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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 ($1{:}\lambda_L$).

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.

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

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).

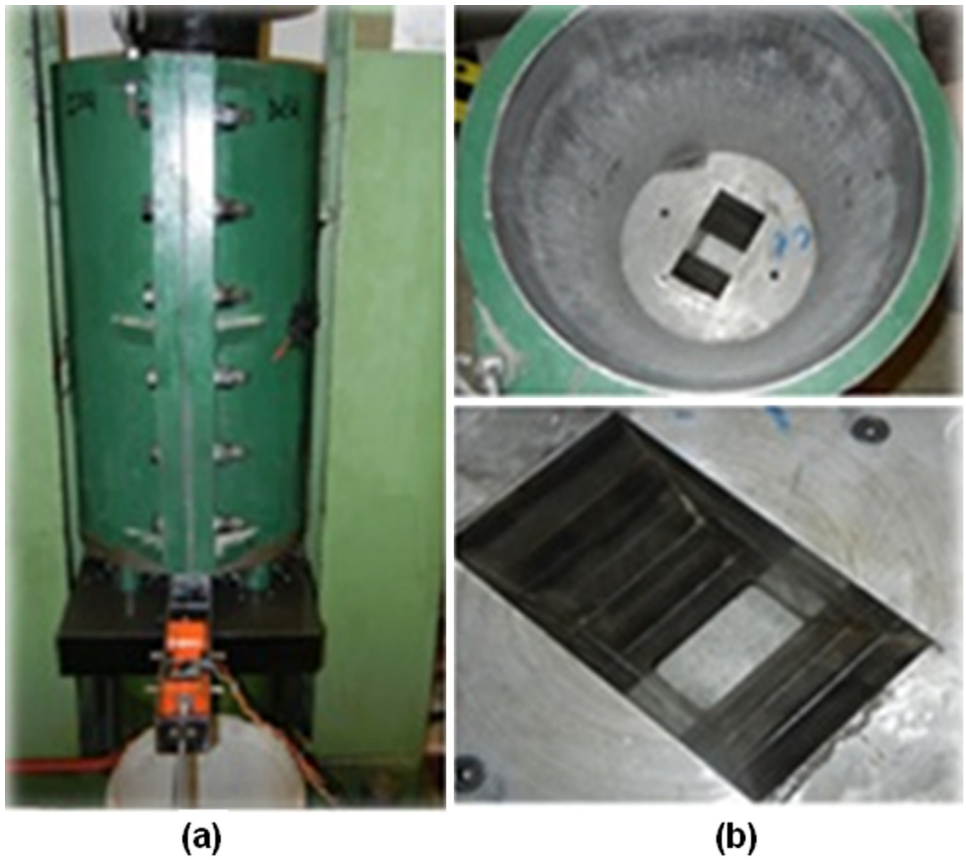

Fig. 1. Experimental model: (a) cylindrical model in a press machine which changes the vertical pressure, σ_V, and (b) drawbell, located at the bottom, center of the model.

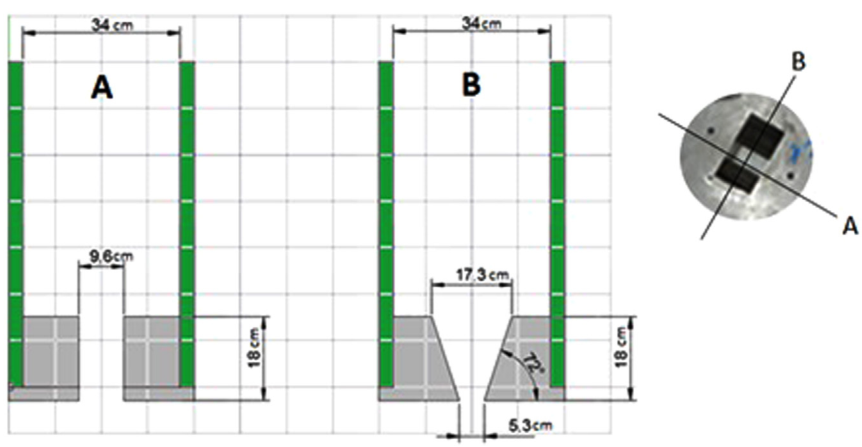

Fig. 2. Physical model dimension.

Table 2
Mine infrastructure dimensions.

