Blast Management

Blast data

Ampang Quarry	*Malaysia*
Rock type	*Granite*
Bench height	*18 m*
Drill-hole diameter	*Ø89 mm*
Drill pattern	*3x3 m^2*
Explosives	
Emulite 150	*5 kg/hole*
ANFO	*70 kg/hole*
Powder factor	*0.46 kg/bm^3*

Photo: S.O. Olofsson

Blast Management

Primary factors for blast design considerations

1. Blast size, shape and edge effects
2. Distribution of explosives in the bench:
   - drill patterns versus drill-hole diameter and rock mass blastability
   - explosive columns and stemming
3. Explosives properties
4. Sequential firing

Shotrock fragmentation and boulder count versus primary crusher performance and end-product quality

Muckpile profiles versus selected loader type and size for maximum loading rates - or minimise ore loss and dilution in mining operations

Blast Management

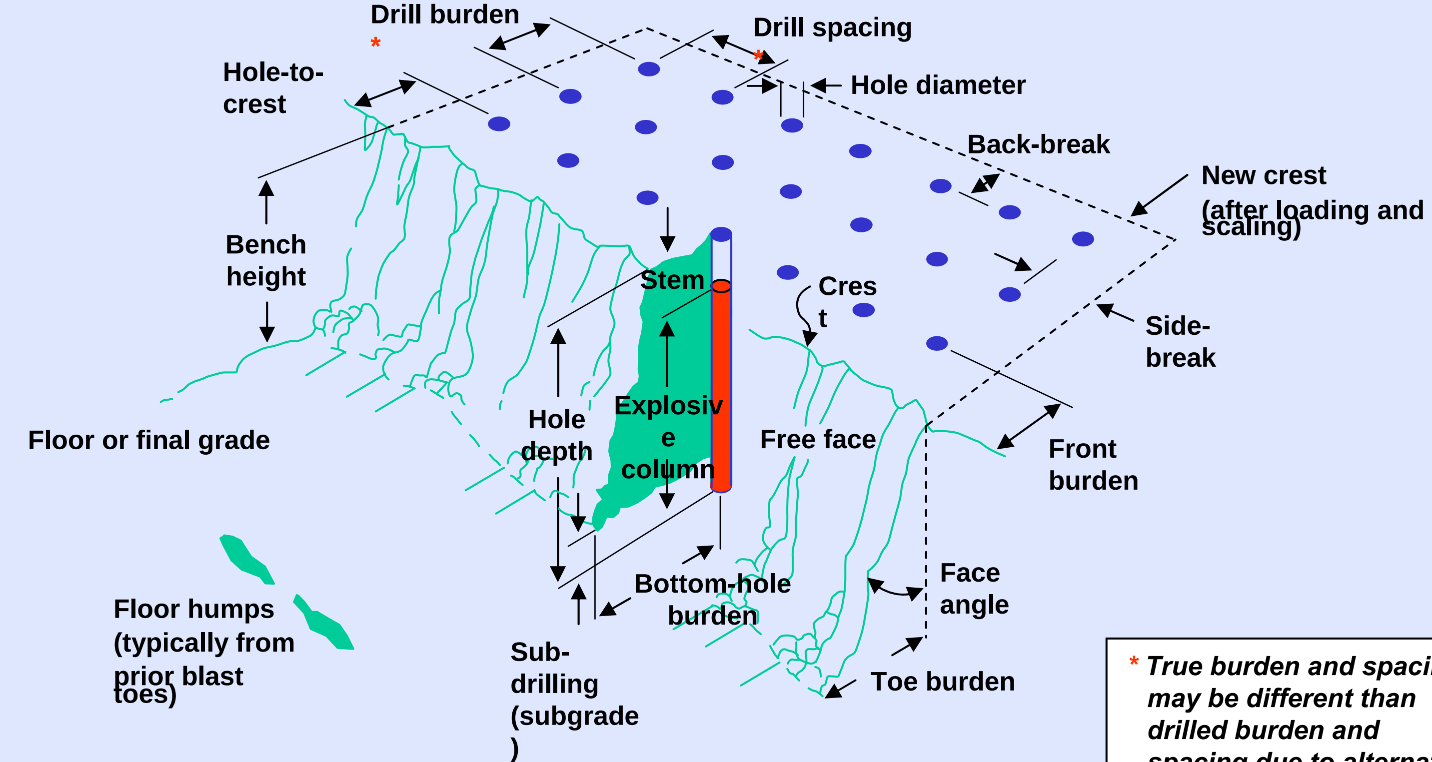
Blast operational items and objectives

Split shot with no stemming and with stem plugs

- blast design
  - blast size including selection of bench height
  - drill pattern including selection of drill-hole diameter
  - charge pattern including selection of explosives and stemming materials
  - firing pattern including selection of firing systems
- blast production reports and work documentation for Quality Assurance
  - explosives and detonator consumption followup
  - documentation of 1st row burden requires the use of both highwall scanners and drill-hole deviation measurement devices
- assessment of shotrock
  - fragmentation (control of boulders/oversize and fines production)
  - swell, throw, local choking and loadability
- minimize blast edge effects such as back-break, side-break and toes and floor humps
- minimize environmental effects such as flyrock, dust, ground vibrations and airblast
- compliance to national and local quarry regulations

Blast Management

Blast design terminology



* *True burden and spacing may be different than drilled burden and spacing due to alternative firing patterns*

Blast Management

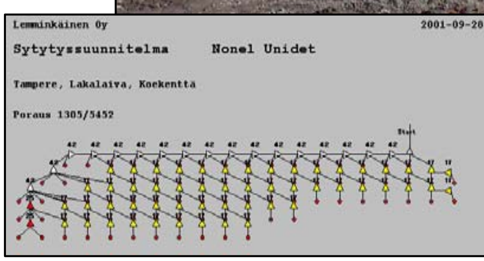
Site preparation

Measure in shotholes

Re-drill crossed shotholes and clean toe area

Explosives delivery and charging

Firing pattern



Remove floor humps

Stem

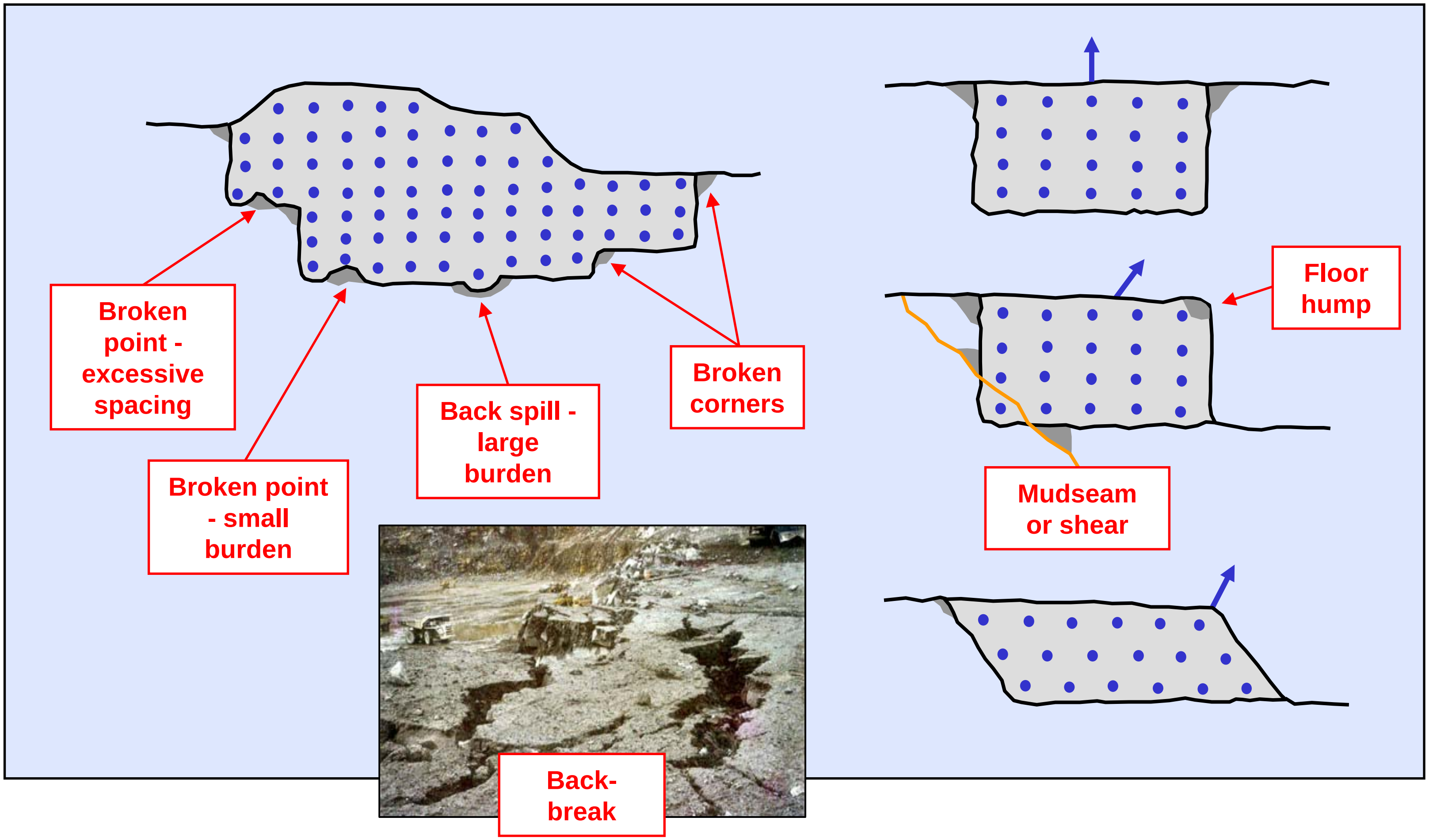
Tie-in

Blast safety supervision

Shotrock evaluation

Blast Management

Adverse blast edge effects



Blast Management

Examples of adverse blast edge effects

Blasting across open shears in the bench

Back-break along intersecting joints

Back-break along shallow dipping bedding planes

Poor toe breakage across the shallow dipping bedding planes

Blast Management

Basic guidelines for geometric bench blast designs

- ***Reduced burden*** = $\sqrt{S \cdot B}$; *or burden for square drill patterns*
- ***Spacing, S*** = *typically 1 to 1.5 times B*
- ***Spacing / burden ratio*** = f ; *keep f close to 1.0 in a jointed rock mass so as to reduce the probability of shothole venting in walls*
- ***Burden, B*** = $\sqrt{S \cdot B / f}$
- ***Bench height, H*** = *1.5 to 7 times* $\sqrt{S \cdot B}$; *bench heights typically 10 - 20 m*
- ***Sub-drilling, SUB*** = *0.2 to 0.5 times* $\sqrt{S \cdot B}$; *increase SUB with bench height and for very low bench heights*
- ***Uncharged length, UCL*** = *0.5 to 1.2 times* $\sqrt{S \cdot B}$; *typically lower values in ore*
- ***Bottom charge, CL_{bottom}*** = *0.05 to 0.4 times CL* ; *increase with bench height and wet holes*
- ***Stemming between decks*** = *6 to 12 times d* ; *increase stem length in wet shotholes*

- ***Typical shot layouts for:***
  - *wheel loader operations* = *long and shallow blasts / 3 - 5 rows*
  - *front shovel operations* = *short and deep blasts / upto 15 rows or more*

Blast Management

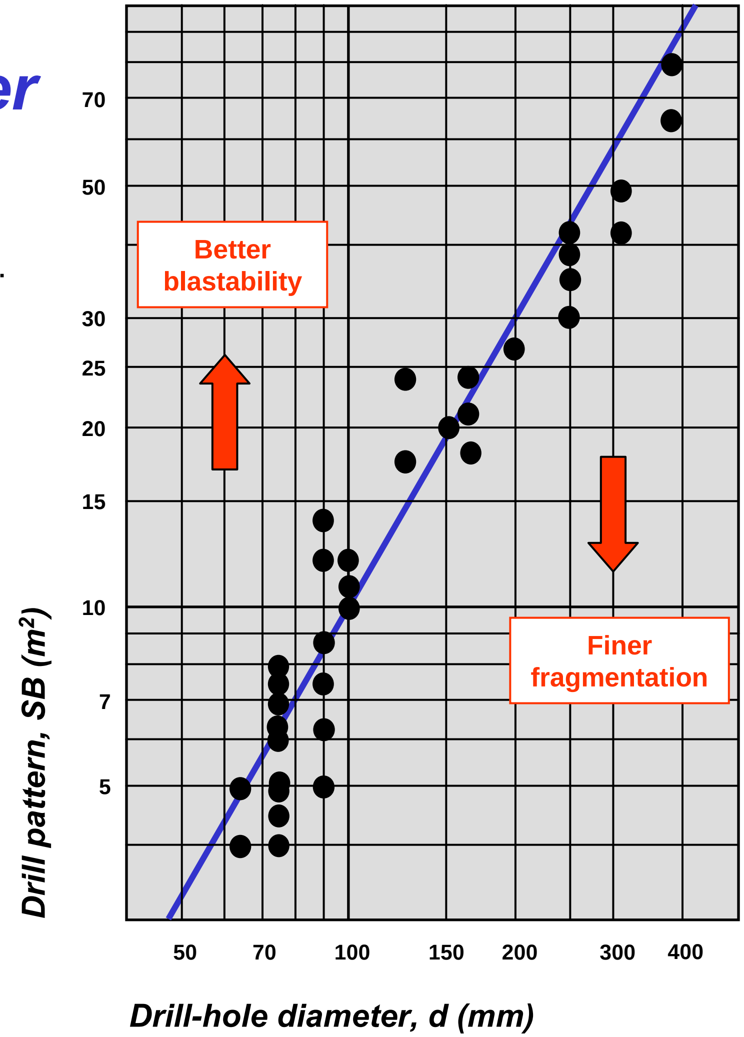
Drill pattern versus hole diameter

Scaled drill pattern parameters:

$$ {}_{\gamma}\sqrt{S \cdot B} = constant \cdot (Q_1 / \rho)^{2/5} \cdot (k_{50} / 270)^{2/5} \cdot $$

