Stochastic Optimization taking account of Seismicity induced by Underground Mining

Work in Progress

Margaret Armstrong EMAp FGV & Mines-Paristech
Erick de la Barra CMM U Chile
Alejandro Jofre CMM U Chile

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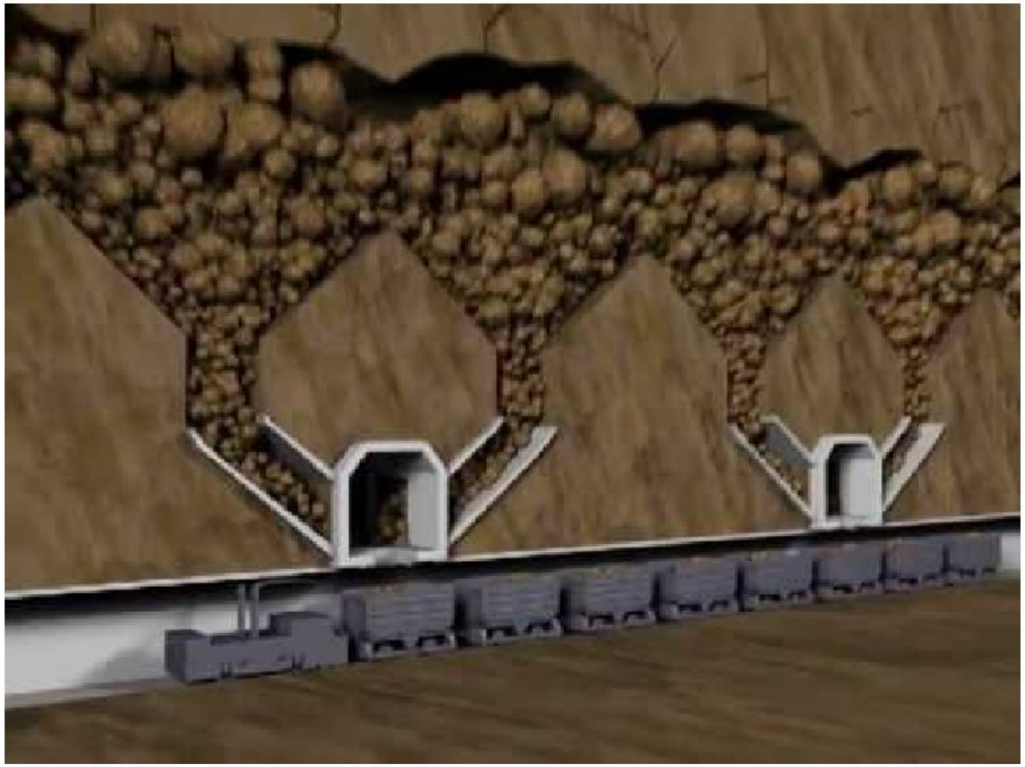
Chiquicamata Open Pit, Chile

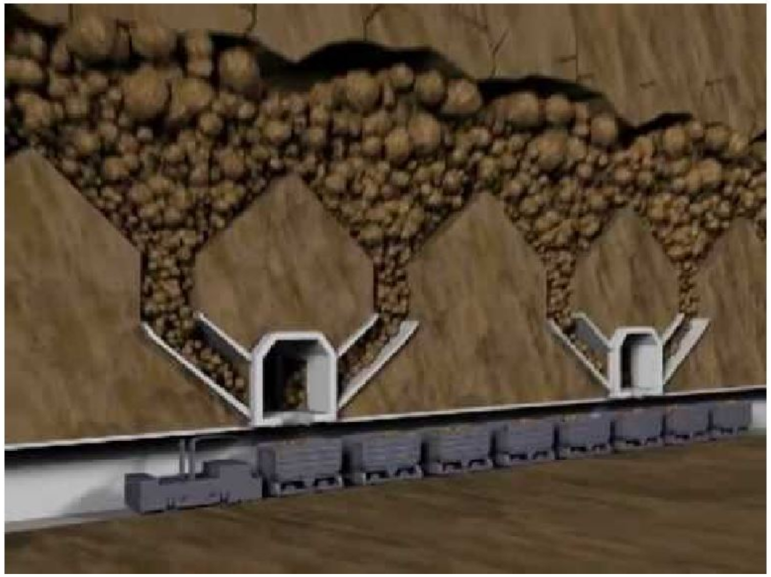
El Teniente Underground Mine, Chile

Vast literature exists on openpit optimization but very little for underground mines

Block Caving: an underground mining method



Block Caving involves undermining an orebody and allowing it to progressively collapse under its own weight.



When block caving is used to extract ore, the removal of such large volumes of rock causes small earth tremors which can damage the workings.