Item	Scaled model value	Actual size
Drawbell angle (A section)	90°	90°
Drawbell angle (B section)	72°	72°
Drawbell height	180 mm	13.5 m
Drawbell apex	53 mm	4 m
Gallery height	60 mm	4.5 m
Gallery width	60 mm	4.5 m

Fig. 3. LHD extraction system.

3.3. Boundary conditions

The cylindrical geometry of the model was selected to prevent the boundary effect related to arching and stress concentration in the corners. Moreover, the design of drawpoints and the LHD system allowed for the study of hang-up occurrence in the drawbell, taking into account the boundary conditions related to

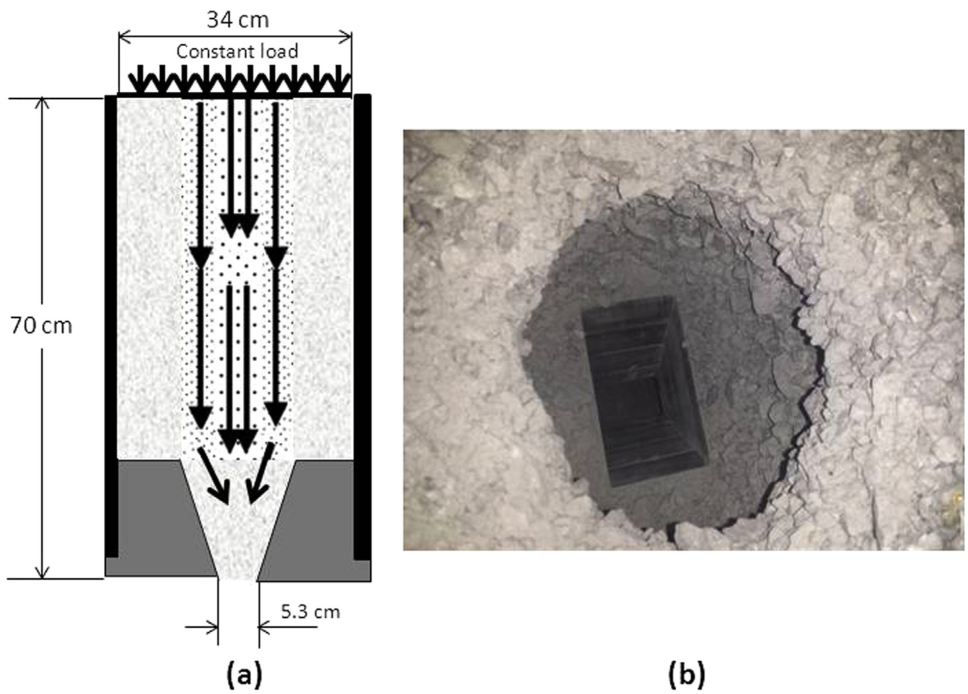

Fig. 4. (a) A schematic view of material core flow pattern and (b) material state after the experiments.

drawpoint geometry and conditions emulating the mine site situation.

Considering the flow pattern within the cylinder, it was supposed that a core flow pattern would occur. Fig. 4a, shows a schematic view of a core flow pattern. The material state at the end of the experiments also confirmed this pattern (Fig. 4b). If the core is narrower than the width of the cylinder (which is 34 cm in this model), as in Fig. 4, the material near the top will cascade down the top surface into the flowing core and will be discharged before material at a lower level.[15] During the experiment the internal flow never reaches the wall of the cylinder. The advantage of this flow pattern is that wall stress peaks occur in the flowing core and the surrounding stagnant material shields the walls to some extent from these effects.

3.4. Model media

The material used in the experiments was crushed sulphide ore with a high aspect ratio to represent the geometry of caved rock, sphericity of 0.58 and a roundness of 0.25. Sphericity measures the degree to which a particle approaches a spherical shape while roundness refers to the sharpness of the corners and edges of a grain. To evaluate the impact of size distribution on hang-up events, two different particle size distributions of the material were prepared and tested: one with the 80% passing size (d_{80}) of 11.8 mm and the second with a d_{80} equals to 15.6 mm (see Fig. 5: Curve 1 and Curve 2, respectively). Both samples had the same uniformity coefficient of 2 ($Cu = d_{60}/d_{10}$). The particle size distributions were scaled from the predicted size distribution of the primary ore (Fig. 5).[16] Table 3 summarizes the characteristics of the samples, showing that the only difference between the samples is in the dimension of the particles.