$$ Q_1 = 0.000785 \cdot CD \cdot d^2 $$

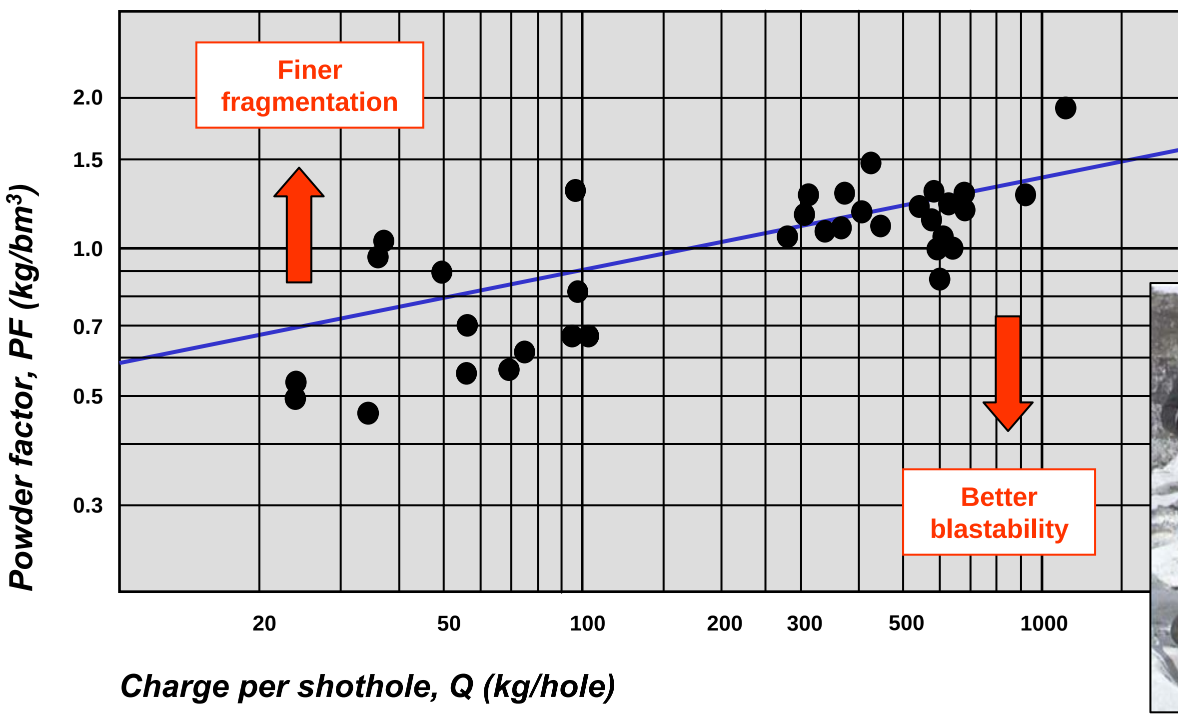
$$ k_{50\text{-}new} \approx k_{50\text{-}old} \cdot (SB_{new} / SB_{old})^{0.8 - 1.3} $$



Blast Management

Powder factor versus shothole charge

Scaled powder factor parameters: $PF_{4/5 \cdot \gamma} = constant \cdot Q^{1/5} \cdot \rho^{4/5} \cdot (270 / k_{50})$



Blast Management

Stemming for flyrock and airblast control

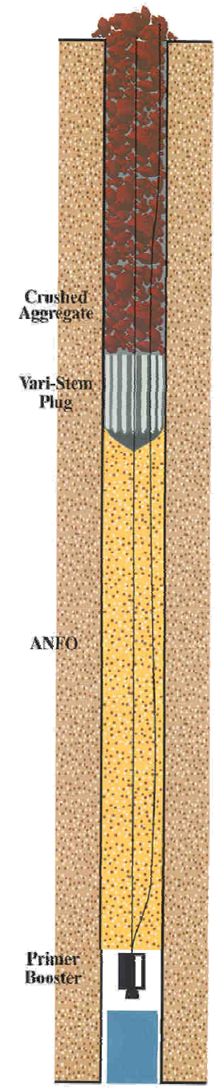
Stemming material and length

Lower values can be used with aggregate stemming; higher values with drill cuttings. For graded aggregates, use 10% of drill-hole diameter as mean fraction size.

Stemming plugs allow for additional stemming length reduction

- Vari-Stem ™
- StemTite ™
- Foam Stem

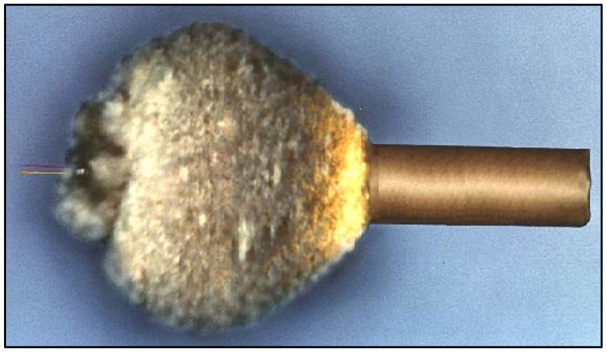
Item	No Plug	Vari-Stem ™
VOD for ANFO charge	3660 m/s	3666 m/s
Time to stemming movement	2.3 ms	5.3 ms
Velocity in stemming	482 m/s	281 m/s



Blast Management

Explosives performance

Scaled explosives parameters: $\frac{CD^{1/5}}{EE^{2/5} \cdot VOD^{2/5}}$



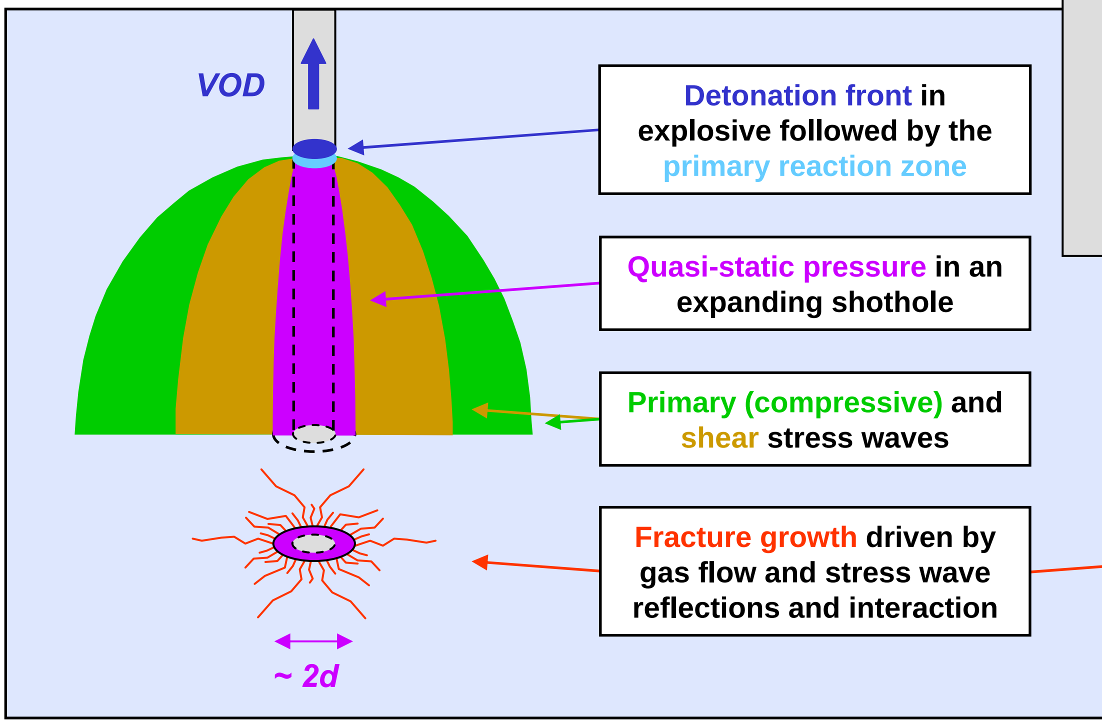
Explosive type	Velocity of detonation, VOD * (m/s)	Energy EE (MJ/kg)	Charge density, CD (g/cm^3)	Water resistance
ANFO **	2200 - 4300	3.9	0.7 - 1.1	Poor
HANFO **	4000 - 5000	3.5	1.0 - 1.35	Fair
Watergels **	4200 - 5000	2.9	1.15	Good
Emulsions **	4200 - 5200	3,1	1.25	Good

* typically commercial explosives have non-ideal detonation resulting in higher VODs and detonation pressures for increasing shothole diameters

** up to 10% Al powder is commonly added to increase bottom charge energy content and detonation pressure

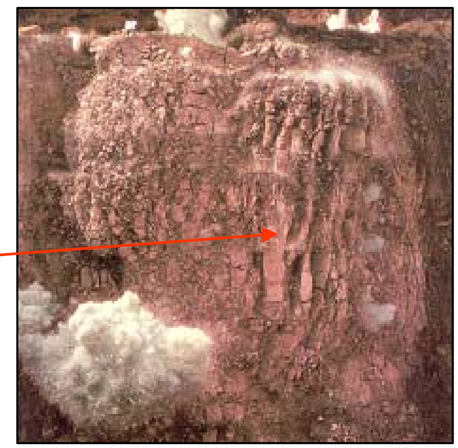
Blast Management

Shothole pressures and radial fractures



Velocities in bench

P-wave:	c_p	~	$\sqrt{E} / \rho$
S-wave:	c_s	~	$0.5 \cdot c_p$
Fracture:	$c_{fracture}$	~	$0.38 \cdot c_p$
Gas flow:	c_{gas}	~	$0.05 \cdot c_p$



Detonation front pressure (MPa) $p_d \sim 0.00025 \cdot CD \cdot VOD^2$

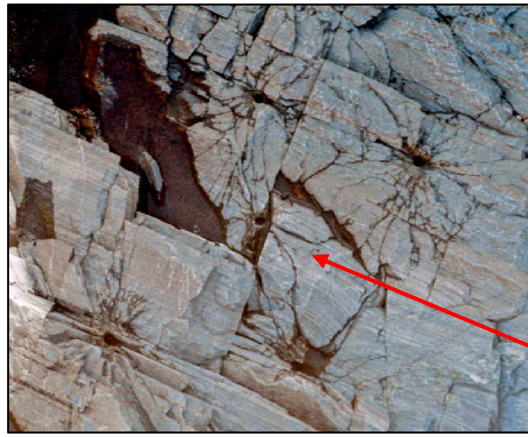
Quasi-static shothole pressure p_s = 30% - 70% of p_d

= dependent on rock mass stiffness $\{ E, \nu, \rho, O \}$

Blast Management

Examples of fracturing around shotholes

Radial (and vertical) fracturing around shothole walls



Radial fracturing can be enhanced or arrested by preexisting rock mass jointing

Horizontal "cone" fracturing from shothole bottom corners

Shothole bottoms in prior subdrill zone

Blast Management

Extent of radial fracturing

- *radial fracture count*

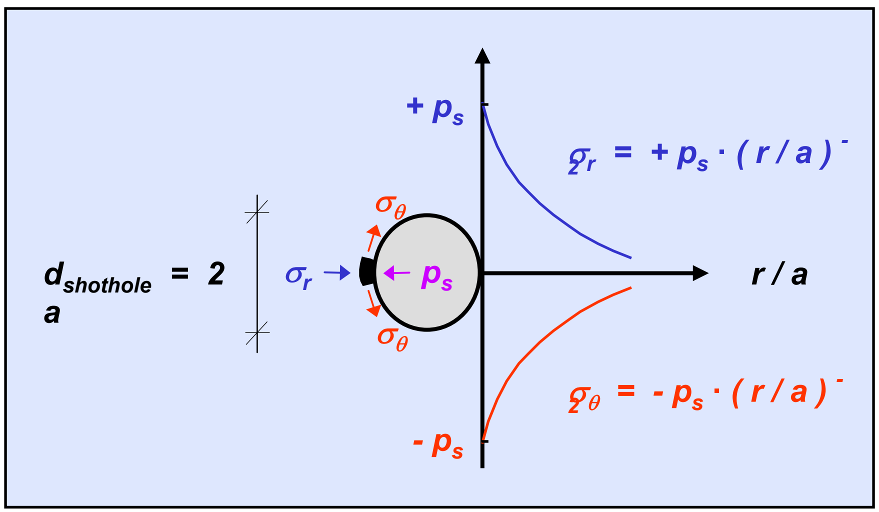
  $N_{radial} = 2000 \cdot D^{1.5} \cdot (r/a)^{-2}$

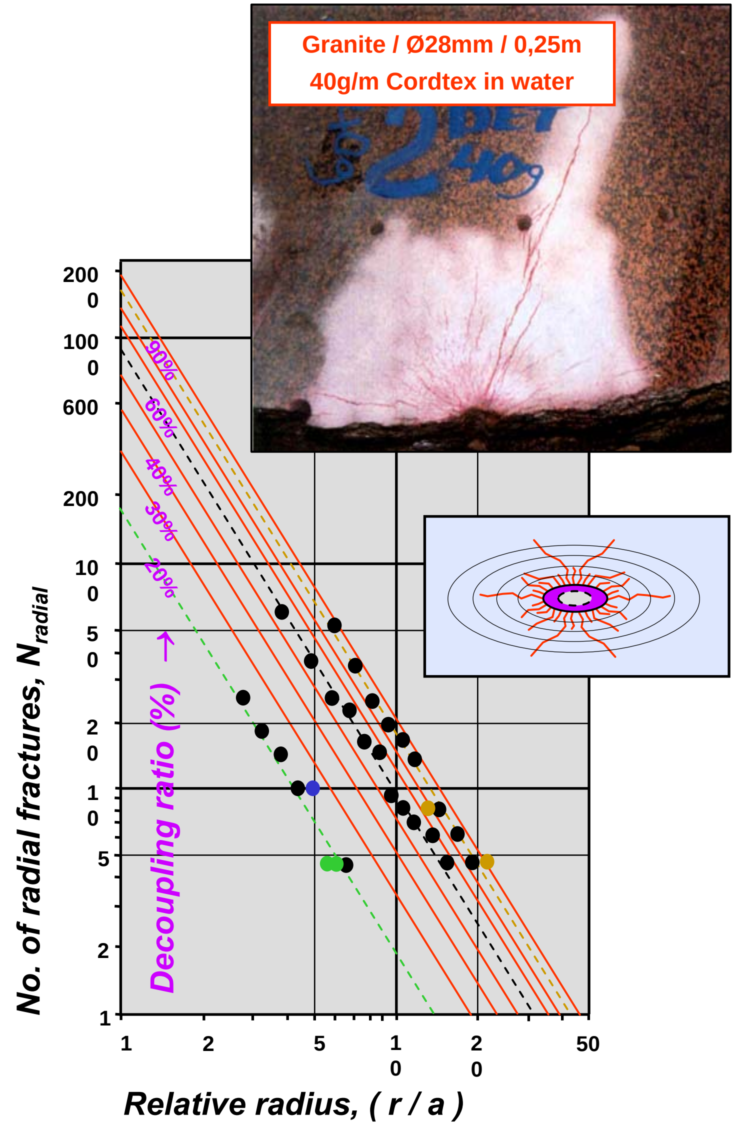
- *volumetric decoupling ratio*

  $D = (d_{explosive} / d_{shothole})^{2} \cdot CL / L$

- *geometric attenuation* (*for cylindrical charges*)