The faster mining advances, the more serious is the micro-seismicity & the more expensive it is to provide adequate roof support.

Old Style Roof Support

Modern Roof Support at El Teniente

Rock Burst

Figure 3—Rockburst damage showing protruding and failed support elements (photograph W.D. Ortlepp)

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Objectives: Stochastic optimization of mining sequence at El Teniente Cu Mine in Chile

- To use multi-stage programming to optimize the mining, taking account of the speed of mining & the induced micro-seismicity, as a function of the Cu price.
- Need to model the relationship between the speed of mining & the induced seismicity
- Need to model the evolution of copper price over time (eg geometric Brownian motion)

Most large mines are openpit nowadays but over the next 20 years many will move underground, making the results of this project more relevant.

Multi-stage Programming

Optimize NPV: decisions made at times t_1 , t_2 ...... up to T.

Let $\omega_{[t]}$ be the history of events up to time t;

$$\textit{decision}\left(x_{n,1}^{\omega_{[1]}}, y_{n,1}^{\omega_{[1]}}\right) \rightarrow \textit{observation}\left(p_{n,1}, m_{s,1}\right) \rightarrow$$

$$\textit{decision}\left(x_{n,2}^{\omega_{[2]}}, y_{n,2}^{\omega_{[2]}}\right) \rightarrow \textit{observation}\left(p_{n,2}, m_{s,2}\right) \rightarrow$$

......

$$\textit{decision}\left(x_{n,T}^{\omega_{[T]}}, y_{n,T}^{\omega_{[T]}}\right)$$

$x_{n,t}^{\omega_{[t]}}$ & $y_{n,t}^{\omega_{[t]}}$ are decision variables

$p_{n,t}, m_{s,t}$ are state variables

In Multi-stage Programming, the scenarios $\omega_{[t]}$ of the state variables are represented by a branching tree (binomial).

With 2 state variables (Rock stress, Cu price) there are 4 nodes per time period (unlike finance not recombining).

After T time periods there are 4^T nodes. Large number of constraints due to mining & processing at each node
$\rightarrow$ Difficult even with CPLEX to solve system.

Finding better ways to solve the system is important.

Multi-stage Programming (3)

To optimize

$$\max \sum_{\omega\in\Omega}\sum_{t\in\tau} w^{\omega}\left[\begin{array}{l} f_1\left(x^{\omega}_{n,1}, y^{\omega}_{n,1}, ton^{inc}_{\omega,s,1}, ton^{dec}_{\omega,s,1}\right)+\dots \\ +f_T\left(x^{\omega}_{n,T}, y^{\omega}_{n,T}, ton^{inc}_{\omega,s,T}, ton^{dec}_{\omega,s,T}\right)\end{array}\right]$$

$$-\sum_{s\in S} R_S\left(M_{\max}\right)$$

where

$$f_t\left(x^{\omega}_{n,t}, y^{\omega}_{n,t}, ton^{inc}_{\omega,s,t}, ton^{dec}_{\omega,s,t}\right)$$

$$=\sum_{s\in S}\left(\sum_{n\in N_S} p^{\omega}_t \lambda_n ton_n y^{\omega}_{n,t} - \sum_{i\in I(s)} a_i x^{\omega}_{1_j,t} - \sum_{n\in N_s} c^{+}_{s,t} ton^{+}_{\omega,s,t}\right)$$

Multi-stage Programming (3)

To optimize

$$\max \sum_{\omega\in\Omega}\sum_{t\in\tau} w^{\omega}\left[\begin{array}{l} f_1\left(x^{\omega}_{n,1}, y^{\omega}_{n,1}, ton^{inc}_{\omega,s,1}, ton^{dec}_{\omega,s,1}\right)+\dots \\ +f_T\left(x^{\omega}_{n,T}, y^{\omega}_{n,T}, ton^{inc}_{\omega,s,T}, ton^{dec}_{\omega,s,T}\right)\end{array}\right]$$