3.5. Experimental program

A total of thirty-three laboratory tests were conducted on granular material under high confinement conditions. Variables measured during tests included hang-up frequency, the height of

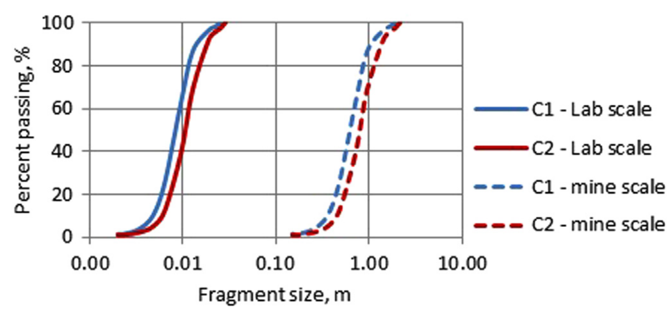

Fig. 5. Comparison of particle size distribution of samples used in the experiments with real size distribution of mining material.

hang-up and secondary fragmentation. The input variables were: size distribution, mean vertical pressure, number of active drawpoints (one or two) in a drawbell and humidity conditions.

During the experiments, different vertical pressures in dry and wet conditions were applied. The humidity conditions were created with 1.6% of water content (mass percent), which caused enough humidity to cover the surface of the fragments with moisture (4.3% saturation). The hang-up frequencies and the heights of hang-ups were recorded while drawing material through one or two drawpoints. Table 4 summarizes the number of experiments carried out for each the vertical pressures applied. In this table, the symbols “1D”, “2D” and “$1D_W$” are related to extraction from one drawpoint, both drawpoints (in sequence) and one drawpoint applying wet material, respectively. The bulk density and void ratio were also recorded for each test in Table 4. These parameters are found to vary significantly with different applied mean vertical pressures. This is mainly due to the rearrangement of the particles. It should be mentioned that bulk densities and void ratios were measured when the pressure had reached its defined value and before ore extraction. In addition, vertical pressure was constant during extraction in each test.

The measurements of hang-ups for all experiments were carried out after 100 LHD extraction cycles were achieved, which equalled approximately five kilograms of extracted material. When

Table 3
Characteristics of the material used during the experiments.

Curve	Average size, d_{50} mm	d_{80} mm	Uniformity coefficient Cu	Drawpoint width/$d_{50, initial}$ d_W/d_{50}	Drawpoint length/ $d_{50, initial}$ d_L/d_{50}	Point load index I_s50, MPa	Initial humidity % (solid by weight)	Density kg/m^3	Internal friction angle °
C1	8.6	11.8	2.0	6.2	11.2	6.2	0.6	2630	39
C2	10.8	15.6	2.0	4.9	8.9				

a hang-up occurred, it was recorded and removed manually. For the 2D tests, the extraction from both drawpoints was performed sequentially until a hang-up occurred. When a hang-up occurred at the drawpoint, drawing from the other drawpoint continued. If a hang-up did not clear naturally after drawing five cycles of LHD from the neighbouring drawpoint, the hang-up was removed manually.

4. Experimental results

Qualitative and quantitative analyses of hang-ups (frequency and height) were performed. For qualitative analysis, three classes for hang-up location were defined (see Fig. 6). Type A illustrates a low hang-up characterised by a vertical slope of broken ore at the drawpoint brow. This type of hang-up was generally reported when coarse fragments collected at the top of the drawpoint. This type of hang-up was mostly cleared by extracting material from the opposite drawpoint (2D tests). The type B hang-up in Fig. 6 corresponds to the low hang-up over the drawpoint. The height of this hang-up was significantly affected by the magnitude of the applied vertical pressure. This type of hang-up needed to be removed manually. Type C represents a high hang-up located at the top of the drawbell. This type of hang-up often appeared when high vertical pressure was applied. Due to the high compaction of material, it was not possible to clear type C hang-up manually. Therefore, the experiment finished when a high hang up occurred.

4.1. Hang-up frequency

The measurement unit of the hang-up frequency was the amount of material extracted between two consecutive hang-ups, *gram/hang-up*, which was subsequently scaled up to *tonne/hang-up* to be comparable with the mine data.

