Determination of drawpoint spacing in panel caving: a case study at the El Teniente Mine

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Synopsis

Currently, in several caving operations, the spacing between the drawpoints is determined by consulting Laubscher's design guide (Laubscher 1994, 2000), a methodology based on the gravity flow characteristics of the caved rock. Laubscher's methodology is based upon the height of interaction between adjacent flow zones, but does not allow calculation of primary recovery for a given layout. In this paper the authors present a technical and economic methodology based on the flow that occurs near the drawpoint and the associated development costs to estimate the optimal spacing. The flow model at the drawpoint was validated at the El Teniente mine, which extracts coarse caved rock. To validate the flow model, small-scale simulations using drawpoint clusters were conducted and results compared to extracted grades, marker recovery, and drill holes to determine ore remnants that are part of the production control programme at the mine. The results indicate that primary recovery depends on the height of interaction, which varies with the friction angle of the caved rock and the spacing between adjacent drawpoints. Primary recovery estimations indicate values from 85 per cent to 97 per cent depending on the drawpoint spacing used. Extrapolations were then conducted to estimate the primary recovery for different drawpoint configurations planned to be used in the New Mine Level of the mine. The results indicate that the optimal drawpoint spacing is 32 m × 20 m with a through length of 18 m. The methodology developed may be used to estimate optimal drawpoint spacing for block caving mines under different metal prices and mine cost conditions.

Keywords
drawpoint spacing, flow model, block caving, panel caving, simulation

Introduction

Block caving and its variations are massive underground methods that are commonly applied to massive low-grade mine deposits. Block caving methods rely on the use of gravity to break and transport large amounts of caved rock from their *in situ* location to drawpoints located at a production level. Thus, in caving methods, the flow characteristics of the caved rock are fundamental to determining the extraction layout design and the draw strategy. Identifying the best extraction layout includes determining the spacing between drawpoints.

In the literature there have been several attempts to determine the optimal spacing between drawpoints for block caving mines. Julin (1992) presented a guideline for spacing based on block/panel caving experiences worldwide. He estimated that the spacing should be on the order of 26 m^2 to 236 m^2, being larger for coarser fragmentation. Hustrulid (2000) elaborated further on Julin's method and established that the radius of the flow zone seemed to be in the range of 8 to 12 times the mean fragment size. Thus, for a mean fragment size of 0.5 m, he predicted an isolated draw zone of 10 m in diameter; this would also be related to the spacing between drawpoints. Both authors made a collection of current practices which do not necessarily represent optimal conditions. Laubscher (1994, 2000) suggested a relation between the size of the caved rock and the isolated draw zone diameter and its associated spacing to achieve interactive draw. Henriquez (1989) defined the drawpoint layout for Panel III at Codelco-Chile's Andina Division using Laubscher's method and considered the development costs for a range of potential layouts. Susaeta (2008) proposed a design guide for production level layouts in terms of the rock type, the layout, and the draw strategy required to minimize dilution. Lately Kvapil (2004) has proposed a graph to determine the diameter of isolated draw for three types of rock for block/panel caving mines. Other authors have proposed the use of flow emulators as tools that, through back analysis, may be used to determine drawpoint spacing. For example Castro *et al.* (2009) used FlowSim, a flow simulator, to determine the dilution entry. The flow model was validated with data from the Esmeralda and Inca Oeste mines in Chile.

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A review of the different approaches and descriptions in the literature indicates that the selection of the drawpoint spacing depends on several factors including recovery estimates, dilution entry, geomechanical aspects, equipment size, and development costs. A summary of the different approaches is indicated in Table I. This table also includes a critical review of the above methods to help mine practitioners understand the information presented by the different authors. It is concluded that until enough full-scale experiments are conducted at caving mines (which may take several years to develop), the best option for selecting drawpoint spacing should be based on current practice and back analysis using numerical flow models. In this paper the authors propose a method that uses a flow model and takes into account both economic and technical factors to arrive at the optimal spacing. A study of the spacing for the New Mine Level at the El Teniente mine (NML) is presented as an example of the approach.