$$-\sum_{s\in S} R_S\left(M_{\max}\right)$$ Cost of Roof Support System

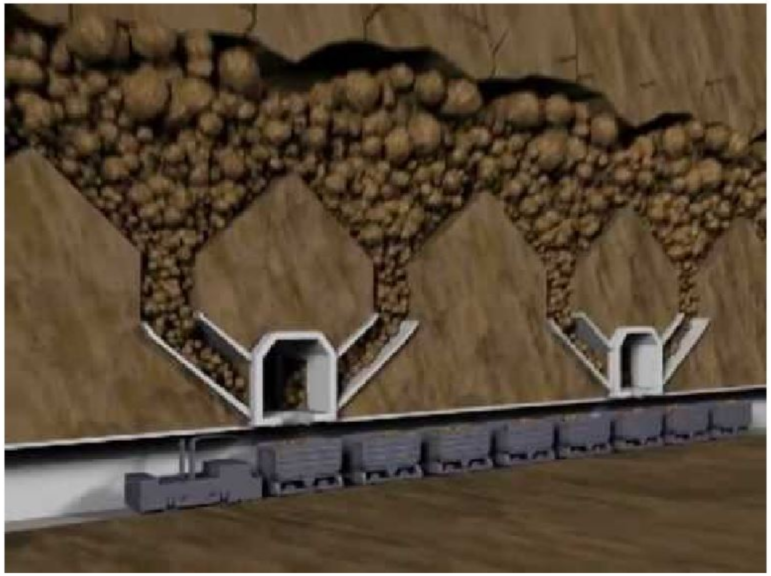
where

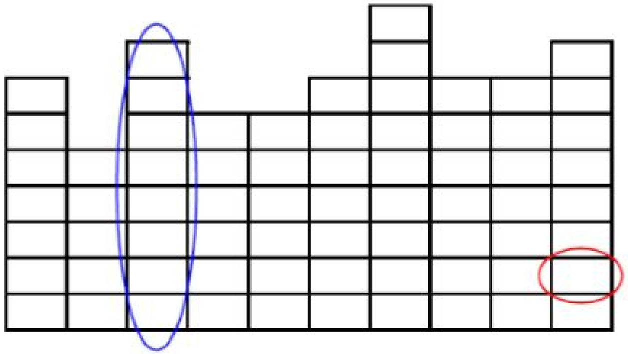
$$f_t\left(x^{\omega}_{n,t}, y^{\omega}_{n,t}, ton^{inc}_{\omega,s,t}, ton^{dec}_{\omega,s,t}\right)$$

$$=\sum_{s\in S}\left(\sum_{n\in N_S} p^{\omega}_t \lambda_n ton_n y^{\omega}_{n,t} - \sum_{i\in I(s)} a_i x^{\omega}_{1_j,t} - \sum_{n\in N_s} c^{+}_{s,t} ton^{+}_{\omega,s,t}\right)$$

Value of Metal — Cost starting new drawpoint — Cost increasing tonnage

Modelling the Orebody





The orebody is divided into different sectors which will be considered as statistically independent of one another.

Each sector consists of columns of blocks (25m x 25m x25m) from 200m to 1000m high.

Typically there are about 10,000 blocks in the model.

Mining costs & block grades are assumed known.

Multi-stage Programming (4)

Optimization subject to large set of constraints

- Sum of block parts ≤ 1
- Block can only be accessed if preceding ones mined
- Height of columns must be similar
- Draw point can only be kept open for certain time
- Upper & lower limits on amount mined in given time
- Extraction rate cannot be increased/decreased rapidly
- Upper bound on the seismic moments
- Non-anticipatory conditions must be respected
- Decision variables are binary $x_{n,t}^{\omega_{[t]}}$
- Decision variables are continuous & bounded $y_{n,t}^{\omega_{[t]}}$
- Decision variables on tons are non-negative: $ton_{\omega,s,t}^{inc}$ & $ton_{\omega,s,t}^{dec}$

