POLITECNICO DI TORINO

Master in Tunnelling and tunnel boring machines

Academic year 2017-18

Post Graduated Master Course
TUNNELLING AND TUNNEL BORING MACHINES

Lecturer : Dr. GIORDANO RUSSO

Subject of the lesson : ROCKBURST

Company / Affiliation : GEODATA ENGINEERING

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A **rockburst** is defined as:

- damage to an excavation that occurs in a sudden and violent manner and is associated with a seismic event (Hedley, 1992; Kaiser et al., 1996).
- a seismic event that causes violent and significant damage to a tunnel or excavations of a mine (Ortlepp, 1997) .
- Explosive failures of rock which occur when very high stress concentrations are induced around underground openings (Hoek, 2006) .

A rockburst is associated with damage to an excavation or its support: hence, a seismic event alone without causing damage is not a rockburst

[extracted from Kaiser, 2017 [18], Cai and Kaiser, 2017 [1], Diederichs, 2014 [9]

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Video	Rockburst
1	Olmos (Perù)
2	Gotthard
3	Chile site A
4	Chile site B_1
5	Chile site B_2
6	Chile site B_3
7	Chile site C_1
8	Chile site C_2
9	Chile site C_3
10	Chile site C_4

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Spalling vs Rockburst

Spalling is a mode of damage and overbreak in tunnels at depth in hard rocks (low porosity).

- **It is defined as the development of visible extension fractures under compressive loading near the boundary of an excavation.**
- **Spalling in hard rock excavations, while brittle in nature, can be violent (rockburst or strain burst) or not and time dependent. Strain bursting is the violent rupture of a volume of wall rock under high stress.**
- **The spalling damage (extension fractures) can happen before the actual rockburst: it is the instability created (example: buckling) by the formation of parallel and thin spall slabs that provides the kinematics for the sudden energy release.**
- **While even weak rocks can spall, the ability to store energy, typical of strong rocks, is required for strain bursting.**

Extracted from Diederichs, 2005 [6]

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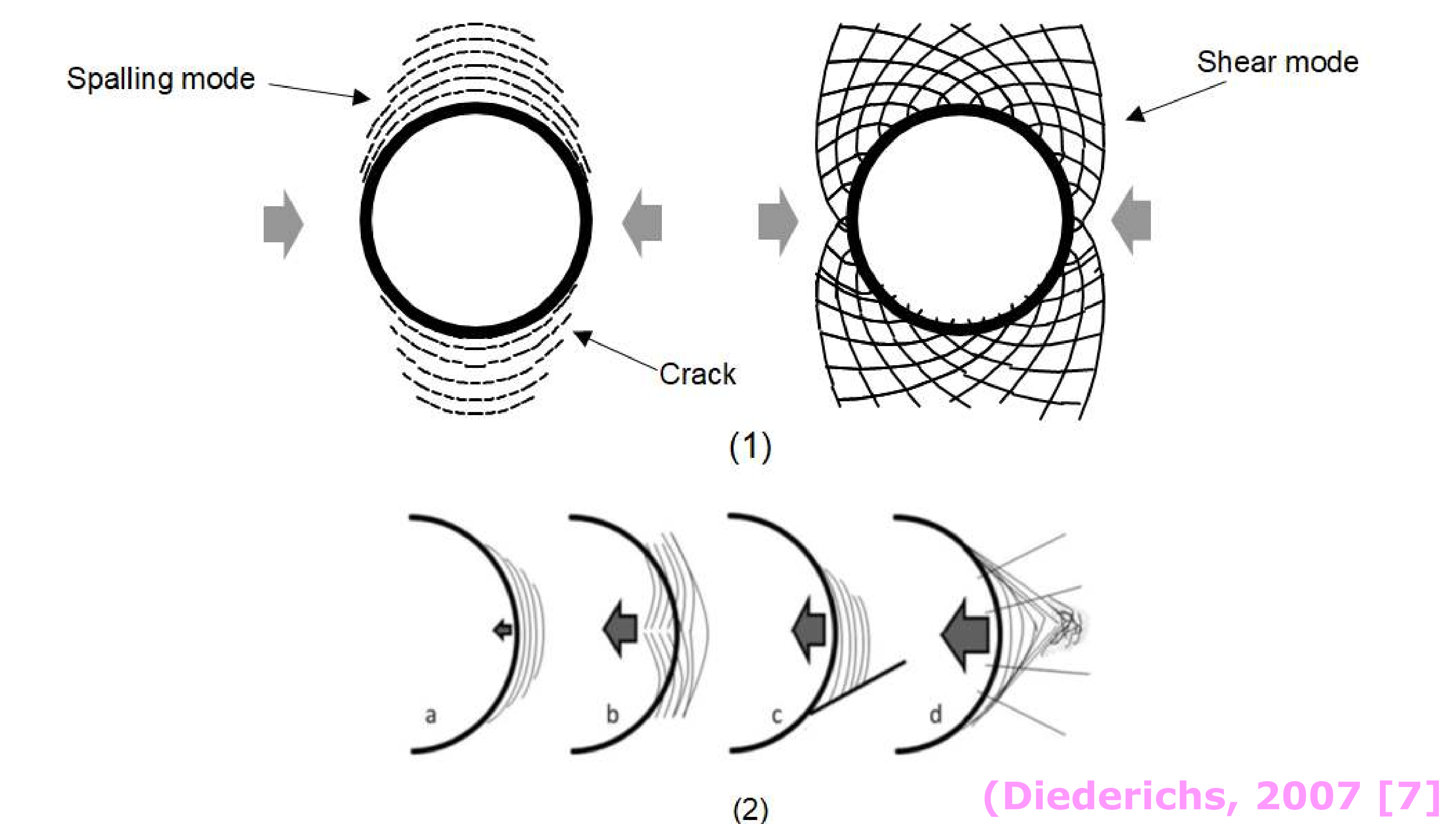
Spalling vs Shear failure mode