Drawpoint spacing based on recovery

The concept of drawpoint spacing based on recovery described in this paper is based on the concept of interaction of adjacent draw zones. In this concept, mass flow occurs only when adjacent flow zones are spaced so that they interact at a given height. This model of flow for caved rock is based on the results of a large physical model in which interaction was extensively studied using a large gravel model (Trueman *et al.*, 2008). As shown in Figure 1, when a drawpoint is pulled at its base, a flow zone develops that could be characterized, among other variables, by the angle of flow. This angle may be calculated from the friction angle of the caved rock. The height of interaction can be calculated from the flow properties of the caved rock and the spacing as:

$$HIZ = \left[\frac{d_p - w_p}{2}\right]\tan(\alpha) \quad [1]$$

$$\alpha = 45 + \frac{\phi}{2} \quad [2]$$

where *HIZ* is the maximum height at which flow zones intercept from the roof of the production level drift in metres, w_p is the width of the extraction drift in metres, d_p is the distance between adjacent drawpoints (drawbell, production, or drawpoint distance), α is the angle of flow, and ϕ is the friction angle of the caved rock.

As shown in Figure 1, the height of interaction is related to the spacing of the drawpoints (d_p). The height of

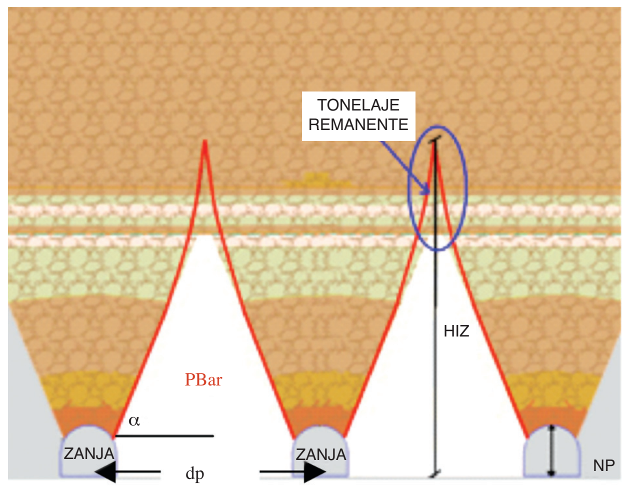


Figure 1—Draw at the base of a block cave. The ore expected to remain unrecovered due to a higher *HIZ* is shown in blue

Table I

Summary of design methodologies for determining the optimal drawpoint spacing

Author	Input parameters	Fundamental basis	Allows ore recovery calculation	Considers stability	Costs included	Observation
Laubscher (1994)	Fragmentation	Sand models were used to establish a relationship between fragmentation and draw zone diameter	×	×	×	Interaction at 1.5 IDZ observed in sand models. Draw zones were not validated at mine scale
Laubscher (2000)	Fragmentation	Review of current practice at caving operations	×	×	×	Method based on current practice. This may not be the optimal condition
Henriquez (1989)	Fragmentation	Same as above	×	×	√	Based on 1. The spacing for Andina was chosen based on the development costs
Julin (1992) 1992). Hustrulid (2000)	Fragmentation	Drawpoint spacing used at different operations	×	×	×	Method based on current practice at 1992. This may not be the optimal condition
Susaeta (2008)	Fragmentation	Sand models and back analysis	×	×	×	Method based on current spacing and draw type draw conditions
Castro *et al.* (2009)	Flow parameters	Flow model	√	×	×	A flow current spacing and draw conditions model is used to build a dilution entry chart at different drawpoint spacing
Kvapil (2004)	Fragmentation	Sand models	×	×	×	A chart is presented which includes the draw zone diameter as a function of fragmentation. There is no data to back up the information presented
Van As and Van Hout, 2008)	REBOP parameters	Use of REBOP simulations	√	×	×	The influence of drawpoint spacing on recovery is presented. No comparison to actual data is presented

interaction is a very important concept in drawpoint spacing because it determines the potential recovery due to the spacing between adjacent draw zones.