Hang-up frequency of the samples (Curve 1-C1 and Curve 2-C2) was measured when drawing from one drawpoint in dry (1D) and moisture ($1D_W$) conditions as well as two drawpoints in the dry condition (2D). The results from applying different vertical pressures are presented in Figs. 7 and 8 (for C1 and C2, respectively). Although three experiments were performed applying a 5 MPa mean vertical pressure, these results have not been displayed in Figs. 7 and 8 as, at the start of the test, a high hang-up occurred on the top of the drawbell due to the high stress conditions. As a result, a gap area was generated during the extraction of the material between the coarse arch and the ore drawn. Therefore, the fragments under the gap area were drawn without confinement.

A downward trend for all drawing strategies (Figs. 7 and 8) reveals that hang-up frequency decreases with increasing mean vertical pressures. The same results were obtained in previous studies with gravel material and a circumferential extraction point.[2] Comparison of different tests shows that lower hang-up frequencies were obtained in wet conditions. The hang-up that appeared in a wet situation scan probably be attributed to the formation of cohesive arches, since water creates an agglomerate of fine materials due to increasing the cohesion between fragments.[3,18] Furthermore, when comparing two size distributions (Figs. 7 and 8), it can be seen that the hang-up frequency of finer material (C1) is significantly higher than that for coarser fragmentation (C2). For instance, during the experiments without confinement, hang-up frequency increased by 40% (C1) and 8% (C2) in the 2D tests, compared to 1D tests. The increase in the hang-up frequency implies a better flowability of broken material. In addition, Curve 1 has less hang-up events due to a high ratio $d_w/d_{50}=6.2$ as compared to Curve 2, where $d_w/d_{50}=4.9$.

A summary of results for the 2D tests is shown in Table 5. The percentage of hang-ups, which were removed automatically, shows that the alternate extraction between drawpoints assists in the removal of hang-ups. Based on the experiments, approximately fifty percent of hang-ups were removed by alternating the extraction between the drawpoints, which shows that it is not always necessary to remove hang-ups manually. Thus, hang-ups can be removed automatically when drawing from the other drawpoint in a drawbell and due to the interaction between drawpoints (at least for the ratios d_L/d_{50} tested between 8.9 and 11.2).

The size distribution has a significant impact on hang-up phenomena. During the experiments, fragmentation was measured before and after each test. Table 6 shows the degree of fragmentation as a function of the mean fragment size. Experimental results show that final fragmentation depends on the applied mean vertical pressure. Lower fragmentation was achieved with an increase in vertical pressure and, with a decrease in material size distribution under increased pressure, there was also a reduction in hang-up frequency. In addition, the vertical stress influence on hang-up frequency is evident in Table 6. For example, in the 1D tests, the same final ratio d_w/d_{50} of 6.2 was achieved for 0 MPa in Curve 1 ($d_{50,\text{initial}}=8.6$ mm) and 3 MPa in Curve 2 ($d_{50,\text{initial}}=10.8$ mm), yet the hang-up frequency in Curve 1 was

Table 4
Experiments carried out during this research.

Mean vertical pressure (MPa)	$d_{50}=8.6$ mm			$d_{50}=10.8$ mm			Bulk density	Void ratio
	1D (Dry)	2D (Dry)	$1D_W$ (Wet)	1D (Dry)	2D (Dry)	$1D_W$ (Wet)	t/m^3	#
0	2	2	2	2	2	2	1.38	0.91
0.8	1	–	–	1	–	–	–	–
1.5	2	1	1	2	1	1	1.48	0.77
3	2	1	1	2	1	1	1.56	0.69
5	1	1	–	1	–	–	1.69	0.56

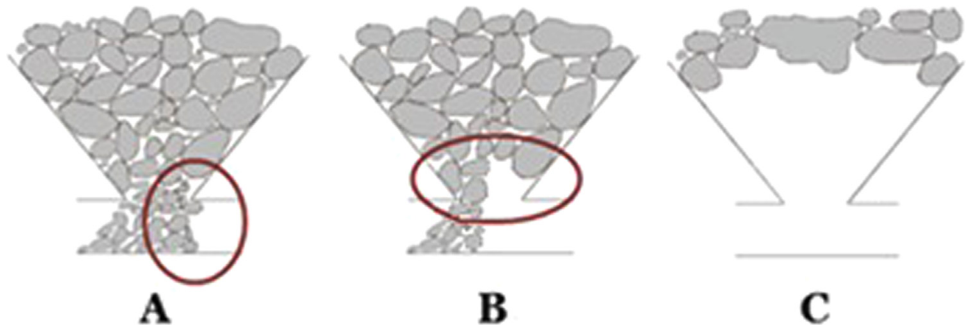

Fig. 6. Types of hang-ups.