  $(r/a)^{-2}$



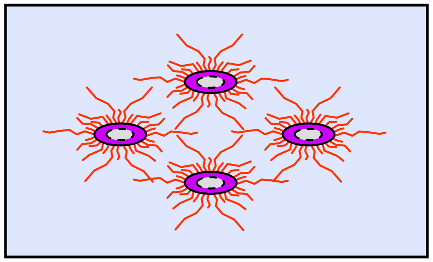


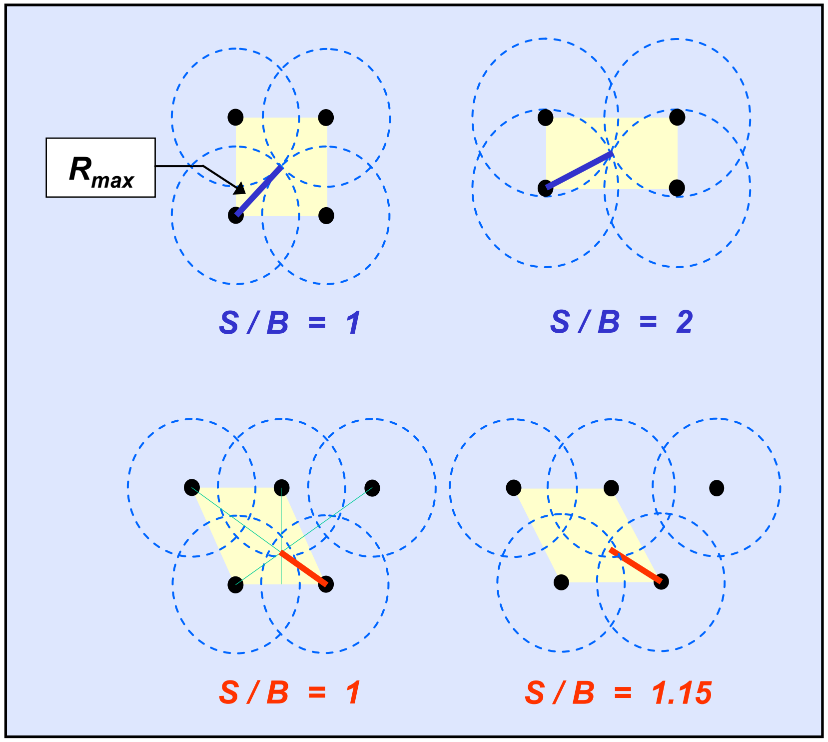
- ● Perspex / Cordtex
- ● Quartzite / Ø38 mm / ANFEX + Cordtex
- ● Quartzite / Ø38 / Ø25 mm Gelignite 60% + Cordtex
- ● Quartzite / Ø38 / Ø18 mm Smoothex + Cordtex

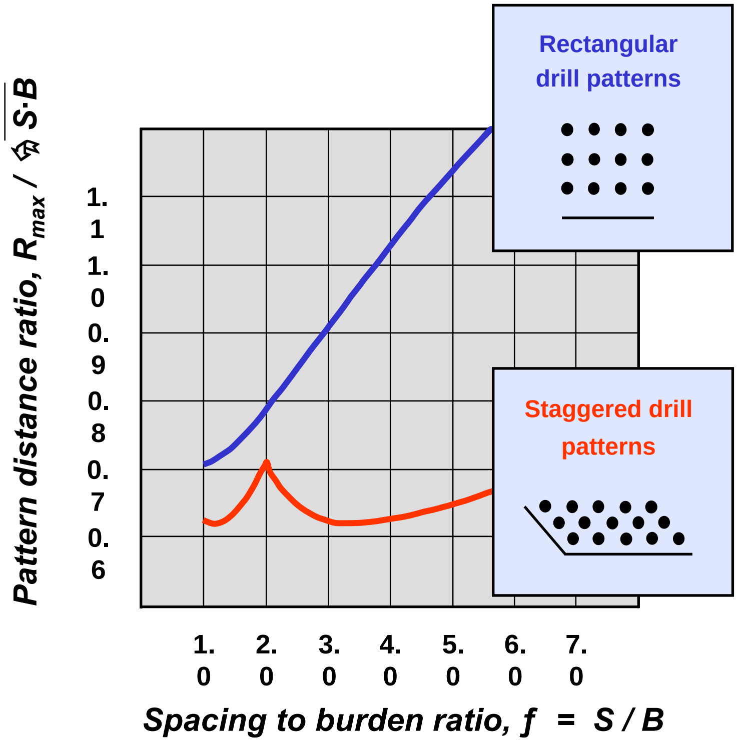
Blast Management

Drill pattern layouts

- *for the systematic distribution of radial fractures in benches*
- *and minimise the occurrence of gas venting from walls*



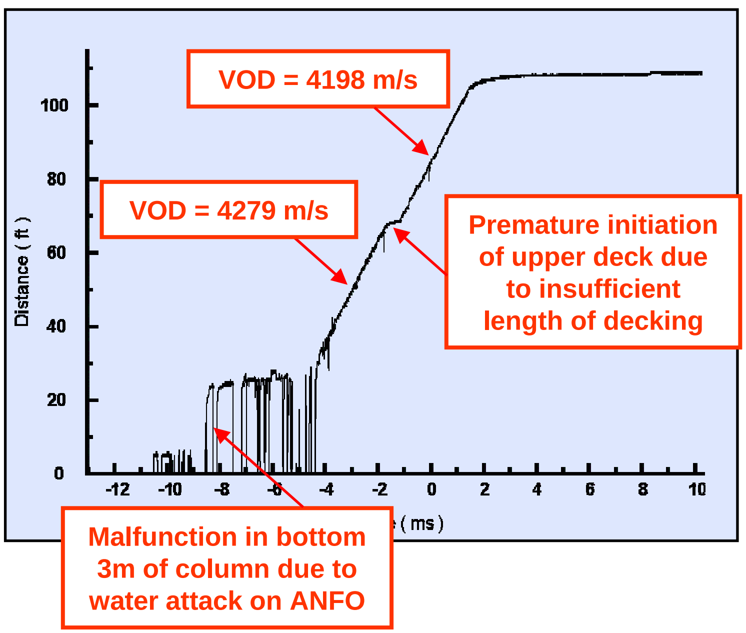


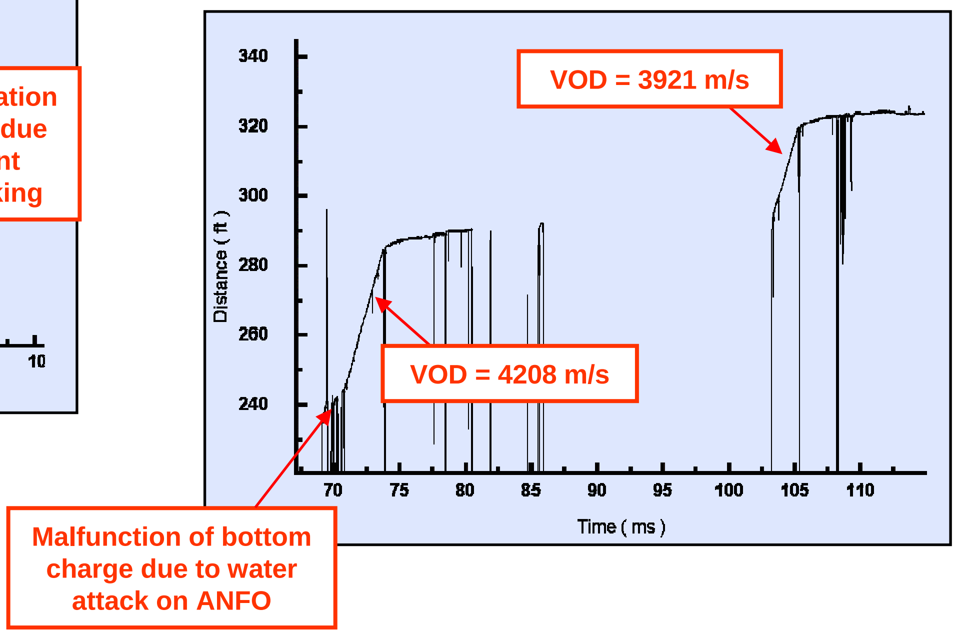


Blast Management

Explosives performance rated by continuous VOD measurements

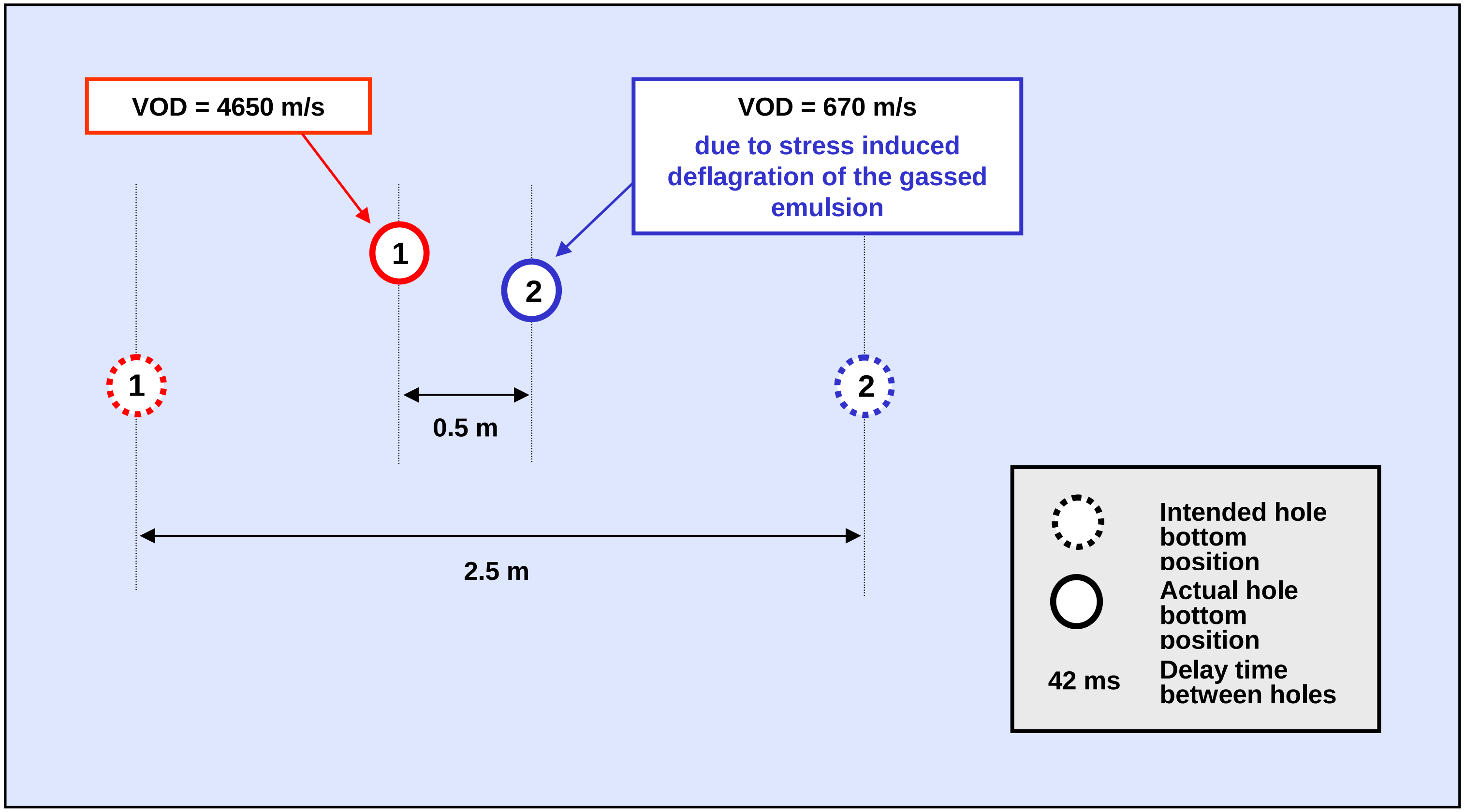
- exact timing of explosive columns
- variation of VOD along explosive columns
- occurrence of malfunctioning explosive columns





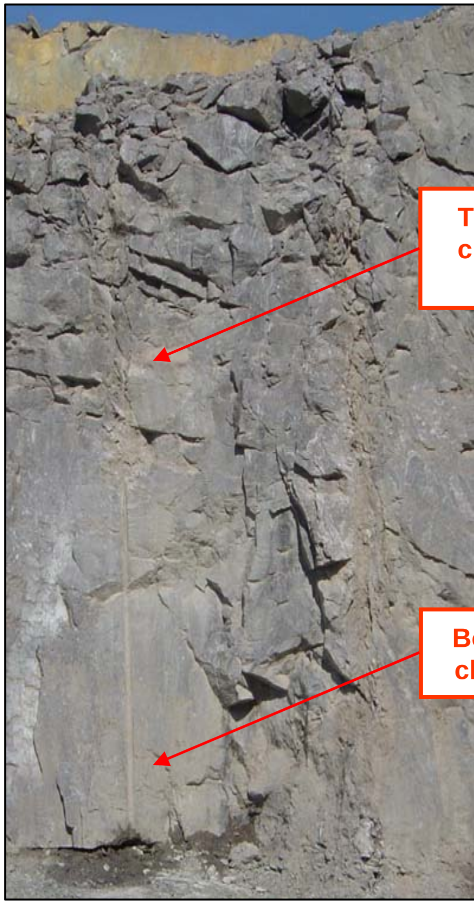
Blast Management

Explosives performance rated by continuous VOD measurements



Blast Management

Explosives performance rated by visual observation



Top portion of column charge initiated by top (backup) primer

Bottom portion of column charge only deflagrated ?