As shown in Figure 2, when establishing the spacing in block/panel caving there are three distances that should be determined: the drawbell length (d_l), the drawpoint drift (d_{pe}) and the production drift distance (d_c). Thus, the height of the interaction zone (and therefore the *HIZ*) changes along the section being measured. From a business perspective it is important to note that material beneath the zone interaction is not going to be recovered by the extraction level without changing the mining method, as for example the application of a front caving that may would occur at the end of the life of the mine. These two factors have an effect on the recovery of high-grade ore located near the extraction level.

A simple economic model to determine the optimal drawpoint spacing is presented below. Consider a mine that benefits from the extraction of copper and molybdenum. The income associated with a particular extraction configuration is given by

$$I = I_{CU} + I_{MO} \qquad [3]$$

where

$$I_{MO} = R_{mine} R_{metall\_MO} \frac{P_{MO}}{100} g_{MO} A(H_c - d_h)\rho_{rock} \qquad [4]$$

$$I_{CU} R_{mine} R_{metall} P_{CU} f g_{CU} A(H_c - d_h)\rho_{rock} \qquad [5]$$

i is the column height (m)
A is the block or panel area (m^2)
P_{Cu} is the copper price including deductions (US$ per pound)
f is the conversion factor from pounds to tons (lb/ton)
$g_{Cu,Mo}$ is the copper and molybdenum grade (%) d_h is the distance between production and undercut level (m)ρ_{rock} is the *in situ* rock density (t/m^3)
R_{metall} is the metallurgical recovery (%)
R_{mine} is the mine recovery (%).

In this equation, recovery is considered to be dependent on caved rock flow. The development costs D_c associated with a given number of drawpoints N_{dp} in a given area is given by:

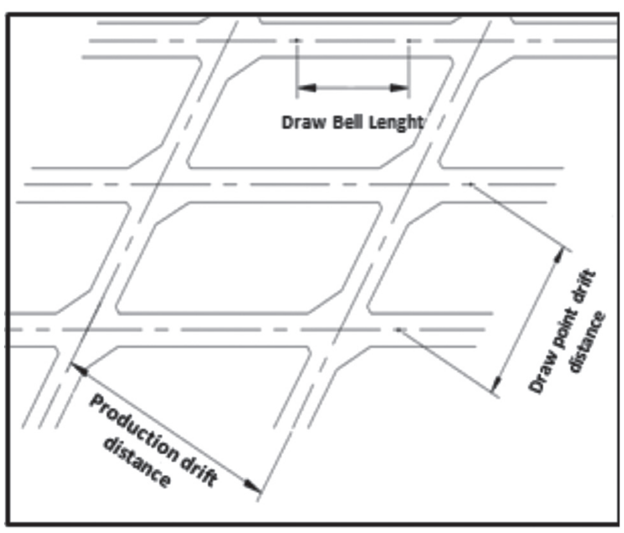


Figure 2—Drawpoint distances in a block/panel caving operation

$$D_c = \left[c_d m_d F_c + c_p m_p F_c + \frac{C_{dr}}{2} + c_{dp} \right] N_{dp} + C_{prep} A \qquad [6]$$

where
C_d is the cost of drift through (US$ per metre)
C_p is the cost of production drift (US$ per metre)
C_{dr} is the unit cost of drawbell (US$ per unit)
C_{dp} is the cost of drawpoint (US$ per unit)
C_{prep} is the cost of undercutting, transport, and ventilation (US$ per m^2)
m_d is the length of the trough drift associated to the drawpoint (m)
m_p is the length of the production drift associated to the drawpoint (m)
N_{dp} is the number of drawpoints in a given production footprint of area A
$F_{c,i}$ is a factor related to an increase in the support costs due to instability at the production level with respect to a case base.

This increase in costs is related to the ratio to a case base the pillar area and tributary area of the pillar, that is:

$$F_{c,i} = \frac{A_{t,i} / A_{p,i}}{Min(j)(\frac{A_{t,j}}{A_{p,j}})} \qquad [7]$$

where $A_{p,i}$ is the pillar area and $A_{t,i}$ is the tributary area, and Min(j) is the most stable condition.