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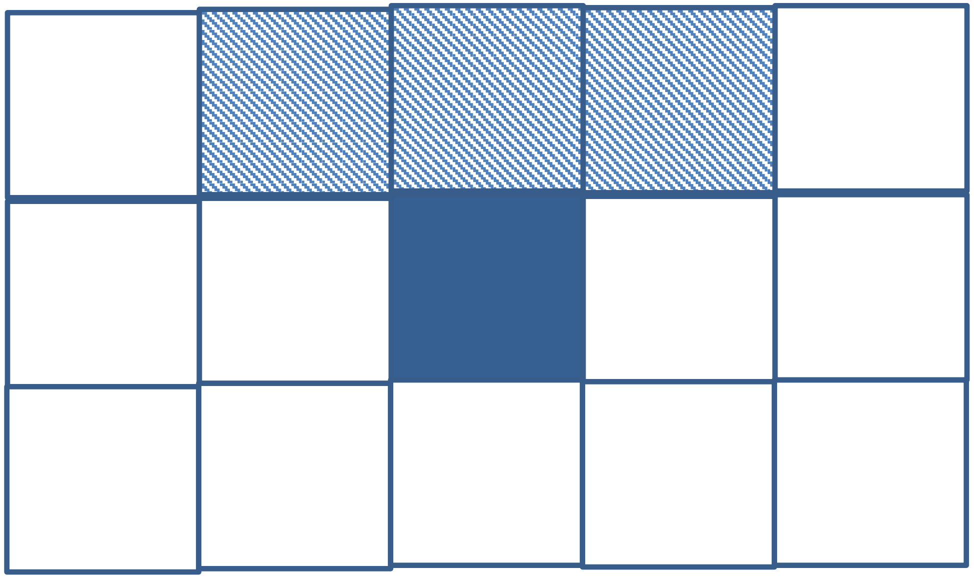
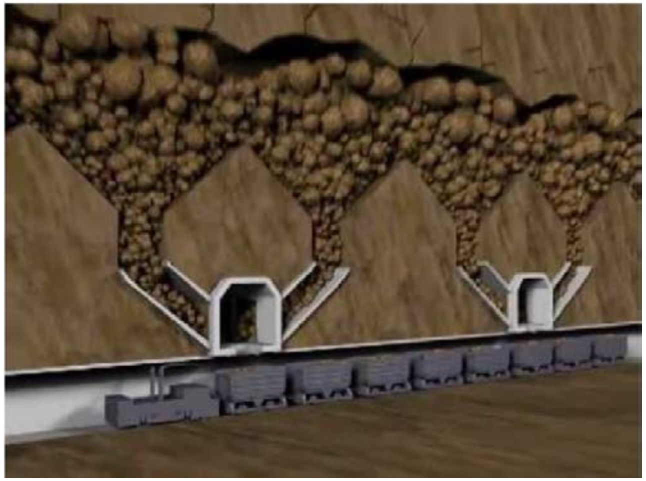
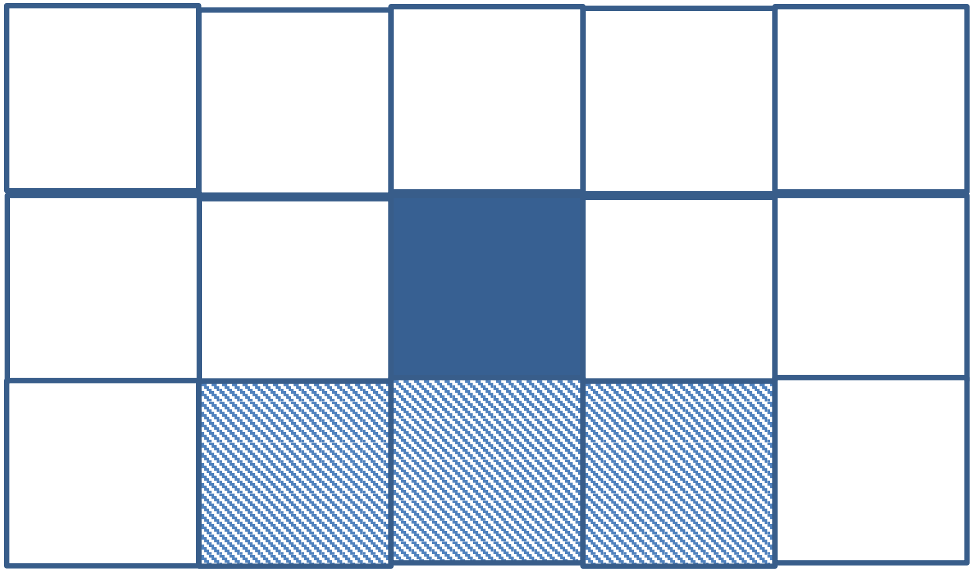
Accessibility

In open pit mines you have to extract the cone of blocks above the one under study in order to get access to the one below.







In block caving you have to extract the blocks in the cone below in order to get access to the shaded one.

Modelling the induced seismicity as a function of the speed of mining

Modelling Microseismicity

Building on from theoretical work by McGarr (1976), Gibowicz & Kijko (1994) demonstrated that the sum of seismic moments ΣM was related to the volume of additional rock extracted ΔV by

$$\sum M = k.\mu.\theta.\Delta V$$

Where

- k is a constant (between 0.5 and 1.33)
- θ is parameter that depends on the rock type & the stress in the rock
- μ is Young's modulus for the medium

Arora, Srinivasan & Yaji (1997) tested McGarr results on underground mines in India & found good agreement between the average sum of the seismic moments & the quantity of rock extracted.

Stochastic Model of Microseismicity

We assume that the number N(t) of seismic events in time t follows a Poisson dist with a constant parameter λ.

Secondly we assume that the seismic moment M of an event follows a Pareto dist with parameters β, M_- & M_+ where these are the minimum & maximum possible moments.