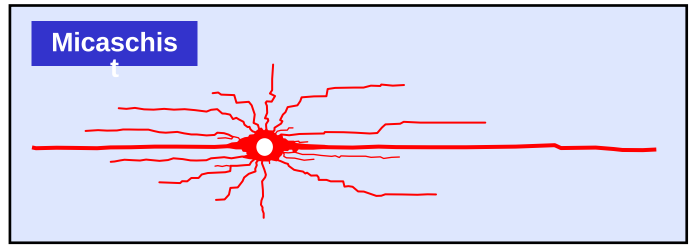
Potential for flashover initiation or dead-pressing or deflagration through open joints - when the flushing medium comes out of neighbouring drill-holes

Blast Management

Rock mass blastability - effect of intact rock blastability

Scaled rock mass blastability parameters:

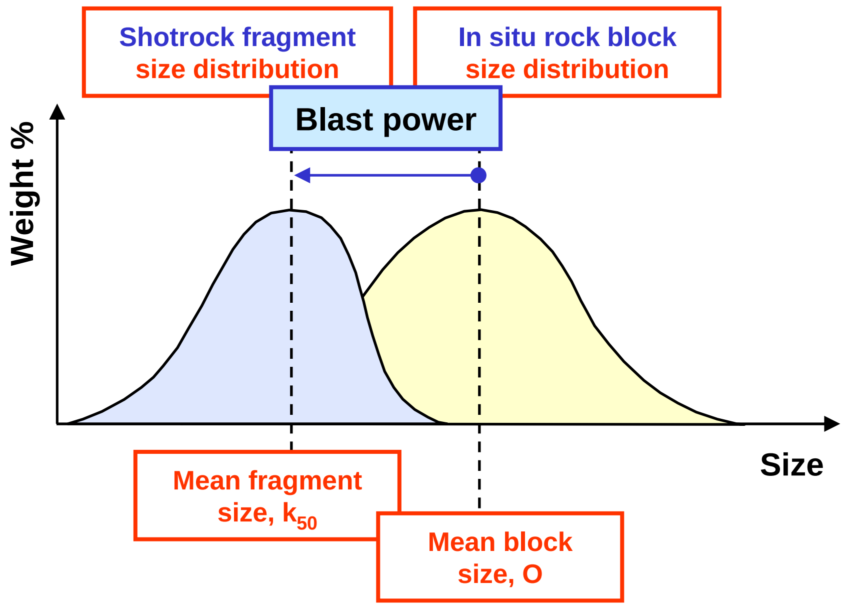
$$\frac{I_a^{3/5} \cdot 0^{1/2} \cdot (c_p^{2}\rho)^{3/10}}{n^{2/5} \cdot \rho^{4/5}}$$

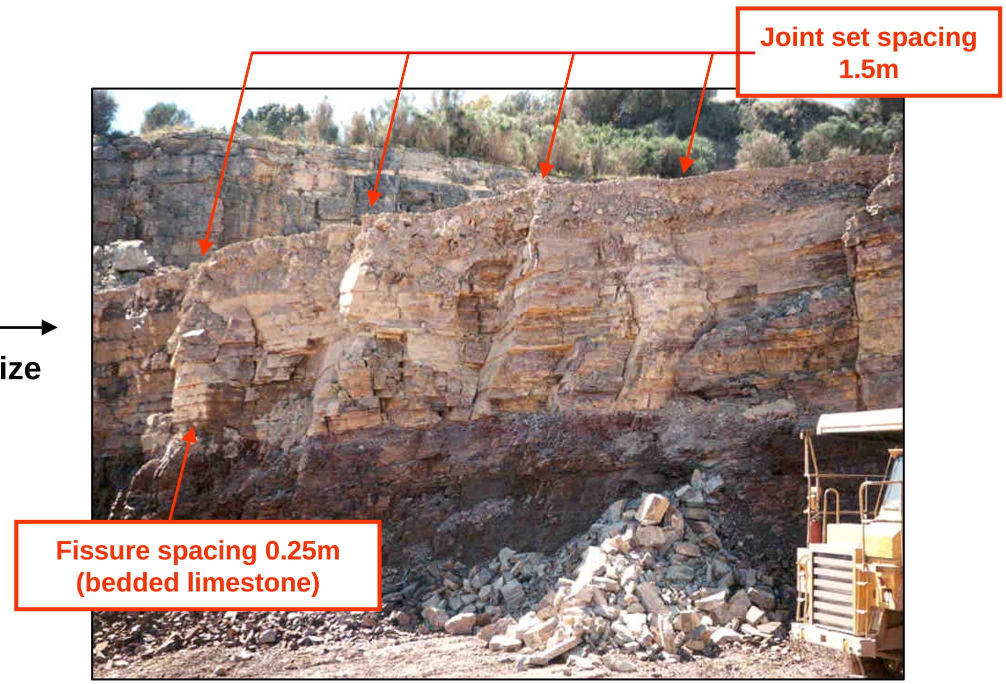


Rock type	Sonic (dry) velocity, c_p (m/s)	Anisotropy I_a	Porosity n (%)	Density ρ (g/cm^3)	Blastability rating
Poorly cemented limestone	2800 -	1.0 - 1.2	< 35	2.0 - 2.8	Extremely good
Limestone	- 5000	1.0 - 1.2	0.5 - 1.5	2.6 - 3.0	Good
Granite	3000 - 4500	1.0 - 1.4	0.5 - 1.5	2.6 - 2.7	Good
Gneiss	2500 - 4500	1.1 - 1.9	0.5 - 1.5	2.7 - 3.0	Medium
Micaschist	1800 - 3300	1.5 - 3.5	< 1.5	2.6 - 2.9	Poor

Blast Management

Rock mass blastability - effect of rock mass discontinuities



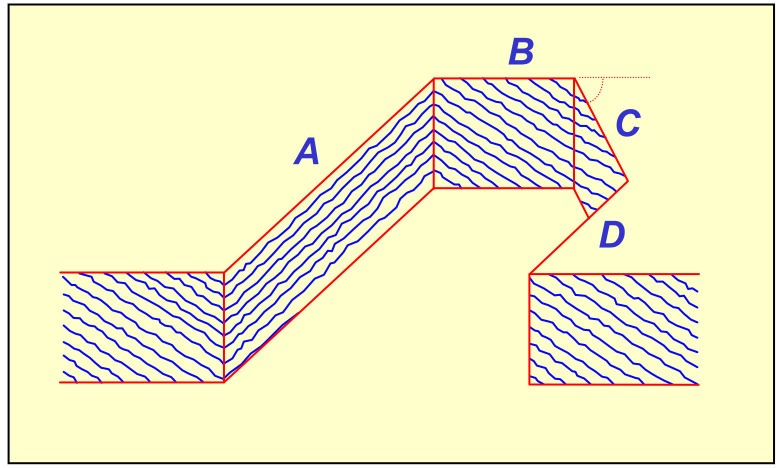


Blast Management

Rock mass blastability - blasting directions

Isotropic rock with shallow dipping joints - e.g. quartzites, granites, limestones , ...

Backwall type A

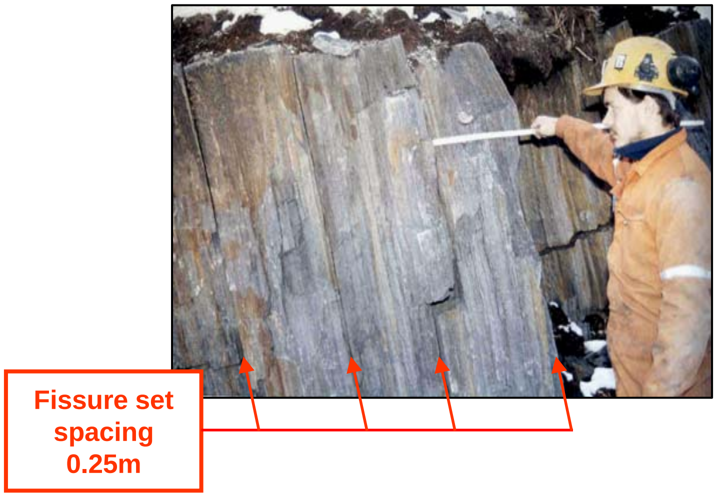


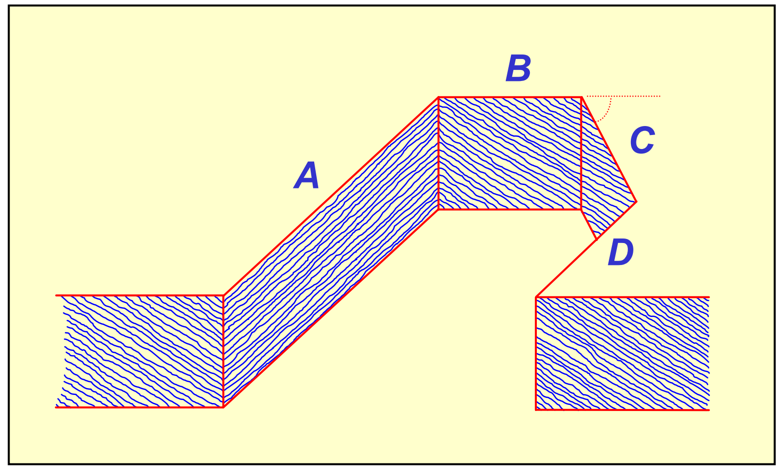
Firing	Backwall	Fragmentation	Back-break & Toe	Floor
→	A	Poor	Major	Major
↓	B	Good	Some problems	Average
↙	C	Good +	Minor	Average
←	D	Good	Minor	Average - Poor

Blast Management

Rock mass blastability - blasting directions

Anisotropic rock with shallow dipping fissures - e.g. micaschist, micagneiss, ...



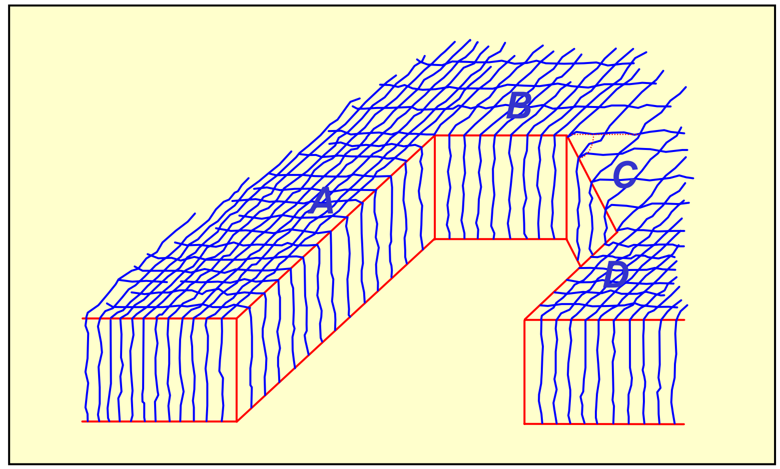


Firing	Backwall	Fragmentation	Back-break & Toe	Floor
→	A	Poor	Extensive	Extensive
↓	B	Good	Minor	Average
↙	C	Good	Minor -	Average
←	D	Good	Minor	Average - Poor

Blast Management

Rock mass blastability - blasting directions

Isotropic rock with steeply dipping joint sets - e.g. quartzites, granites, limestones, ...



Firing	Backwall	Fragmentation	Back-break & Toe	Floor
→	A	Good	Minor	Average
↓	B	Poor - Minor	Uneven	Varying
↙	C	Good -	Major	Minor
←	D	Good	Minor	Average

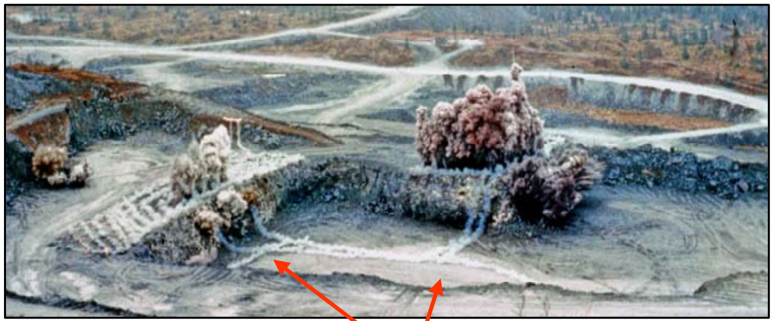
Blast Management

Sequential firing systems

- *electric caps*
- *fuse + detonating cord + surface delays + NONEL*
- *NONEL UNIDET*
- *electronic caps*

Sequential firing guidelines

- *sequential firing of straight rows (increased burden relief results in a longer throw)*
  => *max. muckpile throw (typical for wheel loader operations)*
- *sequential firing of "V shaped rows" at site specific delay times*
  => *peaked muckpiles (typical for shovel operations)*
- *sequential firing to reduce throw - but not heave and fragmentation*
  => *max. degree of selective loading of ore (typically shovel operations)*



Blast Management

Results of tight timing between rows

Blasting front walls shaped by back-break:

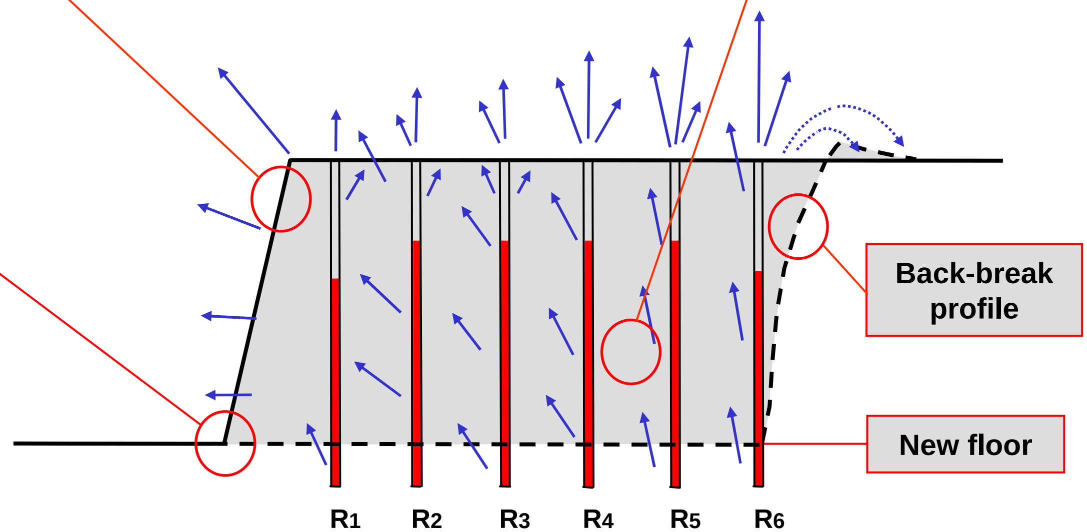
- excessive flyrock due to high column charge or small front row burden giving rise to ***gas venting*** of shotholes
- followed by an excessive loss of shothole pressure with reduced heave as a result

Primary toe problem area since:

- excessive bottom-hole burden results in reduced front row throw
- with insufficient ***heave and liberation*** of the fragmented rock mass before the next row is on its way

Rear-end packing of muckpile occurs due to decreasing *burden relief* in the last rows, i.e. insufficient room for volume expansion or *swell* of each row.