The benefit associated with a particular layout is given by:

$$B = I - Dc - Cmine \qquad [8]$$

where C_{mine} is the operational costs associated with the extraction of minerals.

$$C_{mine} = R_{mine} C_{extr+proc} A(H_c - d_h)\rho_{rock} \qquad [9]$$

where
$C_{extr+proc}$ is the sum of the extraction and processing costs (US$ per ton)
A is the footprint area under study, m^2
H_c is the column height, m
d_h is the distance between the production and undercut levels, m.

Then the drawpoint spacing, which is determined by the drawbell length (d_l), drawpoint drift spacing (d_{pe}), and production drift distance (d_c), should be that which maximizes the total benefit— that is, *Max (B)*. From the above equations, the term that comprise the spacing are the flow of caved rock, which is that related to the recovery at the mine (R_{mine}), and m_p and m_d, which are the development lengths associated to a given drawpoint spacing.

Comparison of the flow model with El Teniente data

El Teniente's sector layout and draw control

In this investigation we compared the small-scale flow model at El Teniente mine, considering the layouts and draw history of four sectors that have extracted coarse caved rock (Table II). In this table the distortion is defined as the ratio between the maximum and minimum distance between adjacent drawpoints; the drawpoint stability number is (*1-r*) %, where r is the area excavation ratio for a given spacing ($r = A_t - A_p/A_t$) and the drawpoint area of influence as (d_c x d_{pe})/2.

Table II

Layout characteristics of El Teniente's sectors used in this study

Sector	Production level type	Production drift distance (d_c), m	Drawpoint drift distance (d_{pe}), m	Drawpoint Influence area, m^2 (d_{pe} x d_c)/2	Distortion	Drawpoint stability number, % 1-*r*
Teniente 4 Sur	Teniente	30	17	299	1.18	74
Reservas Norte	Teniente	30	20	340	1.13	87
Esmeralda	Teniente	30	20	289	1.5	74
Diablo Regimiento	Teniente	34	20	340	1.13	59

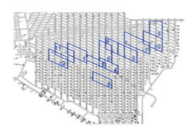
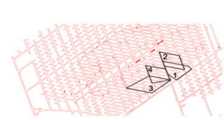
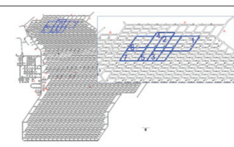
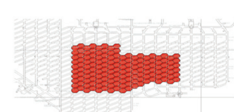
	Data under analysis	Cluster location
Teniente 4 Sur	Number of potential clusters: 12 Amount of tonnage per cluster: 3.5 Mt Mean uniformity index: 69% Sampling rate: 3746 t per sample Height of draw: 160 ±86 m Number of selected clusters for analysis: 6	
Reservas Norte	Number of clusters: 4 Amount of tonnage per cluster: 4.6 Mt Mean uniformity index: 87% Sampling rate: 4722 t per sample Height of draw: 219 ±16 m Number of selected clusters for analysis: 4	
Esmeralda	Number of selected clusters: 7 Amount of tonnage per cluster: Mean uniformity index: 92% Sampling rate: 2365 t per sample Height of draw: 109 m	
Diablo Regimiento	Number of selected drawpoints: 130 Amount of tonnage: 11 Mt Mean uniformity index: 92% Height of draw: 219 ±161 m No holes were drilled in broken rock	

Figure 3—Clusters and draw control characterization of selected sectors

Those sectors extract competent ore with an RMR greater than 50. Validation of the methodology was carried out with draw control data from Esmeralda, Reservas Norte, El Teniente 4 Sur, and Diablo Regimiento (Figure 3). From the possible clusters, a selection was made based on the amount of sample data available based on the sampling rate and the presence or absence of drill holes. In the case of Teniente 4 Sur, only 6 of the potential 12 clusters were used due to sampling frequency (less than 3000 t between sampling at drawpoints). From those, the only sector that did not have drill holes in broken ore was Diablo Regimiento, so a simulation of the whole sector was carried out to estimate the error in determining the extracted copper grades.

