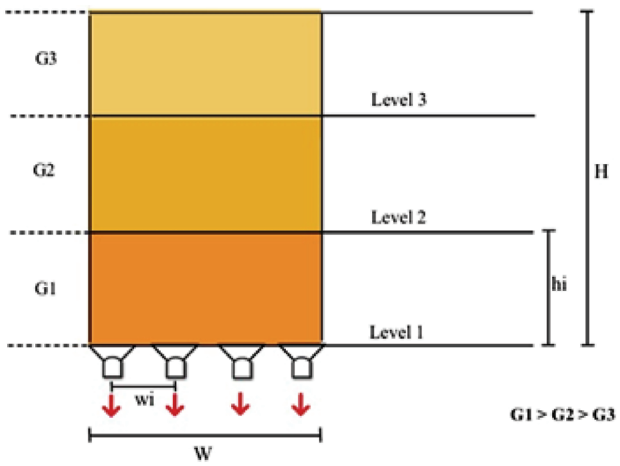

Figure 1—Conceptual design of a sublevel stope. (*Gi* is the grade of ore in the stope, *hi* is the distance between levels, and *wi* is the distance between drawbells)

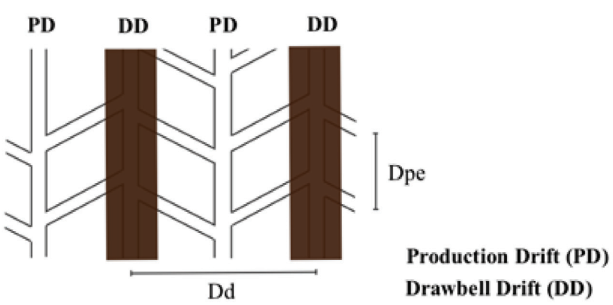

Figure 2—Plan view of a typical production level drawpoint/drawbell spacing for a large sublevel stope

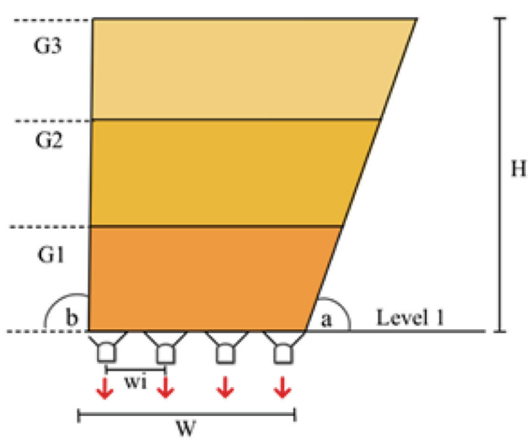

Figure 3—Conceptual design of a sublevel stope. (*Gi* is the ore grade, *H* is the height of the stope, *wi* is the distance between drawbells, and *a* is the dip of the stopes

Gravity flow studies have been extensively conducted in block and sublevel caving applications using scaled models (Kvapil 1965; Lausbscher 2000; Brown 2007) and full-scale tests (Power, 2004; Brunton *et al.*, 2012; Viera *et al.*, 2014). These studies have served to define the location of drawpoints for a flat or an inclined production level and the ore mixing due to flow, results that are extensively used for mine design and planning of caving methods. Guidelines for inclined drawpoint spacing in block caving consider dips from 35° to 40° and a width of the flow zone of 12 m for finely-fragmented caved rock (Laubscher, 2000). Given the differences between SLS and caving methods, the gravity flow experiments may not necessarily be applicable to SLS design and planning.

We conducted research, based on experiments, on the gravity flow characteristics of fragmented rock in SLS applications. The results of the experiments were used to define the location of drawpoints for flat and inclined footwalls in SLS.

Laboratory experiments

To understand the effects of flow on the design of large SLS applications, controlled experiments were conducted. The objective of the laboratory experiments was to study the ore flow within a sublevel stope under inclined geometries. For the purpose of the experiments, a physical model having a typical geometry of a large stope with a footwall inclination of a = 70° and hangingwall inclination of b = 90° was built in the laboratory (Figure 4). During the design stage of the experiments, all the laws of kinematic similitude for granular materials – that is geometrical similitude, extraction rate and friction angle – were taken into consideration (Pineda, 2012).