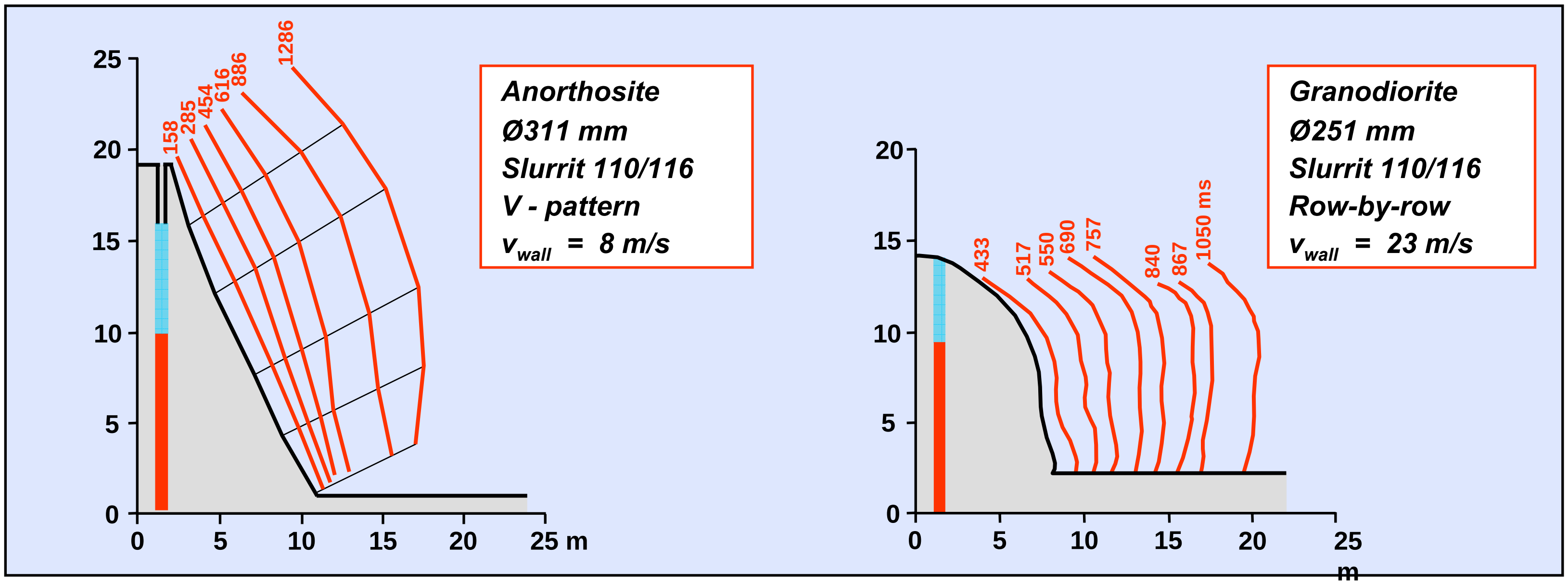
Floor heave, back-break and back-spill also tend to increase with row count for tight timing between rows.



Blast Management

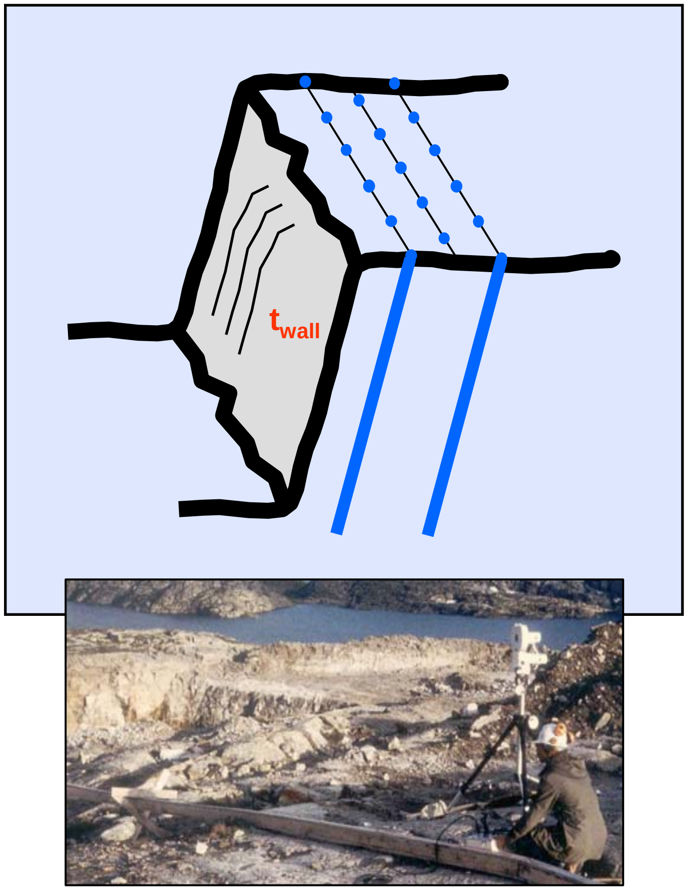
Blast analysis using high-speed photography or video

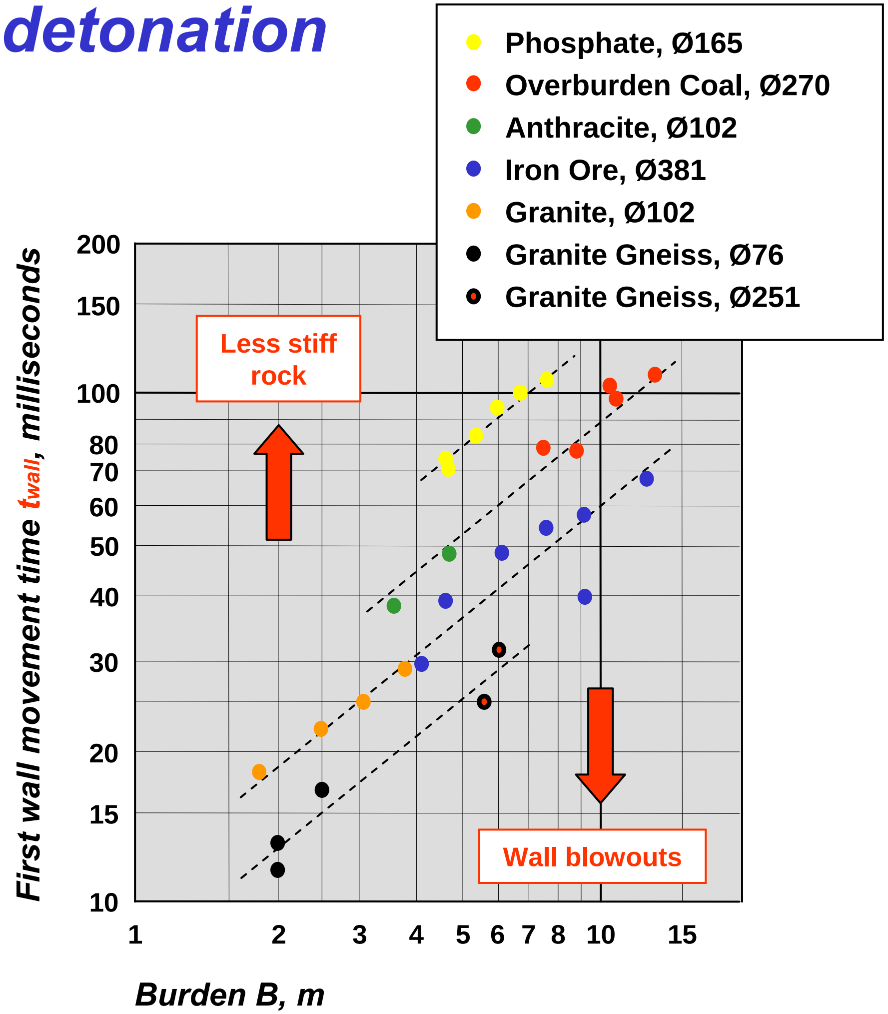
- functionality of stemming
- occurrence of undesirable events such as gas venting and stemming ejection
- flyrock and its origin
- bench face and bench top displacement profiles and velocities
- accuracy of firing times - especially surface delays



Blast Management

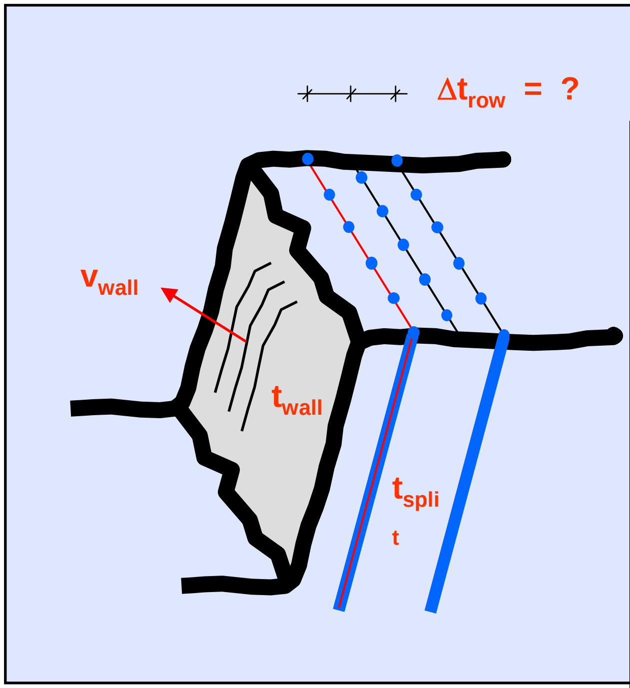
First bench movement after detonation





Blast Management

Illustration of row-by-row shot firing events

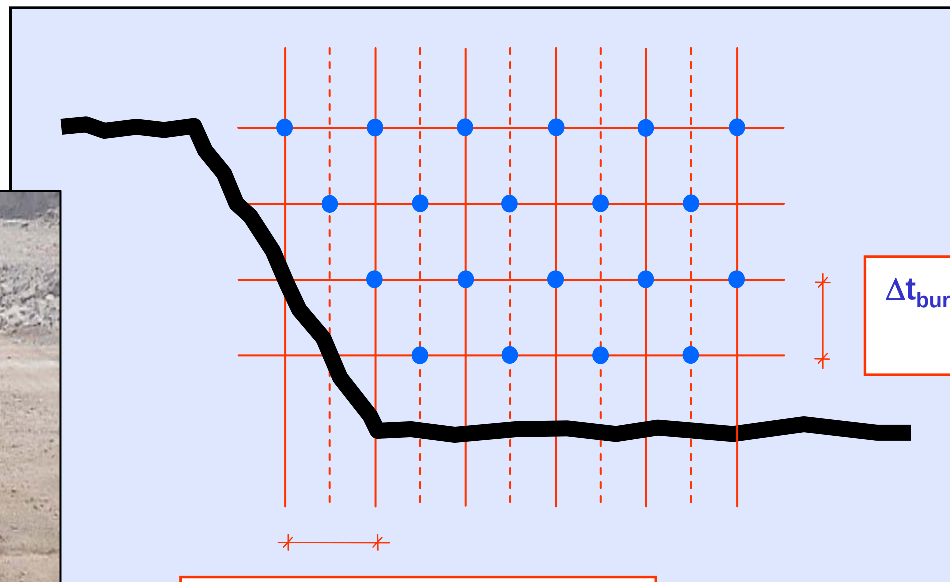


t_{split}	=	*split-along-row fracture time*
t_{wall}	=	*first bench wall movement time*
	=	*max. time for split-along-row to open*
	~	*5.5 ·B (range 3 - 18 ms/m)*
$t_{row\ expansion}$	=	*time for 100% burden relief*
	~	*0.25 ·B · 1000 /* v_{wall}
v_{wall}	=	*average bench face start velocity*
	~	*15 - 20 m/s (range 6 - 25 m/s)*
Δt_{row}	=	*time delay per row*
	=	*affects both fragmentation and throw*

Blast Management

Summary of shot firing delay windows

Wall control delays	0	$<$	$\Delta t_{shothole}$	$\sim$	$t_{split\ fracturing}$
Shotrock fragmentation delays	$t_{split\ fracturing}$	$<$	Δt_{row}	$\sim$	t_{wall} (or $t_{split\ opening}$)
Burden relief delays	t_{wall}	$<$	Δt_{burden}	$\sim$	$t_{wall} + t_{row\ expansion}$
Spacing relief delays	$\sim t_{wall} \cdot S / B$	$<$	$\Delta t_{spacing}$	$\sim$	$(t_{wall} + t_{row\ expansion}) \cdot S / B$



Δt_{burden} = inter-row delay

= *constant* $\cdot$ B

$\Delta t_{spacing}$ = inter-hole delay

= *constant* $\cdot$ S

Blast Management

Example of shot firing event applications

Occurrence	Accumulated time	Mt. Coot-tha Quarry	Delay constants
Detonate row #1	$t_1 = 0$	$t_1 = 0$ ms	
Split-along-row #1 fracturing	$t_2 = t_{split}$	$t_2 = 1 + 4.0 \cdot 1000 / (0.38 \cdot 5000)$	
	$\sim 1 + S / (0.38 \cdot C_p)$	$= 3.1$ ms	$3.1 / 4.0 = 0.78$ ms/m
Bench wall movement commences	$t_3 = t_{wall}$	$t_3 = 5.5 \cdot 3.5$	
(and split-along-row #1 opens)		$= 19.3$ ms	
Expansion time for rock in row #1	$t_4 = t_{wall} + t_{row\ expansion}$	$t_4 = 19.3 + 0.25 \cdot 3.5 \cdot 1000 / 15.7$	
		$= 19.3 + 55.7 = 75.0$ ms	
Detonate row #2 at $t_5 = t_1 + \Delta t_{row}$:			
Optimum fragmentation	$t_5 < t_1 + t_{wall}$	$t_5 < 0 + 19.3$ ms	$19.3 / 3.5 = 5.5$ ms/m
Optimum burden relief	$t_5 \approx t_1 + t_{wall} + t_{row\ expansion}$	$t_5 \approx 0 + 19.3 + 55.7 = 75.0$ ms	$75.0 / 3.5 = 21.4$ ms/m

Blast Management

Basic guidelines for shot firing delay constants

Shotrock fragmentation delays, $\Delta t / B$ and $\Delta t / S$

• lower limit	(t_{split} / B and S)	1	3	ms/m
• upper limit	(t_{wall} / B and S)	4	16	ms/m

□ hard and brittle rock mass
□ soft and ductile rock mass

Row burden relief delays, $\Delta t / B$

• lower limit	(t_{wall} / B)	4	16	ms/m
• expansion time	($t_{row\ expansion} / B$)	12	20	ms/m
• upper limit	($\Delta t_{wall\ +\ row\ exp.} / B$)	16	36*	ms/m

* the upper delay limit can be reduced by introducing individual shothole spacing delays or by increasing $\Delta t_{row\ exp.} / B$ with row count