The draw control data collected at El Teniente is based on diverse sources of information: metal content from sampling at drawpoints, dilution entry, and artificial markers. Additionally, to evaluate the ore left between drawpoints, it is usual practice to drill holes through the caved rock after draw has ceased in a given area. During the drilling campaign, the caved material precedence is usually identified by the geologist as either what is termed secondary ore (which is rounded and red in colour due to the presence of oxides and clays) and the primary ore (which is gray and breaks into angular fragments) (Seguel and Millan, 2004). The secondary rock is mostly remnant ore from previous extraction levels. In some areas there are also reports from the time when material from old workings (concrete, wood, rails) entered the drawpoints. This data is used to estimate the dilution entry point when available.

Height of interaction zone

The height of interaction may be determined, as described previously, as a function of draw angle (or friction angle) and distance. At El Teniente mine the height of interaction was calculated from the data observed through a drilling campaign used to define the copper grades and the lithology in the broken rock (Seguel and Millan, 2004). The data shows that the flow model had an error of 9 to 4 m for coarse caved rock, as indicated in Table III.

Mine production data

The interaction of adjacent flow zones as presented earlier has been included in REBOP, a flow model that could be used as a draw control tool for block caves (Pierce, 2010). REBOP considers not only the flow at the base of the drawpoint, but also the material movement due to different draw sequences. REBOP has been calibrated and validated with experimental results using a sensitivity analysis and compared to block caving operations (Pierce, 2009). In the present investigation, additional comparison to El Teniente sectors using the cluster concept was performed. Simulations were carried out using four sets of parameters as part of a sensitivity analysis (Vargas, 2010). The simulations were compared to historical data to determine the errors in the cluster analysis in terms of copper tonnage extracted, broken material entry, height of interaction, and the grades of the remnant ore. The estimation of relative and absolute error indicates that the estimated copper tonnage per month ranges from 0.1 per cent to a maximum of 24 per cent, with an average of 18 per cent and a mean square error of ± 12 t of copper per month. For the Diablo Regimiento mine, it was possible to run a sector simulation including the propagation of the cave as it was observed during the initial part of the extraction. In this case the total error decreases from 30 per cent to 0.2 per cent, as the simulated dilution entry showed values near the actual measurements. This means that the incorporation of caving into the analysis could have a significant impact on determining dilution entry. Therefore, for forecasting of grades and dilution, a full analysis should be pursued. For drawpoint spacing analysis, a cluster analysis seems appropriate.

Primary ore recovery estimates

Before discussing of drawpoint spacing, as mentioned in this article, some definitions are required. Primary ore recovery is defined as the percentage of the *in situ* ore column or solid rock extracted during the mining process. The remnant ore is defined as the amount of reserves that are not extracted at the base of the production level and above the undercut level. The calculation of the extracted tonnage and the remnant ore is based on the overlap of adjacent draw zones and the HIZ, assuming interaction (see Table IV). The results demonstrate the effect of spacing between drawpoints on the ore recovery and the remnant ore estimates. The current production level layouts of Diablo Regimiento have a greater amount of potential remnant ore compared with Teniente 4 Sur, which has the smaller spacing.

Drawpoint spacing for the NML

Given the flow zone for a drawpoint it is possible to quantify the potential ore recovery for different production level layouts for distances between production drifts, drawpoint drifts, and drawbell length. For the NML we considered 24 possible configurations, each with a given primary ore recovery potential (see Table IV). The primary recovery estimate determines the potential remnant tonnage per drawpoint. It is noted that when the spacing between drawpoints increases, there is a greater amount of non-recoverable ore; this is because the separation is larger along the major apex, generating an increase in the height of the interactive zone (HIZ) and leaving more ore between drawpoints. As indicated in Table V, the extraction layout proposed for the project at the prefeasibility (30 m × 20 m) stage has a potential ore loss of 8 861 t. Simulated alternatives show that this situation can be improved by a smaller layout (30 m × 18 m) having a potential loss of 6 673 tper drawpoint, which is 2 188 t less than originally proposed.

To complete the study, an economic evaluation was performed based on the costs and benefits attained from the different configurations defined in the previous section. The evaluation was performed using ore recovery extraction per drawpoint and considers the costs of development and ground support. The economic analysis was performed based on an extraction layout located in an area of 1 700 000 m^2 and considering a column height of 240 m. The remnant ore matrix (Table V) was used to determine the ore to be extracted by each production level layout while Equations [4] to [9] were used to define the benefit for each configuration.