The model was built using plexiglass to enable observation of the flow and to consider an axisymmetric condition by using near-frictionless walls. The geometrical design was based on a typical drawbell spacing used in large stopes, *i.e.* Dd = 48 m. The dimensions of the model were 1.6 m height × 1 m length × 0.25 m width. The base of the model held an extraction system of 11 drawpoints and the drawbell geometry with a 'shovel' installed at each drawpoint. The 'shovels' were linked to a servomechanism that provided an electrical impulse controlled through a software algorithm, allowing the extraction rate to be varied.

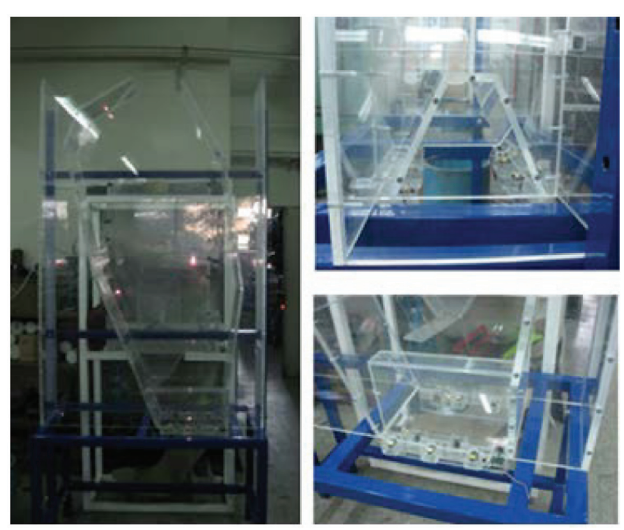

Figure 4—Experimental set up- physical model (left), drawpoints and apex (right)

The size distribution of the material used in the model was based on the rock size distribution as measured at SLS mine operation, with fragment size due to blasting leaning towards fine material with a mean characteristic size or d_{50} of 0.3 m (Figure 5). Therefore, for the experiments, crushed gravel with a mean size of 2 mm was used, as shown in Figure 6.

Methodology

Five experiments were conducted to gain an understanding of gravitational ore flow. During the first experimental stage, all drawpoints were extracted concurrently from a horizontal level during each experiment. For the second stage, drawpoints were added at the footwall to simulate the use of more than one draw level. Table I lists the objectives and the draw strategy for each of the five experiments:

- *Experiment 1*—an understanding of flow under a single drawpoint
- *Experiment 2*—study of the flow under multiple drawpoints from a single production level
- *Experiments 3 and* 4—flow behaviour when drawing from an extra level 30 m above the first level
- *Experiment 5*—flow behaviour when dilution could enter the stope continuously from the levels above the draw level.

Table I

Experimental plan

Experiment	Draw strategy	Objective
1	Isolated draw	To determine isolated flow zone geometry for the model media
2	Uniform draw	To determine the flow mode when drawing from a single draw level
3	Uniform draw	To determine the flow mode when drawing from a single draw level
4	Uniform draw	A repetition of experiment 3
5	Uniform draw	This experiment simulates continuous dilution entry at the top of the stope. The aim is to quantify the flow mode when dilution from the back is continuous