Shothole spacing relief delays, $\Delta t / S$

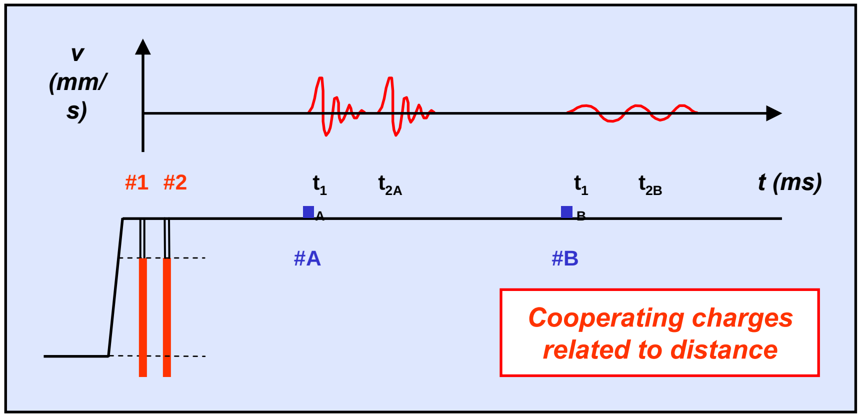
• lower limit	(t_{wall} / S)	4	16	ms/m
• upper limit	($\Delta t_{wall\ +\ row\ exp.} / B$)	16	?**	ms/m

** increasing spacing delays results in more oversize and less throw

Blast Management

Passive control of ground vibrations and air blast

- *reduce number of shotholes per cap #*
- *use single-shot sequential firing - avoid detonating shotholes at times where stress wave amplitudes from adjacent shotholes can interact*
- *reduce charge weight per cap # by using:*
  - *smaller shothole diameters*
  - *decoupled charges*
  - *decked charges*
  - *air-decked charges*
- *use stemming and stemming plugs to reduce air blast*



Active control

- *use of single-shot response analysis to accurately simulate and evaluate the overall seismic effects of multi-shot blast responses*
- *map property as to seismic anomalies*
- *use of more accurate firing systems than those currently available based on pyrotechnic cap technology*
- *increase blast size to minimise the occurrence of blast induced annoyance to neighbours*

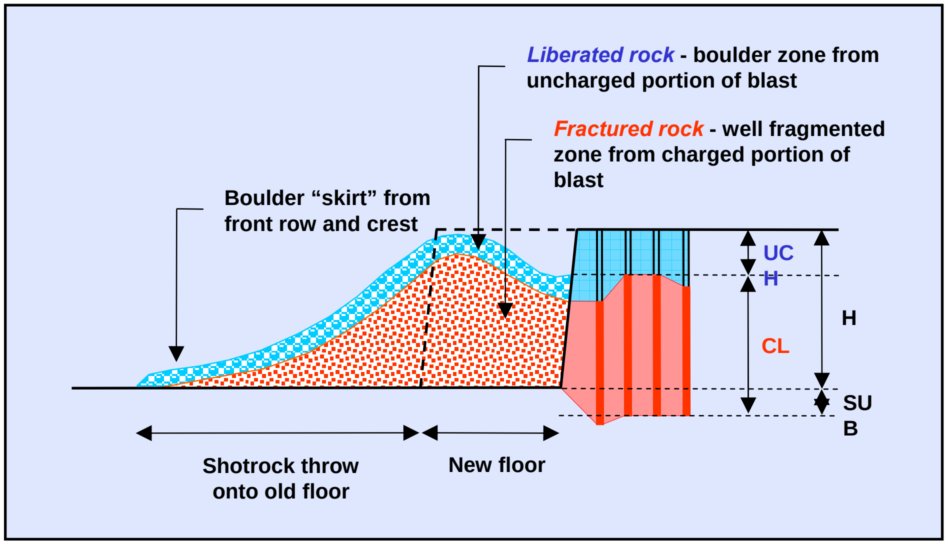
Blast Management

Blasting results

=> *shotrock fragmentation*

=> *muckpile throw, swell and loadability*

=> *side / back break and floor humps*

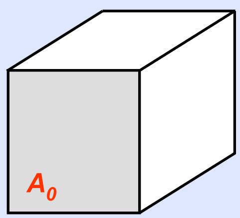


Blast Management

Measuring shotrock fragment size distributions

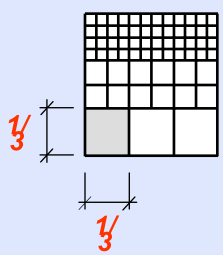
- *splitting samples into retained fractions on bar grizzlies, rectangular or square screens (1 or 2D volumetric based method)*
- *photo and video image analysis (2D area based method)*
- *rock fragment count method incorporating fragment dimension ratios (2 or 3D area based method)*

Link between retained volumetric and area based methods



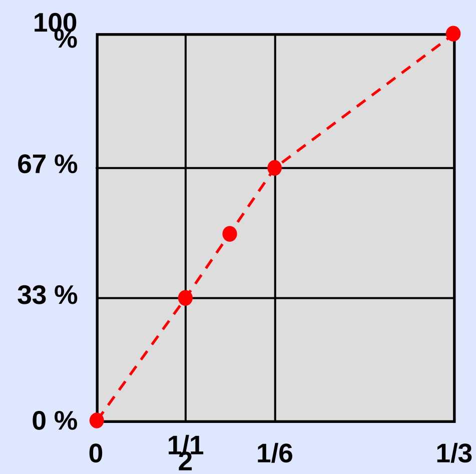
Volume of cube = V_0

Area of square = A_0



Relative volume (of coarse fraction) $= \frac{(1/3)^3 \times 9}{1^3} = 1/3$

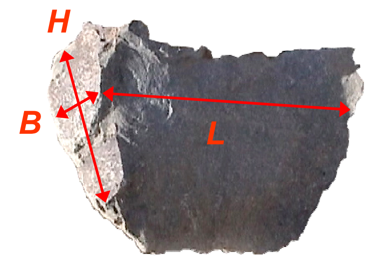
Relative area (of coarse fraction) $= \frac{(1/3)^2 \times 3}{1^2} = 1/3$



Blast Management

Shotrock fragment dimensions

Shotrock fragment dimension ratios H / B and L / B are fragment size dependent. Fragments become more cubical as their distance of origin from a shothole wall increases.



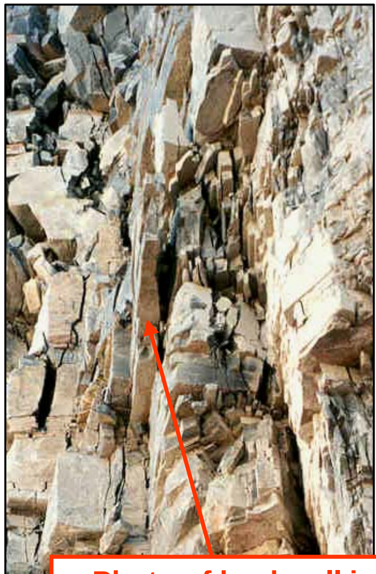
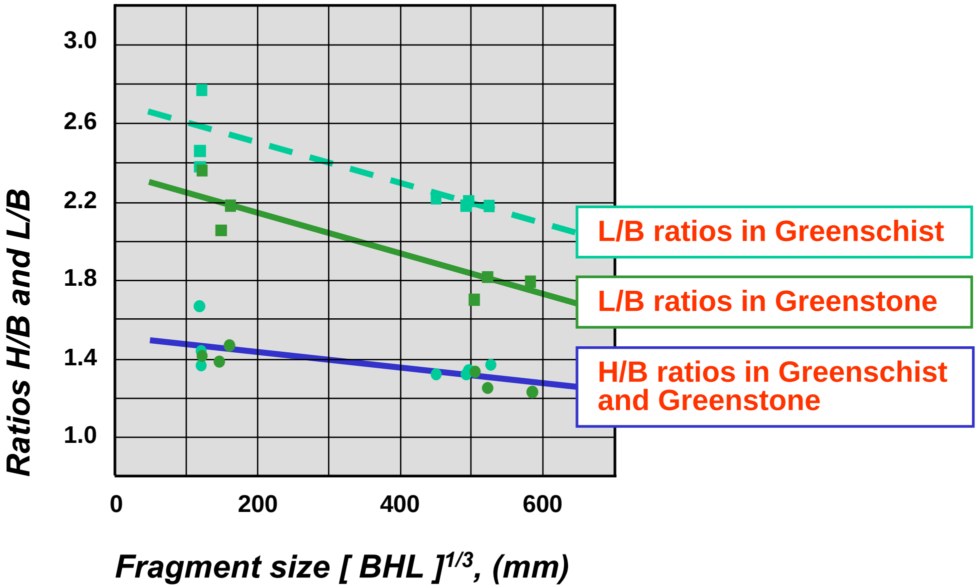


Photo of backwall in limestone.

Note the platy shaped fragments located close to the shothole.



Blast Management

Characterisation of shotrock fragment size distribution

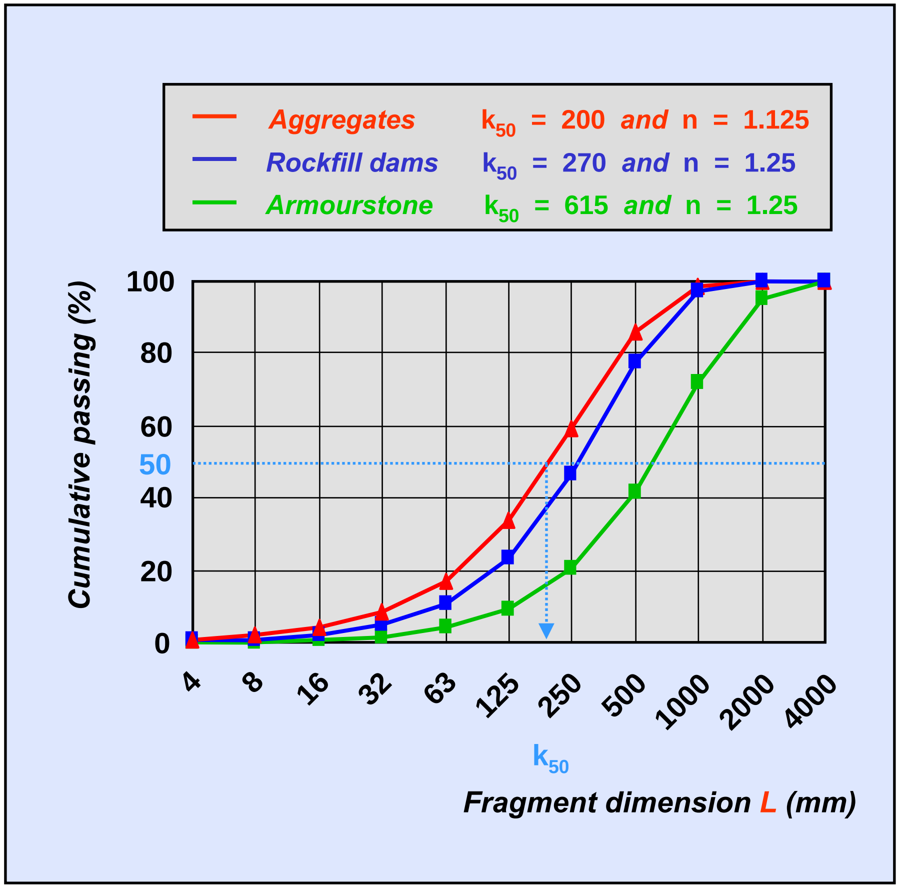
$$P(k_i) = 100 \cdot [\ 1 - e^{-\ln 2 \cdot (k_i / k_{50})^n}\ ]$$

$P(k_i)$ = passing in % for size k_i

k_i = fragment size in mm (L_i)

n = uniformity index

k_{50} = mean fragment size (50% passing)



Blast Management

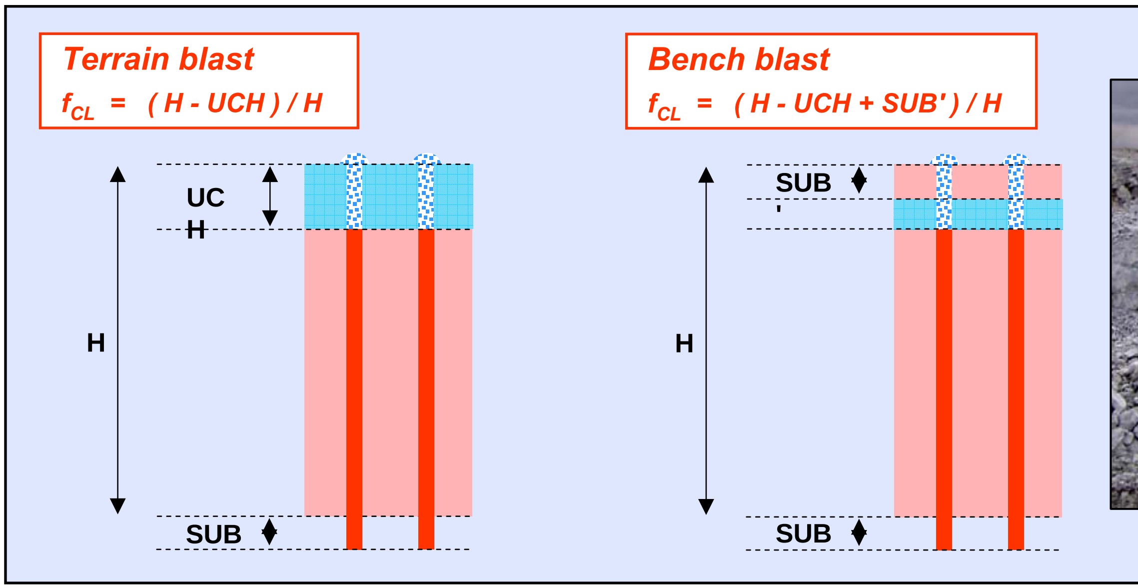
Uniformity index n - effect of bench charging zones

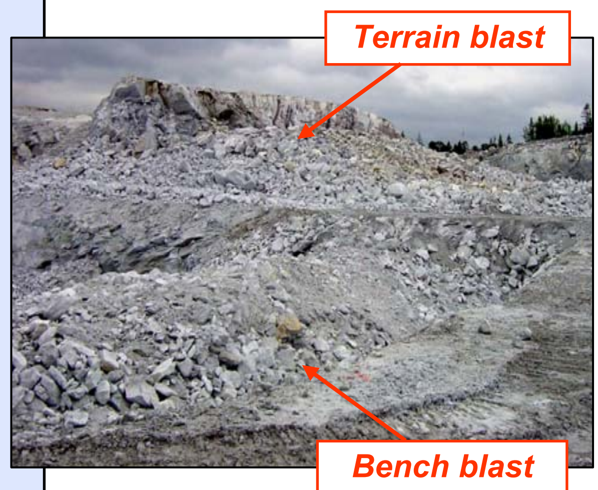
A simplified expression for estimating the shotrock uniformity index is:

$$n = 1.60 \cdot (k_{50} / 270)^{0.61} \cdot f_{CL}$$

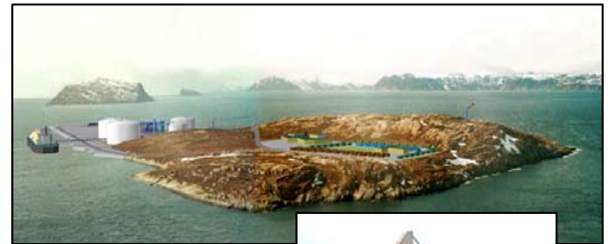
$$f_{CL} = \text{"charged" bench height ratio}$$

Since the shotrock fragment size distribution parameters k_{50} and n are dependent parameters, this leads to a simplification in that it is not necessary to find seperate blast design guidelines for both size distribution parameters - only the mean fragment size k_{50}.