The cumulative probability of an event with a seismic moment up to M^* is

$$F\left(M^*\right) = \frac{M_-^{-\beta} - M^{*-\beta}}{M_-^{-\beta} - M_+^{-\beta}}$$

Stochastic Model of Microseismicity (3)

Endogenous uncertainty

The difficulty in constructing a binomial tree for seismicity is the presence of the decision variables:

$$M_{s,t}^{\omega} = m_{s,t}^{\omega}\left(K_s \sum_{n \in N_s} y_{n,t}^{\omega} ton_n \right)$$

Way out: the mine has data on tonnages extracted, which gives us its distribution.

We want $M_{s,t}^{\omega}$ to have a Pareto distn.

We can deduce the distn for $m_{s,t}^{\omega}$ & hence build tree.

See Boland et al (2008) & Goel & Grossmann (2006) for information on endogenous uncertainty

Conclusions

With work done to date we can construct

- Binomial tree for copper prices

Good progress has been made on

- increasing the size of the systems that can be solved
- Binomial tree for microseismicity.

Next steps are to apply this to El Teniente data & to model impact of intensive preconditioning (blasting & fracking).

Perspectives for Future Work

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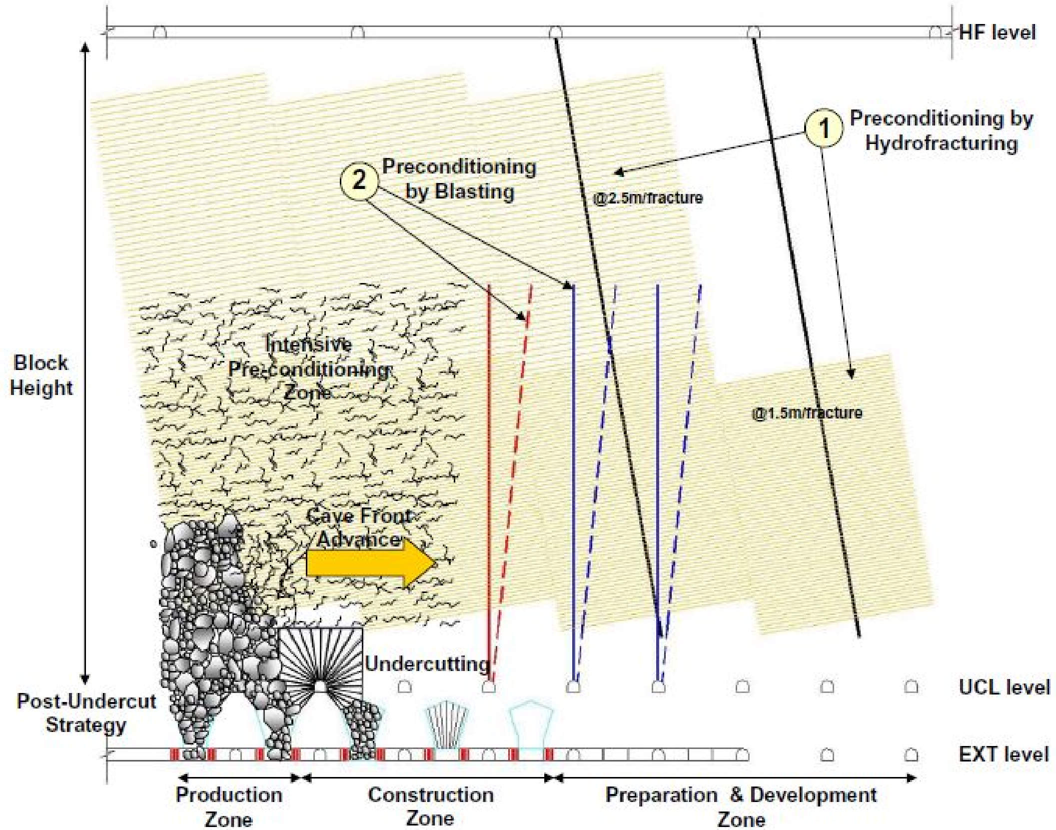

Figure 1. Sequence to Implement the Intensive Preconditioning (Catalan et al., 2012).