It is important to emphasize that the economic evaluation was conducted in terms of ore recovery and construction costs. Other topics, such as the productivity of the design, are more related to the ore pass spacing to achieve an optimal design. The results indicate that the optimal drawpoint spacing is 32 m × 20 m for a through length of 18 m.

Discussion and conclusions

This paper describes a technical and economic method to estimate the optimal drawpoint spacing for a panel caving mine with application to the New Mine Level of the El Teniente mine. Primary recovery estimates using the method indicate recoveries from 85 per cent to 97 per cent of the total column height. The proposed drawpoint spacing for the project at the feasibility stage is 32 m × 20 m with a drawbell length of 18 m. The drawpoint flow model has been derived

Table III

Error estimation of the height of interaction zone (Equation [1]) for different sectors al El Teniente

Sector	Drill holes under analysis	Friction angle	Error, m
Esmeralda	7	$\phi = 50°$	9.0
		$\phi = 30°$	6.1
Reservas Norte	4	$\phi = 50°$	4.3
		$\phi = 30°$	1.6
Teniente 4 Sur	6	$\phi = 50°$	10.6
		$\phi = 30°$	15.7

Table IV

Estimated primary ore recovery and remnant ore for production level layouts

Sector	Production level layout, m	Drawbell length, m	Primary ore recovery, %	Remnant ore/ drawpoint, t
Esmeralda	30 × 20	12	91.5–95.9	6 297–3 088
Reservas Norte	30 × 20	14	95.3–97.5	6 938–3 703
Diablo Regimiento	34 × 20	16	93.1	8 288
Teniente 4 Sur	30 × 17	11	85.9–95.1	5 611–1 965

Table V

Remnant ore per drawpoint (tonnage)

	Drawbell length = 15 m			Drawbell length = 18 m		
d_c/d_{pe}	18 m	20 m	23 m	18 m	20 m	23 m
30 m	6 673	8 688	11 219	5 872	7 618	10 417
32 m	8 688	8 861	14 892	7 186	7 798	11 954
34 m	7 696	10 867	16 881	7 580	10 091	13 954
36 m	9 573	12 821	19 621	8 836	13 628	17 836

Table VI

Relative decrease of benefit for different drawpoint spacings at the NNM

		d_l=15 m			d_l=18 m		
		d_{pe}, m			d_{pe}, m		
		17	20	23	17	20	23
D_c	30	0.7%	1.0%	1.1%	0.1%	0.3%	0.8%
	32	0.2%	0.6%	2.5%	0.7%	0.0%*	1.0%
	34	0.5%	1.3%	3.0%	0.6%	0.9%	1.6%
	36	1.3%	1.8%	3.6%	0.8%	2.3%	2.9%

(*) is the maximum benefit scenario

from flow theory and experiments using gravel (Seguel and Millan, 2004) and the data supported by the current information al El Teniente. The results therefore will require to be confirmed by means of marker trial measurement at mine scale during the operational stage of the project. Regarding the height of interaction, in Figure 4 the proposed HIZ and Laubscher's original HIZ for an RMR of 50 (and a range of RMR within the ore column) and the height of the caved rock estimated through drill holes for the different mines are presented. The results indicate that Laubscher's proposed HIZ tends to overestimate the height of interaction for coarse caved rock. These results would need to be further confirmed by trials using markers, which are under way at various mines (Castro and Armijo, 2012).

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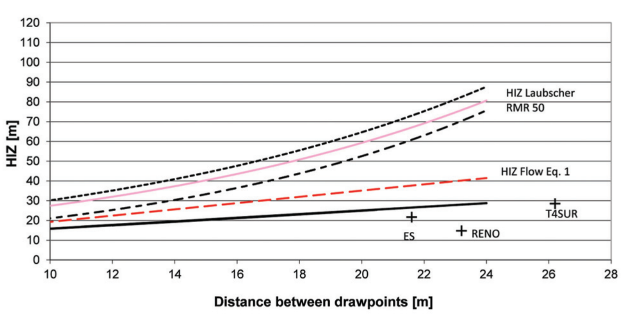

Figure 4—Maximum and measured *HIZ* as a function of drawpoint spacing

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