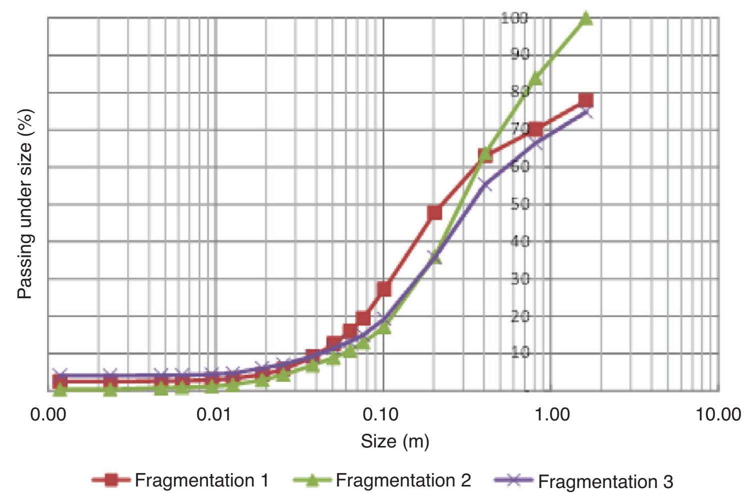

Figure 5—Fragment size distribution for SLS operation

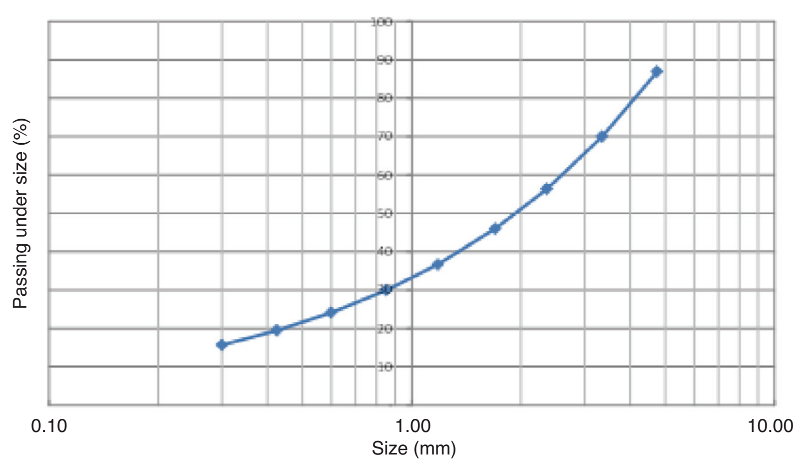

Figure 6—Fragment size distribution for experiments

Experiment 1

During the first experiment, we measured the isolated movement zone or IMZ, which is defined as the disturbed zone due to flow (Castro *et al.*, 2007). As shown in Figure 7, the IMZ has a cylindrical shape, with a diameter d of 15 cm in the model, which corresponds to 30 m in diameter at 300 m draw height when scaled. This corresponds to the measurements of flow zones during gravity flow in granular materials. Figure 7 also shows that the angle of draw α is in the range from 69° to 76°, which should be considered when designing the location of drawpoints.

Experiment 2

In this experiment, flow was induced by drawing from the full geometry at the base of the stope. Figure 8 shows the geometry of the flow for different stages of the draw. As noted, the flow zone due to the extraction from all drawpoints did not propagate *en masse* but developed the shape of the isolated draw zone that propagated towards the lower column height (Figure 8a). Consequently, the flow velocity was higher in the columns with smaller column height. Subsequently, the flow reached a steady state, where the flow was mainly vertical. Subsequently, granular material at the surface moved down due to rilling (Figure 8c). This condition continued as more material was drawn, as shown in Figure 8d. This shows that the flow causes the material to mix. These phenomena should be considered when planning the extraction of a stope that continues to be stable during draw.

The experimental results show that the material located at the production level is not mobilized during flow. The authors developed the force relationships using equilibrium analysis to understand the factor of safety of the wedge. The calculations indicated that failure of the wedge could be expected, which, as noted previously, did not occur during the experiment.

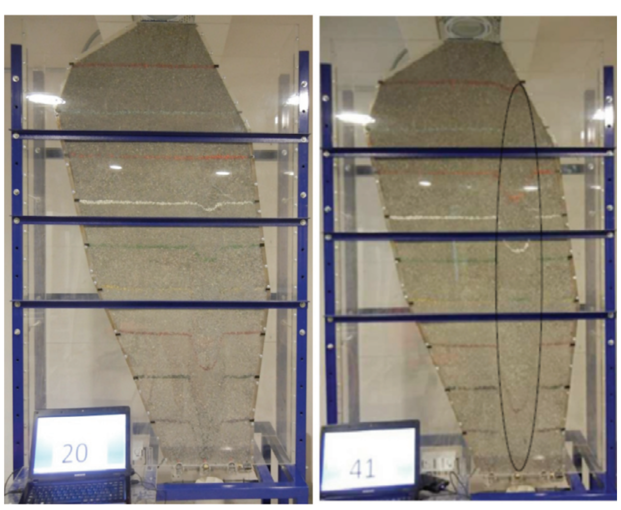

Figure 7—Isolated draw zone as measured during Experiment 1.at a) 33,280 ton for the drawpoint and at b) 68,224 (scaled values)

Experiment 3 and 4

These two experiments were undertaken to determine whether the inclusion of another level is necessary to extract the ore above the footwall in SLS, under the assumption that flow of the wedge does not occur. The new level was located 60 mm above the production level (30 m when scaled to a real sublevel stope). Draw from this level started after the initial draw of material from the production level. As indicated in Figure 9, the flow zone of the drawpoint located at the footwall was connected to that developed due to the flow of Level 1 (Figure 9a). Drawing from this new level improved the early recovery of ore located at the base of the footwall, as shown in Figure 9b.