(Diederichs, 2007 [7])

1) Creation of boundary parallel spalling fractures compared to the progressive shearing assuming in plasticity; (2)Transition from non-violent spalling (a) to bursting through buckling (b), interaction with structure (c) and dilational yield (d)

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Different types of rockbursts

Fault-slip rockburst refers to damage to an excavation caused by energy released from a shear slip or shear rupture source that is remote from the excavation. Damage is caused by dynamic disturbances from the fault-slip source and may, in part or exclusively, be related to the intensity of the related seismic event. This intensity is directly related to the source size

A **pillar-rockburst** refers to damage to an excavation that is caused by excessive loading of a pillar such that the pillar wall (edge or face) or the pillar core fails.

A **strainburst** is a sudden and violent failure of rock near an excavation boundary caused by excessive straining of an un-fractured volume of rock (burst volume). The primary or a secondary seismic source is co-located at the damage location.

[1,3]

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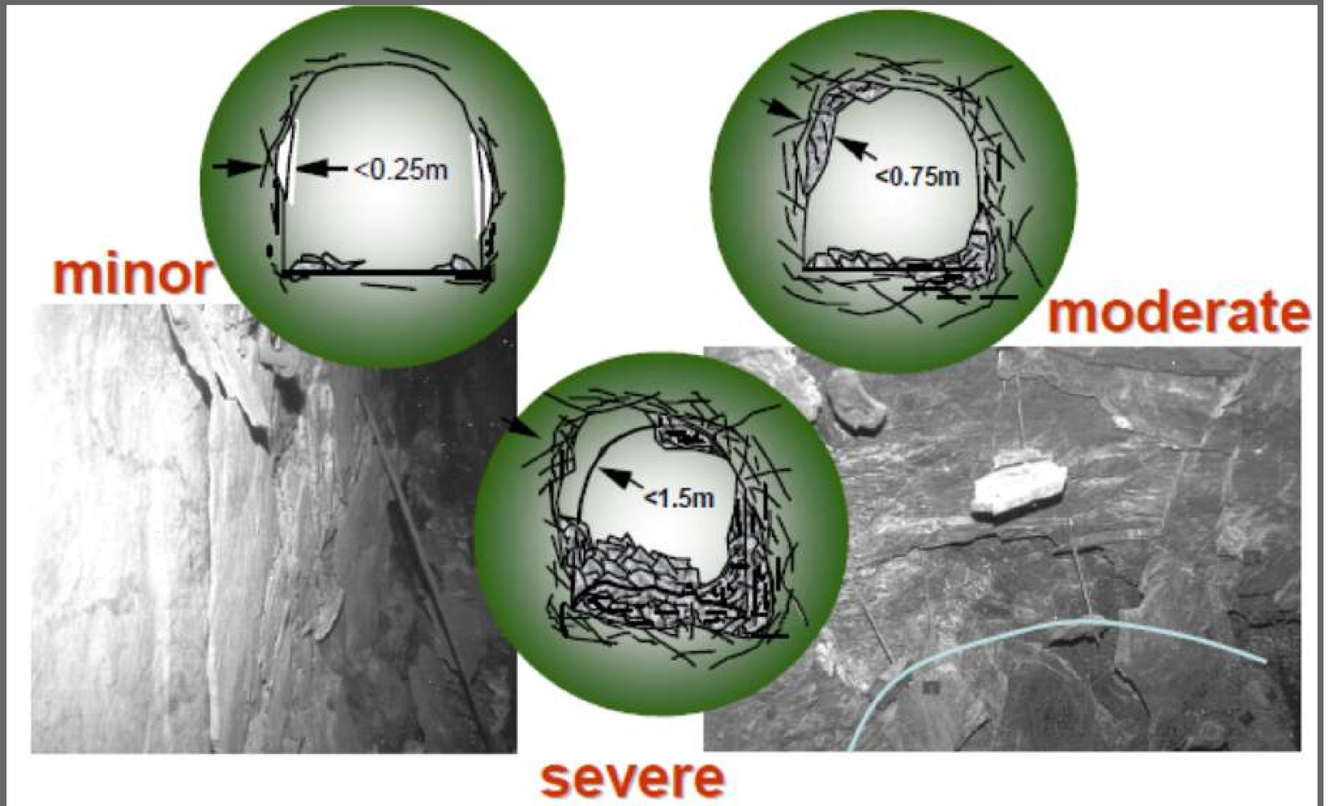
Rockburst Type	Postulated Source Mechanism	First Motion from Seismic Records	Richter Magnitude M_L
Strain-bursting	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	-0.2 to 0
Buckling	Outward expulsion of larger slabs pre-existing parallel to surface of opening	Probably implosive	0 to 1.5
Pillar or face crush	Sudden collapse of stope pillar, or violent expulsion of large volume of rock from tabular stope face or tunnel face	Possibly complex, implosive and shear	1.0 to 2.5
Shear rupture	Violent propagation of shear fracture through intact rockmass	Double – couple shear	2.0 to 3.5
Fault-slip	Sudden movement along existing fault	Double – couple shear	2.5 to 5.0