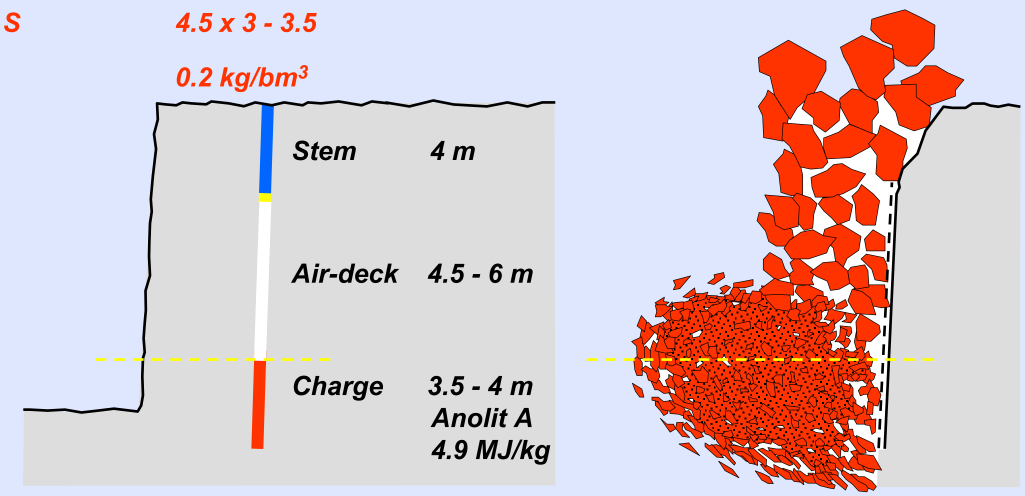
Blast Management



Melkøya LNG Plant Site Preparation

Joint Venture	*AF Spesialprosjekt A/S - Phil & Søn A/S*
Duration	*July 2002 - May 2003*
D & B excavation volume	*2 400 000 bm^3 peaking at 80 000 bm^3/week*
Breakwater armourstone	*670 000 compacted m^3*
Rock mass conditions	*Terrain benches in fractured gneiss*

Bench heights	*10 - 12 m*
Shothole	*Ø102 mm*
Inclination	*6°*
B x S m^2	*4.5 x 3 - 3.5*
PF	*0.2 kg/bm^3*

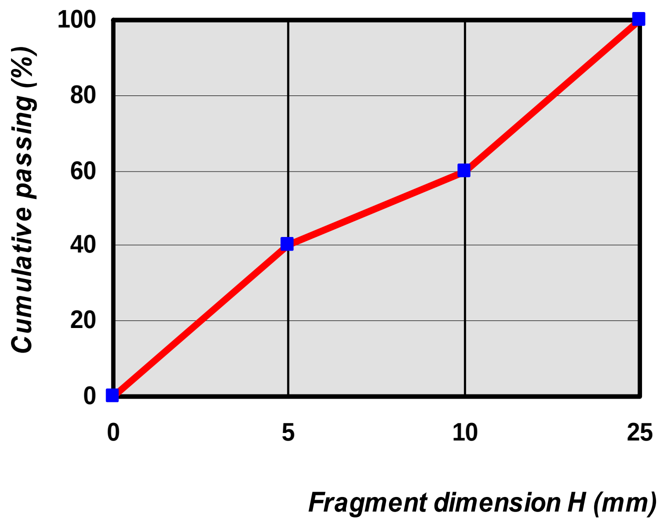


Armourstone Class	m (t)	L (mm)
oversize	> 35	> 2920
I	20 - 35	2420 - 2920
II	10 - 20	1920 - 2420
III	4 - 10	1420 - 1920
IV	1.5 - 4	1020 - 1420
V	0.5 - 1.5	710 - 1020

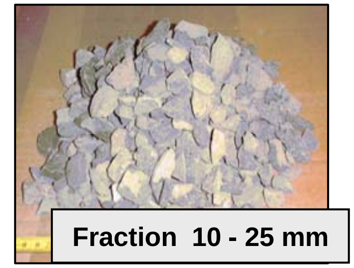
Blast Management

Fragment size distribution

Mesh opening, d (mm)	Size fraction (mm)	Retained on mesh (kg)	Cumulative retained (kg)	Cumulative retained (%)	Cumulative passing (%)
25	> 25	0	0	0	100
10	10 - 25	4	4	40	60
5	5 - 10	2	6	60	40
0	0 - 5	4	10	100	0




Fraction 0 - 25 mm

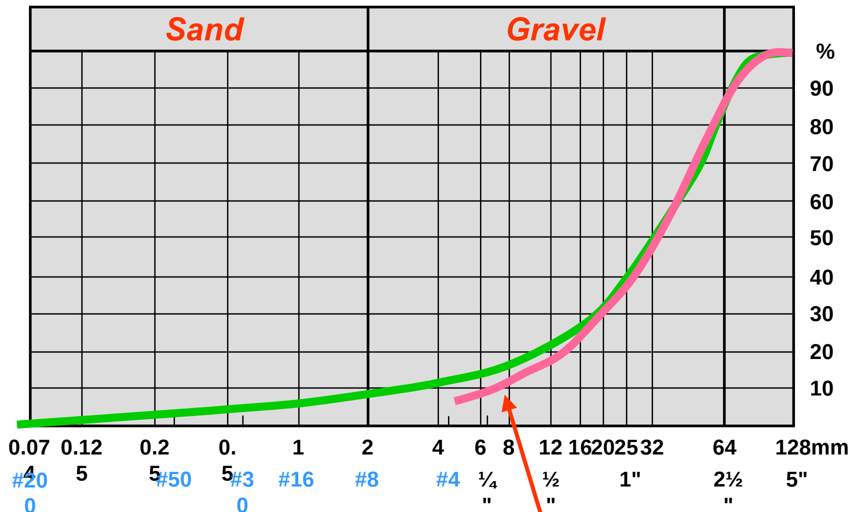

Fraction 10 - 25 mm


Fraction 5 - 10 mm


Fraction 0 - 5 mm

Blast Management

Sieve versus photo image analysis of stockpile size distribution



Discrepancy due to segregation in stockpile as can be seen in the analyzed stockpile photos

DynoConsult

SANDVIK

Blast Management

Examples of rock fragment size distribution

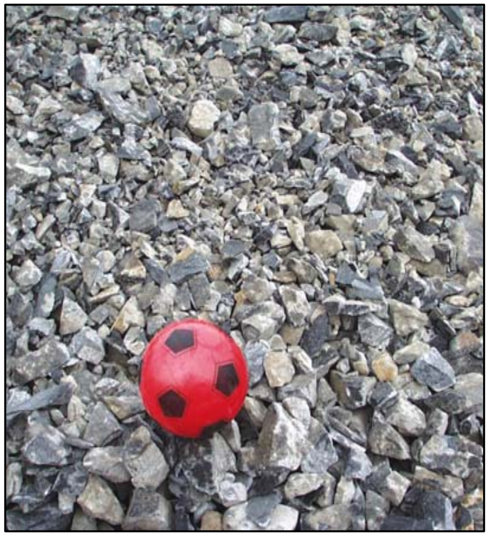
Top of muckpile

k_{50} = 526mm
n = 1.69

Loading front

k_{50} = 214mm
n = 1.19

Scale: Balls
∅206mm



Stockpile (mesh sizing)

d_{50} = 32mm
n = 1.60

Blast Management

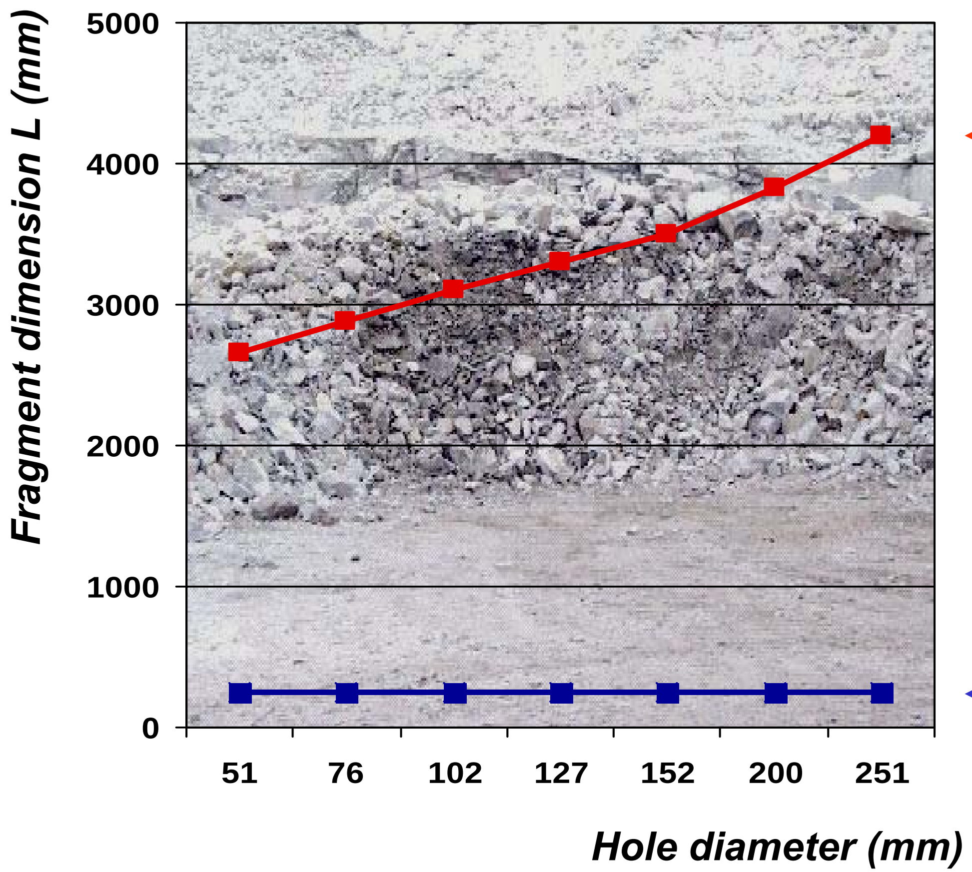
Shotrock assessment

Bench Blasting Operations	Shotrock Designation	Mean Fragment Size, k_{50} [mm]	Loading Equipment
Aggregate Quarries	Crushing & Screening	125 - 290 [1]	Wheel Loaders, Front Shovels or Hyd. Excavators
Rockfill Dam Quarries	Supporting Fill:		
	Fine Zone	160 - [2]	Wheel Loaders
	Fine Zone	200 - 250	Wheel Loaders
	Coarse Zone	250 - 320	Wheel Loaders
	Coarse Zone	- 440 [3]	Wheel Loaders + Hyd. Excavators
Open Pit Mining	Crushing & Milling	160 - 250 [4]	Shovels + Wheel Loaders
Road Construction	Sub-base	200 - 310	Hyd. Excavators

1) Targeted mean fragment sizes dependent on primary crusher openings, primary crusher capacities and marketability of fines.
2) Blasts with a high portion of shotrock for transition zones (k_{max} = 200 mm).
3) Blasts with a high portion of shotrock for dam slope rip-rap and crown cap. Fragment size criteria for supporting fill is typically $k_{max} \approx 2/3$ of placement layer thickness.
4) Blasts with the largest mean fragment sizes were observed for orebodies with low mechanical strength properties.

Fines and Boulder Management

Trendlines for shotrock fragment size distribution



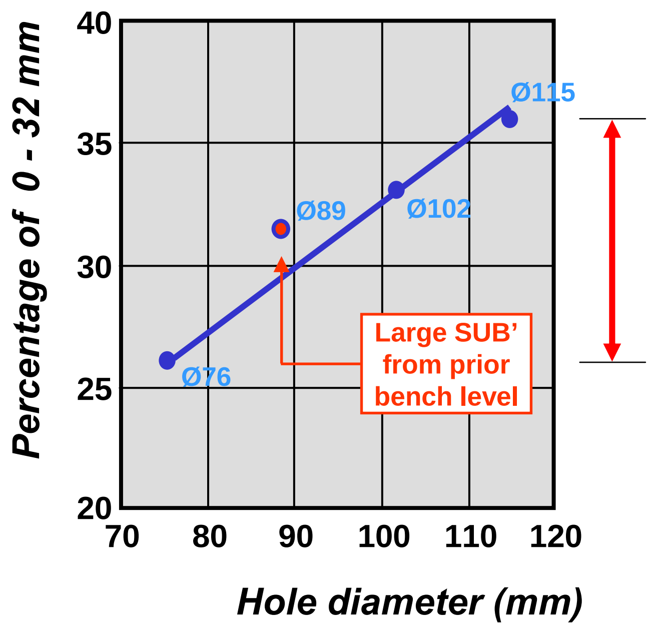
k_{max} and production of oversize increases with drill-hole diameter due to use of longer uncharged lengths and drill patterns. The shotrock uniformity index n decreases.