Preconditioning has been used in Australia & in Chile to weaken rock & fracture it, thereby reducing the stress in it & the chance of rock bursts. See Catalan, Onederra & Chitombo (Apr 2017)

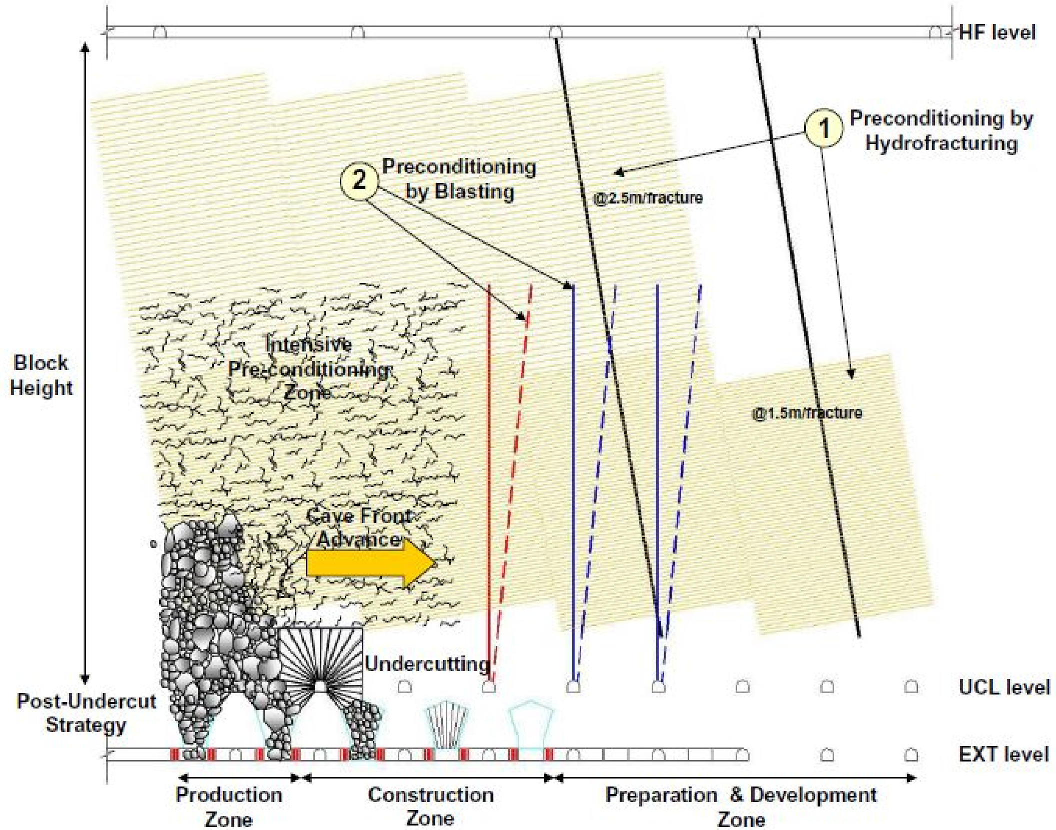

Figure 1. Sequence to Implement the Intensive Preconditioning (Catalan et al., 2012).

Next step: to model its impact & compare results with & without preconditioning

RFG 2018

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Resources for Future Generations

Vancouver, Canada 16-21 June 2018

Session:The impact of climate change on financing for mining & oil companies.

Aimed for oil & gas and mining companies including coal, the finance sector, NGOs & regulators; to discuss the impact of climate change on financing for those companies & on how to value potentially stranded assets in disclosure statements.

Any Questions?