Experiment 5

This experiment investigated the case of dilution entering the stope from above due to stope instability. The dilution was simulated by adding a granular material, which was finer in size than the initial 'ore' size and coloured red for contrast, on top of the stope. Figure 10 shows different stages during draw. As noted in previous experiments, the flow zone developed faster at the lower column height. Subsequently, the dilution moved down according to a flow velocity profile that was faster in a zone where the height of the column is lower. This type of flow continued until the material reached the height of interaction and rapidly appeared at a drawpoint,

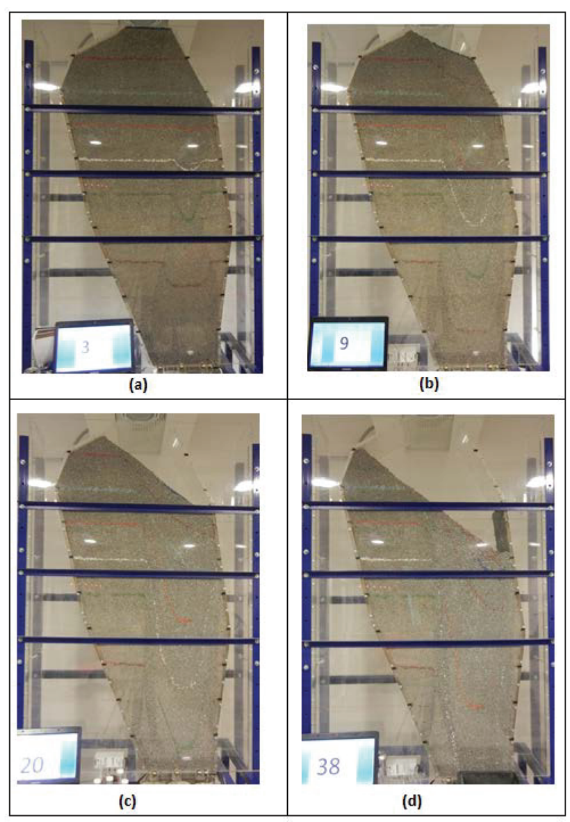

Figure 8—Flow zones during experiment at different stages of draw. (a) Initial draw stage; (b) flow zones breakthrough to surface; (c) further draw; (d) rilling from surface

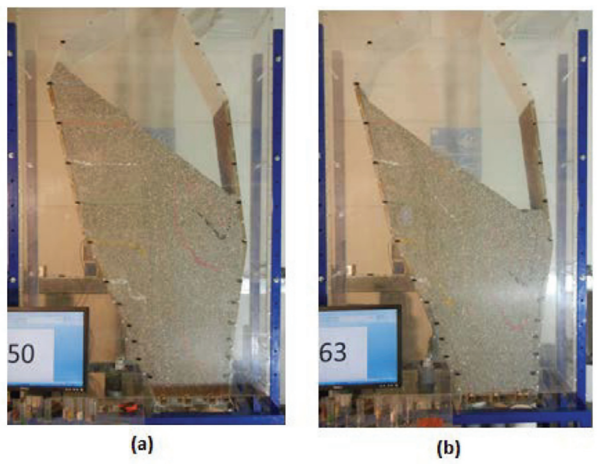

Figure 9—Draw from production level and level located at 30 m for different stages of draw. (a) Initial draw from upper level; (b) further draw and surface rilling

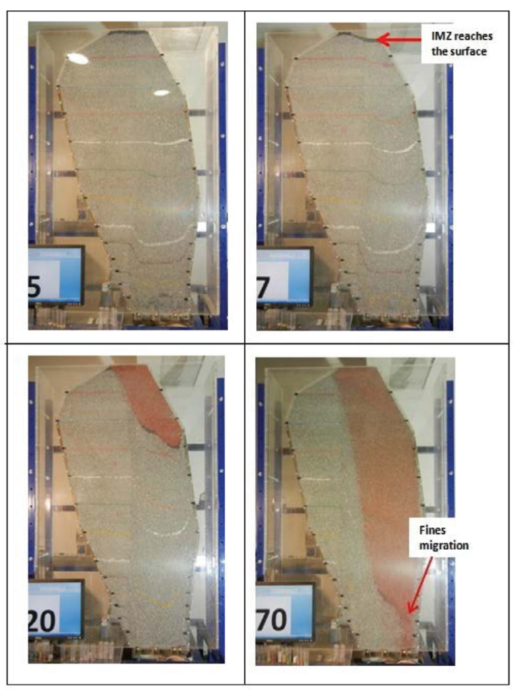

Figure 10—Influence of vertical dilution on flow. (a) Initial draw; (b) flow zone breakthrough to surface; (c) dilution (in red) flow towards drawpoints; (d) fines migrate to the drawpoints with the smallest column height