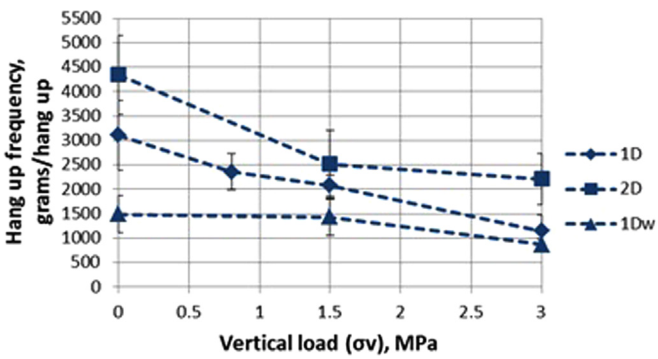

Fig. 7. Curve 1 (d_{80} = 11.8 mm) hang-up frequency results.

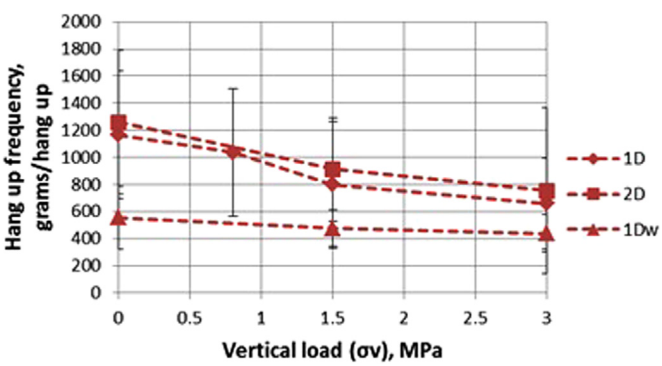

Fig. 8. Curve 2 (d_{80} = 15.6 mm) hang-up frequency results.

almost five times that of Curve 2.

5. Hang-up analysis

The experimental results were scaled up to enable a comparison with mine site data. A complete database of three caving mines was considered in this study. This database includes the DOZ mine of Indonesia, the Palabora mine of South Africa, and four sectors of the El Teniente mine in Chile. Due to the different drawbell geometry

Table 6
Summary of experimental results.

Test Condition	**Vertical pressure** MPa	**d_{50} initial** mm	**d_{50} final** mm	**d_w/d_{50} Final** #	**Hang up frequency** g/hang up	**Standard deviation** g/hang up
1D	0	8.6	8.6	6.2	3109.3	713.1
	0.8		7.8	6.8	2358.3	376.7
	1.5		7.6	7.0	2074.9	210.7
	3		7.1	7.4	1147.9	327.1
	0	10.8	10.8	4.9	1163.2	471.1
	0.8		9.1	5.8	1036.3	471.3
	1.5		8.7	6.1	797.6	465.8
	3		8.6	6.2	657.4	337.0
1Dw	0	8.6	8.6	6.2	1492.9	386.0
	1.5		8.4	6.3	1434.5	372.5
	3		8.2	6.5	866.4	104.0
	0	10.8	10.8	4.9	555.0	230.3
	1.5		10.5	5.1	476.5	134.6
	3		10.0	5.3	437.6	137.7
2D	0	8.6	8.6	6.2	4342.4	810.7
	1.5		7.6	7.0	2515.0	688.8
	3		7.1	7.4	2208.7	528.4
	0	10.8	10.8	4.9	1258.8	529.6
	1.5		8.7	6.1	910.7	382.5
	3		8.6	6.2	753.2	611.9

Table 7
Ratio between the drawpoint apex and the mean fragment size.

Data	**Ratio ($d_W/d_{50,initial}$)**
Curve 1 (Test)	6.2
Curve 2 (Test)	4.9
Palabora	4.7
Reno	6.8
Diablo Regimiento	6.8
Teniente 4 Sur	6.2
Esmeralda	ND
DOZ	5.1

ND: no data.

Table 5
Hang-ups in Test 2D strategy.