Perspectives for Future Work

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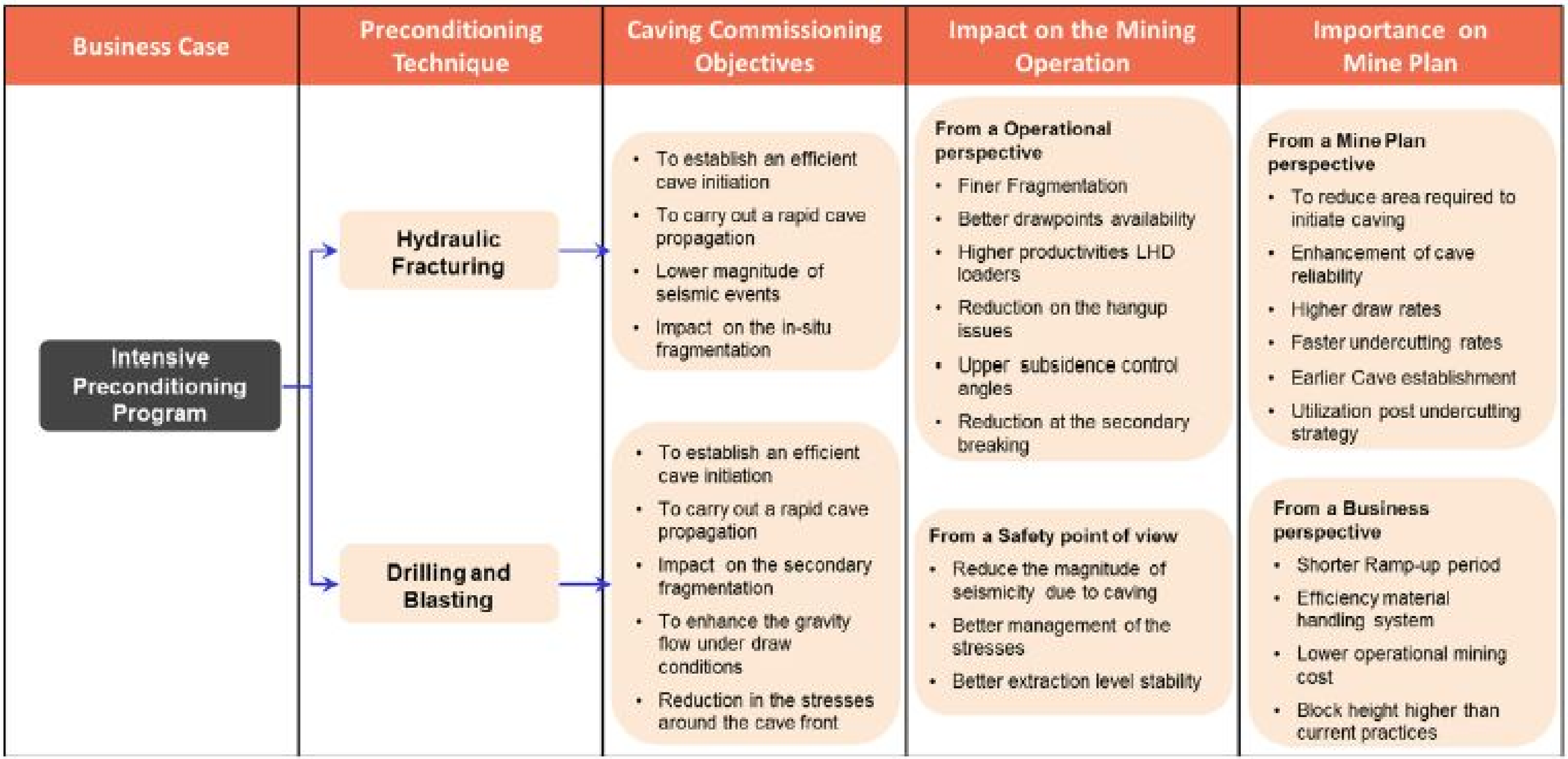
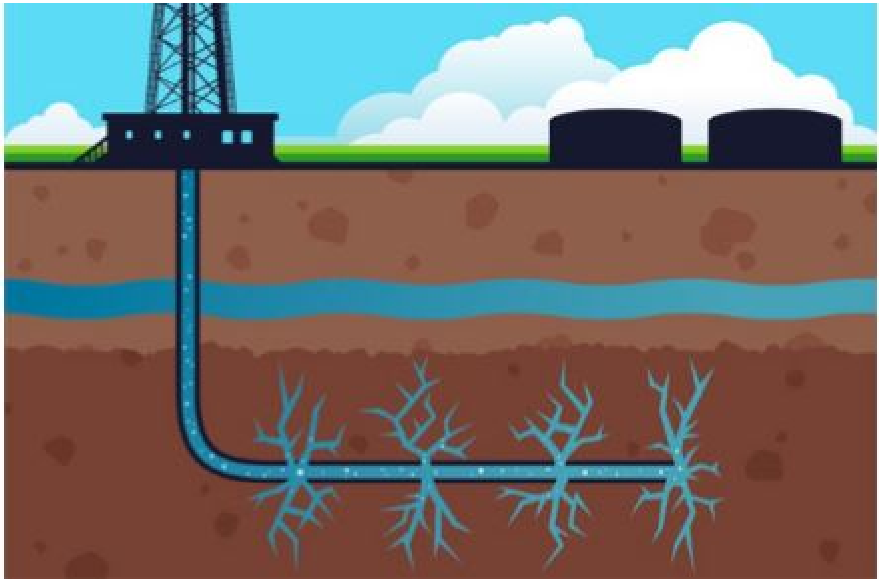
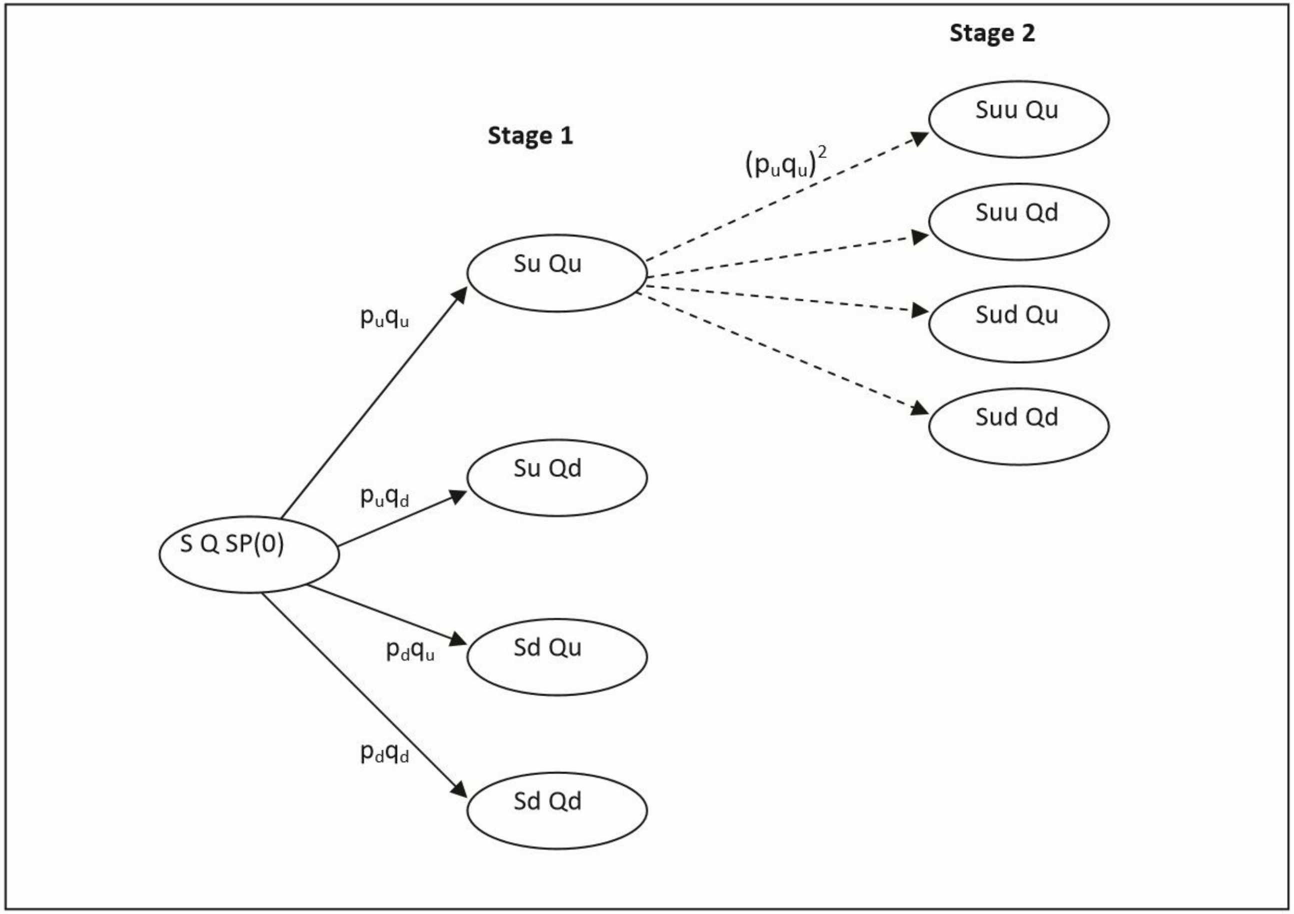