as noted in block caving experiments (Laubscher, 1994). As this point, the dilution entered the drawpoints at a faster rate, as shown in Figure 10d.

Discussion: SLS design guidelines considering flow

The results of the experiments described in the previous section clearly show that the design guidelines should consider the effects of material flow on the location of drawpoints and draw levels in a sublevel stope.

1. Firstly, the fragmentation due to blasting needs to be estimated. The smaller the fragments the smaller the flow zone and, therefore, the smaller the width of the IMZ. The converse also applies. It must be noted that the results provided in this paper refer to free flow conditions, where no cohesion exists in the granular material
2. Secondly, if the stope is vertical (a = 90°), a single draw level may be considered. In this case, it is necessary to calculate the height of interaction according to the angle of flow (α) and the width of the drawbell drift, and to calculate the spacing of drawpoints according to the desired height of interaction (Castro *et al.*, 2012), that is:

$$HIZ = \left[\frac{d_d - w_p}{2}\right]\tan(a) \qquad [1]$$

3. Thirdly, the spacing of drawbells and drawpoints should be designed for the IMZ to overlap. No reliance on extra spacing rules should be considered, as presented in block caving experiments (Trueman *et al.*, 2008)
4. Finally, if the stope is inclined (a <90°), more than one level may be considered, vertically spaced at a height of h_i metres. As shown in Figure 11, the location of the levels would depend on the width of the IMZ and the inclination of the stope. In this case, the horizontal spacing should be such that the IMZs, with diameter of d metres, overlap. In Figure 11, an example is provided where there is a main draw level (Figure 11a) and other three draw levels are located at the footwall of the stope (Figure 11b) to achieve maximum recovery of the stope. In this case the vertical distance (h_i) between drawpoints is:

$$h_i = d \times \tan(a) \qquad [2]$$

Conclusions

SLS has been widely used in the mining industry for many years. Current design guidelines and mine planning are based on rock stability and equipment, and appear to take into consideration the flow properties of the fragmented rock under gravity.

In this paper, based on laboratory experiments, we prove the importance of flow in the design and operation of large sublevel stopes.

If dilution from the back of the stope is not expected to occur, it is envisaged that SLS would recover most of the ore during drawing, as the stope is emptied. In this case, the spacing of drawpoints may not be key to the success of an operation, but mine planners should consider the mixing of the ore that occurs within the fragmented column and the surface rilling to better estimate the production grades. In the case of an expected instability at the back of the stope, large amounts of dilution could mix with the ore. In this case, ore recovery would not be efficient unless the gravity flow characteristic of the fragmented rock is included in the design

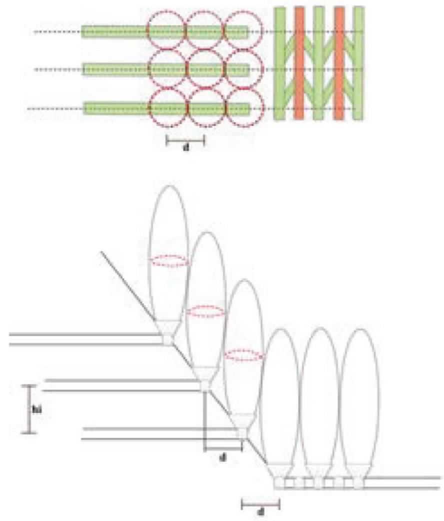

Figure 11—a) Plan view and b) section of proposed draw levels for an inclined stope

and draw strategy. The design of the spacing should ensure interaction between the flow zones. This is also applicable to an inclined footwall, where an extraction level should be added in order to mobilize the ore. The mixing within the ore could be modelled using some of the latter flow simulators built to predict mixing at caving mines (see Castro *et al.*, 2009, Pierce 2010).

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