Vertical pressure	**Total number of hang-ups**		**Hang up remove manually**		**Hang up removal automatically, %**	
MPa	d_{50} = 8.6 mm	d_{50} = 10.8 mm	d_{50} = 8.6 mm	d_{50} = 10.8 mm	d_{50} = 8.6 mm	d_{50} = 10.8 mm
0	2	4	1	2	50%	50%
0.8	3	4	2	3	33%	25%
1.5	4	6	2	1	50%	83%
3	5	6	1	3	80%	50%
Mean					**53%**	**52%**

and fragment size distributions, the ratio of drawpoint apex (d_W) and mean fragment size (d_{50}) was selected as comparative parameters. Table 7 illustrates these ratios determined from experiments as well as mine site data. The d_W/d_{50} of mine site data ranges from 4.7 to 6.8 and the experimental ratios fall within this range.

The experimental results illustrated the significant influence of mean vertical pressure on hang-ups. Since the mean vertical pressures for the mine data were not available, it was necessary to calculate this parameter for each mine under study. According to the arching effect over the production level, it is not rigorous to calculate mean vertical pressure considering just weight and height of caved material ($\Upsilon * h$).[14] The experimental study by Castro,[14] using fragmented gravels, indicated that mean vertical pressure equals $0.71\Upsilon h$. In addition, numerical modelling also manifested stress arching in granular material.[18] Stress arching occurs when part of the material weight is transferred into the sidewalls, with the forces at the boundaries acting in a different direction to the material weight. Surrounding uncaved boundaries of a caved column are generally rough. Therefore, the Janssen approach[19] was applied to estimate the mean vertical pressure at the bottom of the broken ore (σ_v) in each mine. A general solution of Janssen's equation for mean vertical stress is given by[15]

$$\bar{\sigma_v} = \frac{Rh \bullet \rho_b \bullet g}{Tan(\o_w) \bullet k}\left(1 - exp^{\frac{-k \bullet Tan(\o_w) z}{Rh}}\right) \quad (1)$$

where Rh is the hydraulic radius of the drawn area (m), which can be estimated through the ratio between the production (tpd) and draw rate (tpd/m^2); ρ_b is the bulk density (kg/m^3); g is the gravitational constant (m/s^2); $k = 1 - \sin\o$ is the ratio of horizontal to vertical stress,[14] where $\o$ is the internal friction angle); $\o_w$ is the friction angle at the ore column boundary (rad); and z is the depth of broken ore (m), between production level to surface.

In order to compare the results obtained from the experiments with mine data, hang-up frequency was scaled up through the geometric scale factor (1:75). Accordingly, each tonne per hang up equals (geometric scale factor)^3/10^6 times of one gram per hang up. For instance 1000 g per hang up is equivalent to approximately 422 tonnes per hang up with the geometric scale factor of 75.

Subsequently, the mean vertical pressure was determined for the mines under analysis through Eq. (1), considering the parameters shown in Tables 8–10. Hang-up frequency can be considered as a function of vertical pressure, which is dependent on the height of the draw column. In all mines, the hang-up frequency increased by advancing the extraction of the ore column. This was due to the reduction in the size of the fragments, which is known as secondary fragmentation.[1]

In Fig. 9, the hang-up frequency of different mines as well as experiments (1D and 2D tests for different size distributions C1 and C2) is plotted against the mean vertical pressure. Linear Regression was applied to the experimental results. The influence of the ore fragmentation on hang-up frequency is clearly visible in Fig. 9, which could be used as a practical approach to evaluate the hang-up frequency for different mean vertical pressures and initial fragmentation.

Table 9
Mine data of Esmeralda mine.

Mine		Extraction of primary column	Hang up frequency	Depth	Drawn area	Estimated vertical pressure
Name	**Sector**	**%**	**ton/hang up**	**m**	**m^2**	**MPa**
Esmeralda[7]		10–20	750	650	30,589 (B1), 13,163 (B2)[7]	2.2
		10–20	860			
		10–20	900			
		20–30	1150			
		30–40	1130			
		40–50	1400			

Table 8
Mine data of Diablo Regimiento, Reno, Teniente 4 Sur and DOZ mines.