Figure 2. Intensive preconditioning business case.



Hydraulic Fracturing consists of injecting water under high pressure into the rock to weaken & fracture it, thereby reducing the stress in the rock & the chance of rock bursts.

Would it be a cost-effective?


Stage 2
Stage 1
Suu Qu
Suu Qd
Sud Qu
Sud Qd
$(p_u q_u)^2$
Su Qu
Su Qd
Sd Qu
Sd Qd
S Q SP(0)
$p_u q_u$
$p_u q_d$
$p_d q_u$
$p_d q_d$

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Modelling Microseismicity (2)

Arora, Srinivasan & Yaji (1997) tested McGarr results on underground mines in India & found good agreement between the average sum of the seismic moments & the quantity of rock extracted:

$$\overline{\Sigma M_t} = K \times ton_t$$

Where

ton_t is the tonnage of the rock extracted at time t

K is a proportionality constant

$\overline{\Sigma M_t}$ is the expected sum of the seismic moments

Stochastic Model of Microseismicity (2)

$m_{s,t}^{\omega}$ is the seismic moments in scenario ω (as a %)

$M_{s,t}^{\omega}$ is the expected seismic activity in sector s, at time t, in scenario ω:

$$M_{s,t}^{\omega} = m_{s,t}^{\omega}\left(K_s \sum_{n \in N_s} y_{n,t}^{\omega} ton_n \right)$$

$$M_{s,0}^{\omega} = 0$$