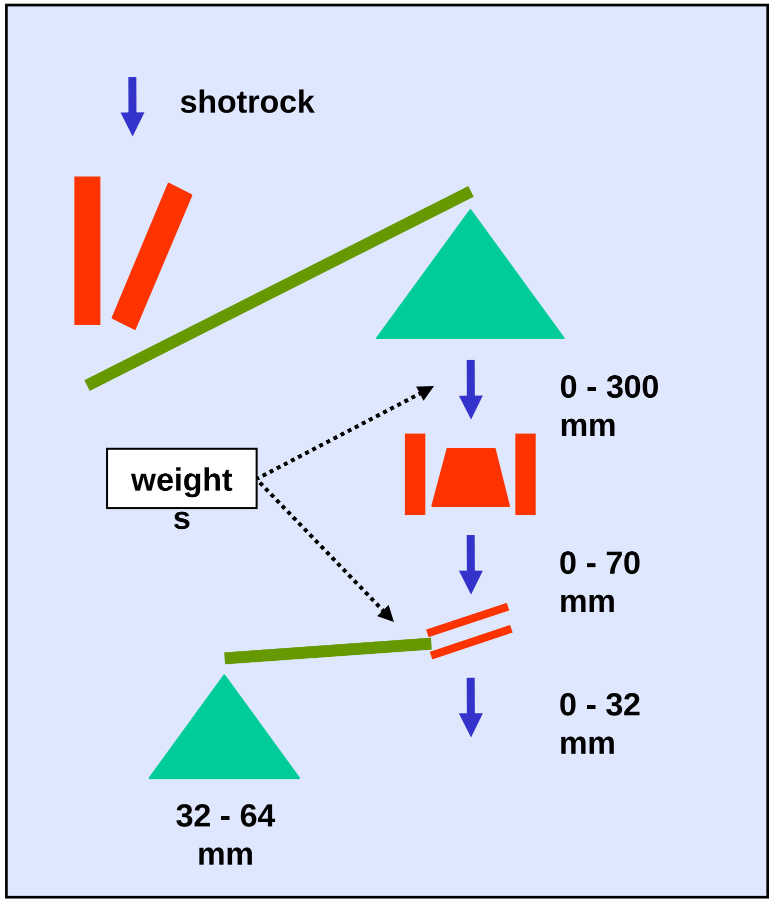
k_{50} remains constant - but the production of fines also increases with drill-hole diameter.

Fines Management

Nodest Vei A/S, Norway - effect of shotrock micro-fracturing

Rock type	*Anorthosite*
Explosive	*Slurrit 50-10*
Test blasts tonnes	*4 x 50 000*
Bench height	*11 m*

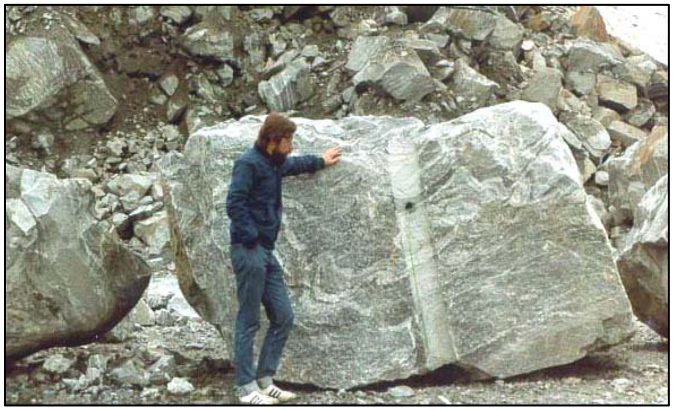




Boulder Management

Boulder handling

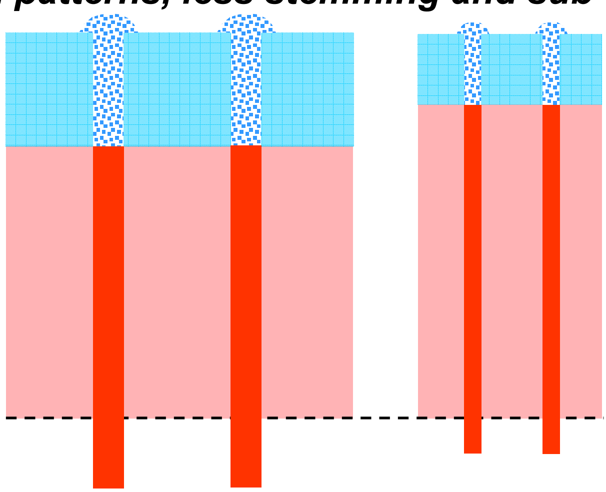
- boulder count dependent on primary crusher opening (and to a lesser extent capacity)
- sort boulders from muck pile
- down-size boulders
- minimize boulder count using reduced uncharged height and/or tighter drill patterns

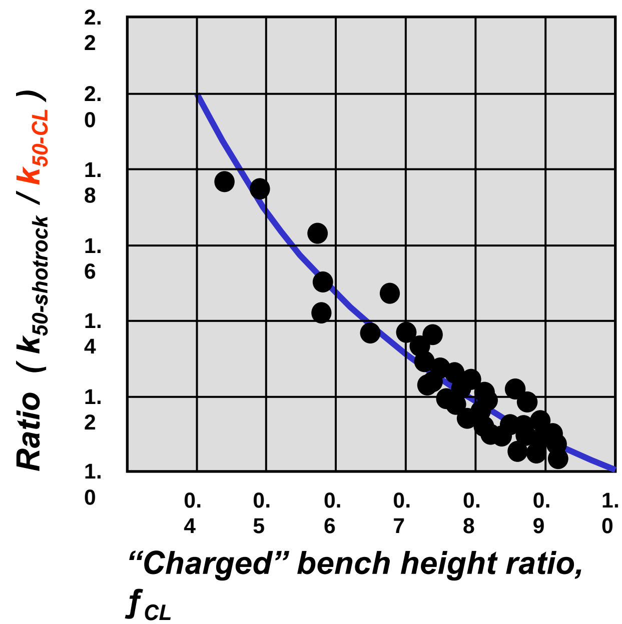


Boulder Management

Shotrock boulder count versus charged portion of blast

Boulders originate from the uncharged portion of a bench blast. To reduce shotrock boulder count and size; the uncharged portion of the blast must be reduced, and if necessary, by using smaller shotholes - which dictate smaller drill patterns, less stemming and sub-drill.



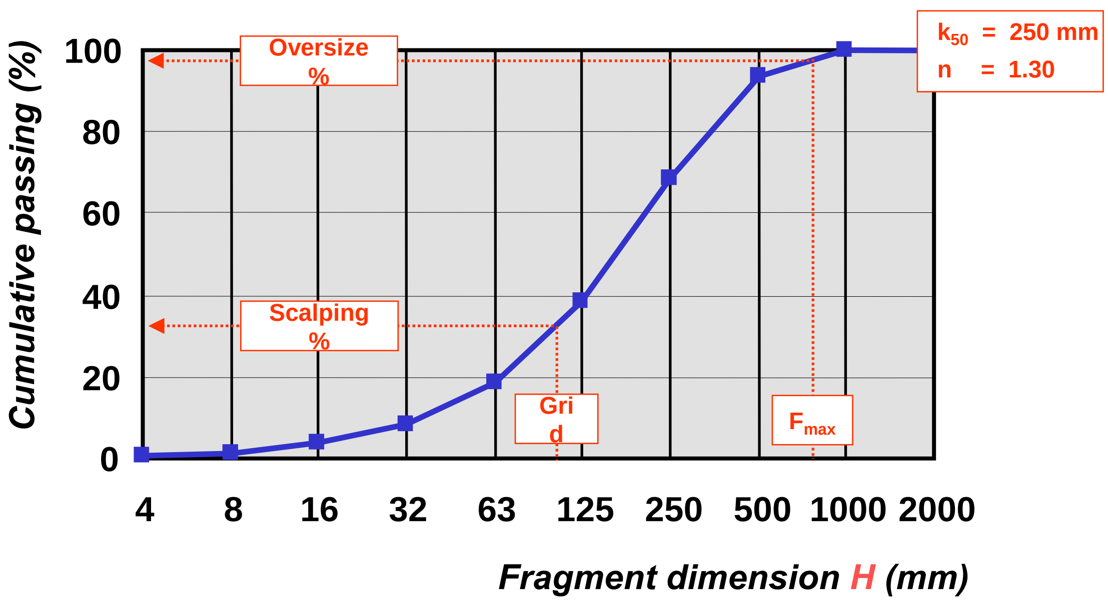


$$k_{50\text{-shotrock}} = k_{50\text{-CL}} / f_{CL}^{0.76}$$

Boulder Management

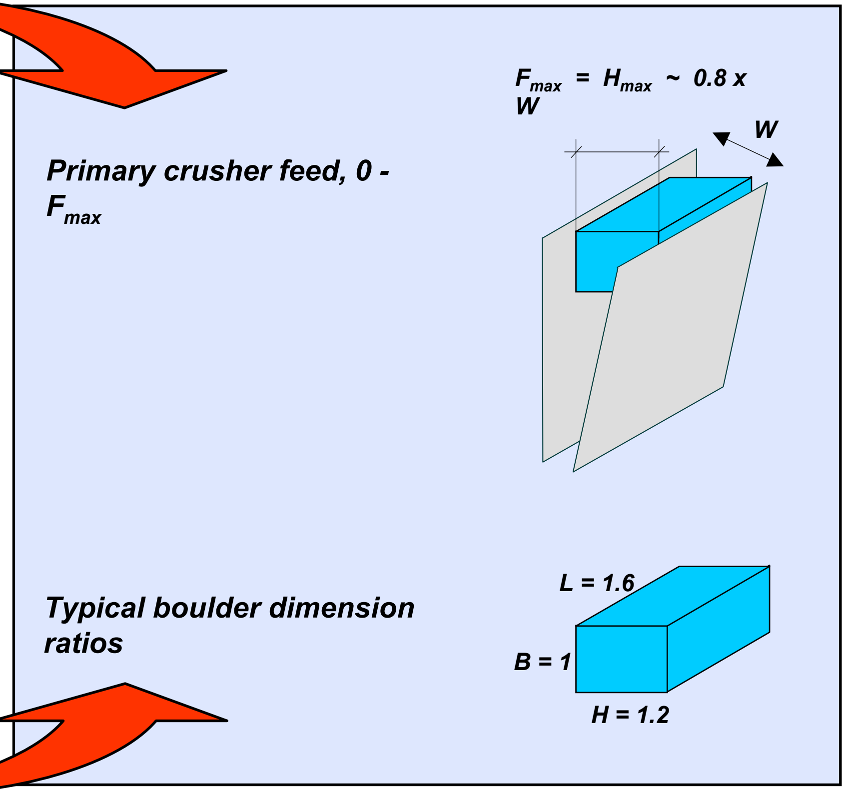
Primary crushing - gross capacity components

- crusher size - design capacity versus feed fragment sizing
- scalping - scalping capacity increases with grid opening
- occurrence of boulder bridging, blockages and delays
- occurrence of no shotrock delivery versus use of pre-primary surge pile
- downtime for maintenance and replacement of wear parts



Boulder Management

Matching boulder size to primary crusher opening



Boulder Management

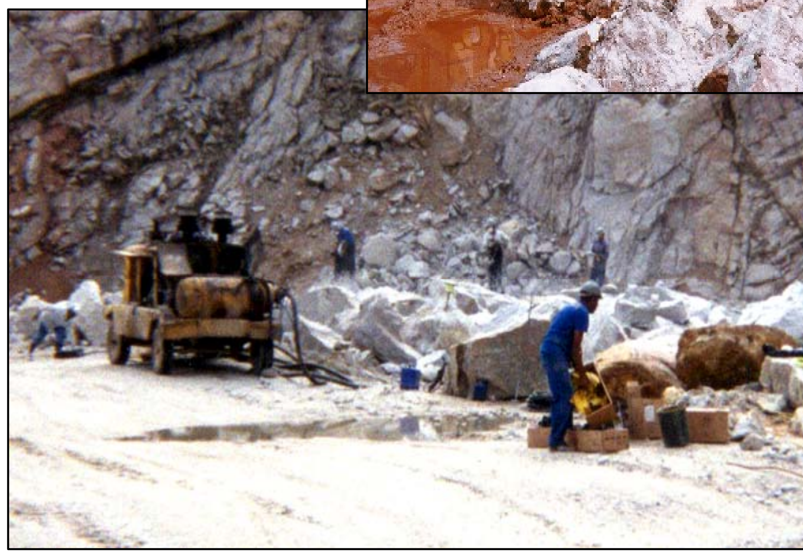
Example of application using shotrock fragment size distribution

Primary crusher opening	W	$= 950$ mm	
Crusher limit as to boulder height	H_{max}	$= 950 \cdot 0.8$	$= 760$ mm
Crusher limit as to boulder length	L_{max}	$= 760 \cdot 1.6 / 1.2$	$= 1013$ mm
Crusher limit as to boulder thickness	B_{max}	$= 760 \cdot 1.0 / 1.2$	$= 633$ mm
Shotrock size distribution parameters	k_{50}	$= 250$ mm	
	n	$= 1.30$	
Shotrock oversize percentage	$P(1013)$	$= 100 \cdot e^{-\ln 2 \cdot (1013/250)^{1.30}}$	
		$= 1.39$ %	
Blast volume	$10\,000$ bm^3		
Shotrock boulder (oversize) count	N	$\leq 10\,000 \cdot 0.0139 / (1.013 \cdot 0.760 \cdot 0.633)$	
		≤ 286 boulders / $10\,000$ bm^3	

Boulder Management

Methods for down-sizing boulders

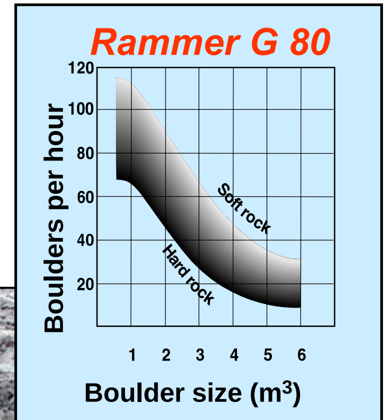
- hammering with breakers mounted on:
  - hydraulic excavators working along the loading front
  - hydraulic excavators working at boulder stockpiles
  - stationary booms located at primary crushers or grizzlies
- drop-weights or swing-balls
- secondary blasting



Boulder Management

Typical inpit usage of hydraulic excavator mounted breakers

- down-sizing boulders
- removing floor humps
- scaling and cleaning back walls
- breaking up frozen sub-drill zones prior to removal



Blast Management

How drilling and blasting affect down-stream operations

Drilling ⟷ **Blasting** ⟷ **Loading** ⟷ **Crushing**

Drilling
- drill patterns
- drilling accuracy

Blasting
- field performance of explosives
- shotrock fragmentation
  - boulders
  - floor humps
  - fines and microcracks

Loading
- muckpile profiles and swell
- loadability and loading capacities
- selective mining

Crushing
- boulder downtime
- crushing capacities
- power consumption
- fines production

Quarry process mapping => Modelling => Objective measurements => Management of operations

Fine tuning drill, charging and firing patterns to local geological conditions is based on extensive field trials incorporating the analysis of blast behaviour by high-speed videos, shotrock fragmentation and throw, ground vibration monitoring, boulder count, loading and hauling capacities, and crushing plant performance studies.