Mine		Draw column height	Hang up frequency	Depth	Drawn area	Estimated vertical pressure
Name	**Sector**	**m**	**ton/hang up**	**m**	**m^2**	**MPa**
Diablo Regimiento[4]		0–45	605	590[20]	16,320[4]	2.0
		0–93	784			
Reno[4]	Fw	0–50	403	830[20]	28,026[4]	2.5
		0–100	531			
		0–200	522			
		0–300	434			
		0–400	782			
	Hw	0–50	458		23,355[4]	
		0–100	596			
		0–200	830			
		0–300	914			
		0–400	914			
	Hw'	0–50	450		–	
		0–100	593			
		0–200	811			
		0–300	844			
		0–400	844			
Teniente 4 Sur[4]		0–50	251	550–660[20]	99,360[4]	4.4
		0–100	327			
		0–200	461			
		0–300	514			
DOZ[5]		0–60	348.2	1200[21]	41,550	3.2
		60–120	294.2			
		120–180	321.4			
		180–240	408.6			
		> 240	609			

Table 10
Mine data of Palabora mine.

Mine: Name	Mine: Sector	Period: year	Hang up frequency: ton/hang up	Depth: m	Drawn area: m^2	Estimated vertical pressure: MPa
Palabora[6]	1	2004	240	500–1260[20]	11,071[6]	2.0
		2005	300			
		2006	380			
		2007	390			
		2008	400			
		2009	380			
	2	2004	360		16,850[6]	
		2005	400			
		2006	620			
		2007	780			
		2008	640			
		2009	640			
	3	2004	400		27,778[6]	
		2005	540			
		2006	820			
		2007	1000			
		2008	600			
		2009	720			
	4	2004	240		11,071[6]	
		2005	240			
		2006	320			
		2007	320			
		2008	340			
		2009	320			

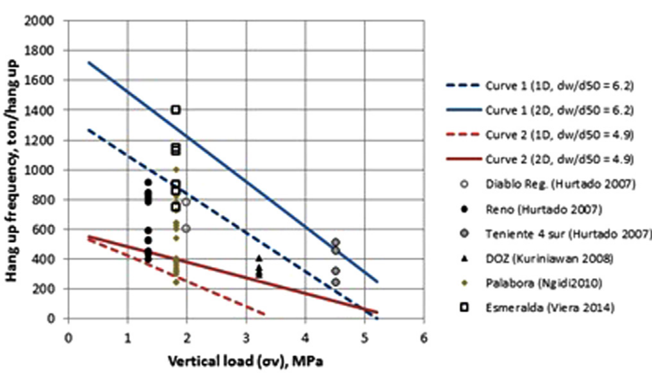

Fig. 9. Hang-up frequency graph. Ref.: Diablo Reg.,[4] Reno,[4] Teniente 4 sur,[4] DOZ,[5] Palabora,[6] Esmeralda.[7]

6. Conclusions

The influence of fragmentation, mean vertical pressure, draw strategies and humidity on hang-up frequency were studied under confined conditions for a single drawbell. During the experiments conducted in the laboratory, hang-up frequency was recorded for different pressure, fragmentation, draw strategy and humidity scenarios.

The review of hang up frequency obtained for each vertical pressure shows the contrary relationship between these parameters. According to the developed frequency graph (Fig. 9), an increase in mean vertical pressure results in a decrease in hang-up frequency. Therefore, vertical pressure should be considered in studies of hang-up frequency.

Besides vertical pressure, this research shows that drawing from one or two sides of a drawbell also influences hang-up frequency. Higher hang-up frequency was observed when using two drawpoints with alternating extraction between the drawpoints due to interaction between the flow zones in the experiments. As a result, it would be possible to increase productivity by changing the draw strategies during ore extraction, provided that the drawpoints interaction takes place. In that case, the natural (due to draw) removal of hang-up was increased when alternate extraction between drawpoints was implemented.

The presence of water mostly changes the geomechanical and geotechnical behaviour of rock. Consequently, the influence of water on hang-up characterisation was analysed in this study, considering one active drawpoint. The results revealed that hang-up frequency is lower in wet conditions ($1D_W$) as compared to dry rock (1D), due to higher cohesion in humid conditions.

Comparison of the experimental results of the samples with two different size distributions showed that coarser fragmentation results in fewer hang-ups. With an increase in the number of large fragments, the probability of blockage at drawpoints increases.

In addition to laboratory experiments, field data was also used to compare with experimental results. The scaled-up hang-up frequency fell within the range of the mine site data. It is thus concluded that experimental results could be used as a practical guide for the analysis and prediction of hang-up events. Accordingly, a hang-up frequency graph was developed, based on scaled-up experimental results, to predict hang up frequencies at a drawbell. This graph shows the influence of vertical pressure, size of material, and extracting from one or two drawpoints on hang-up frequency at a drawbell.

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