Ortlepp and Stacey, 1994, adjusted by Cai and Kaiser, 2017 [1]

Severity of rockburst damage

If an excavation is supported, the severity of rockburst can be related to the support damage (minor, moderate, severe..)

The rockburst damage severity can also be characterized by the depth and lateral extent of the rock around the opening that is involved in the failure process.



[3] for 3÷6m underground excavation

Rockburst damage scale	Rock mass damage	Damaged surface area	Rock support damage
R1	No damage, minor loose	0	No damage
R2	Minor damage, less than 1 t displaced	$< 1\ m^2$	Support system is loaded, loose in mesh, plates deformed
R3	1–10 t displaced	$< 10\ m^2$	Some broken bolts
R4	10–100 t displaced	10 to $50\ m^2$	Major damage to support system
R5	100+ t displaced	$> 50\ m^2$	Complete failure of support system

Potvin, 2009; modified [1]

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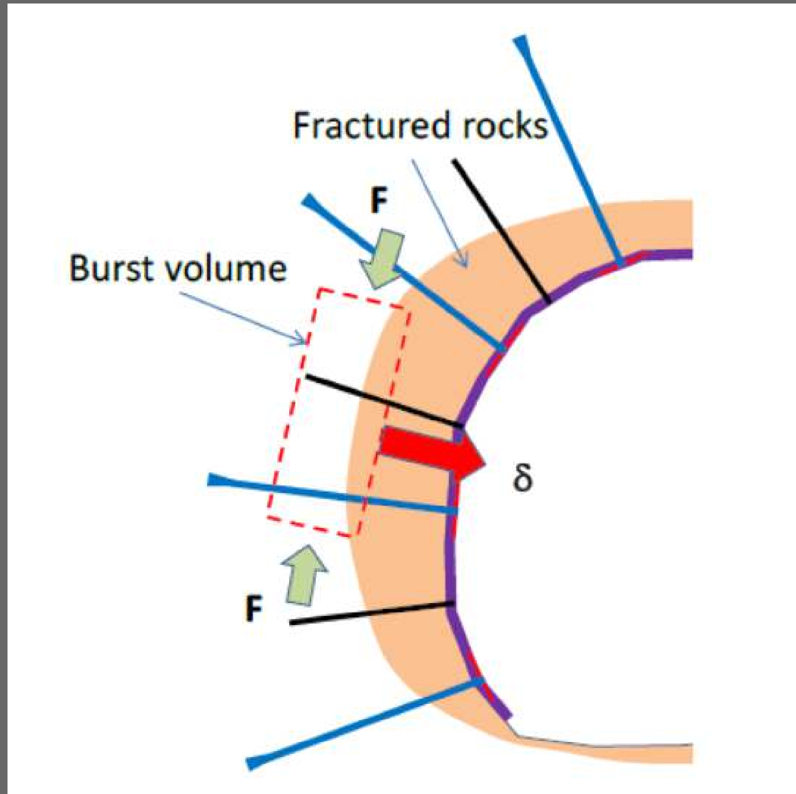
Strainburst

"a sudden and violent failure of rock near an excavation boundary caused by excessive straining of an un-fractured volume of rock." Hence, strainbursts occur when the stress near an excavation reaches the peak strength of the unsupported or supported rock mass and the rock fails by a combination of extension and shear fractures.

- **self-initiated**
- **mining-induced**
- **seismically triggered**
- **dynamically loaded**



Strainburst behind support [1]

Strainburst types	Features	Energy
Self-initiated	Gradual weakening of rock mass; relatively soft loading/mining system	Related to strainburst intensity (local stress-strength conditions)
Mining induced	Induced deformations/strains change local stress reaching the rock strength	Related to strainburst intensity (local stress-strength conditions)
Seismically triggered	Self-inititiated or Mining induced triggered by remote seismic event	Mainly related to strainburst intensity (local stress-strength conditions)
Dynamically loaded	Remote seismic event augments strainburst intensity: -Depth of Failure deepening -Ejection for energy transfer	Mainly from remote seismic event

Derived from [18]

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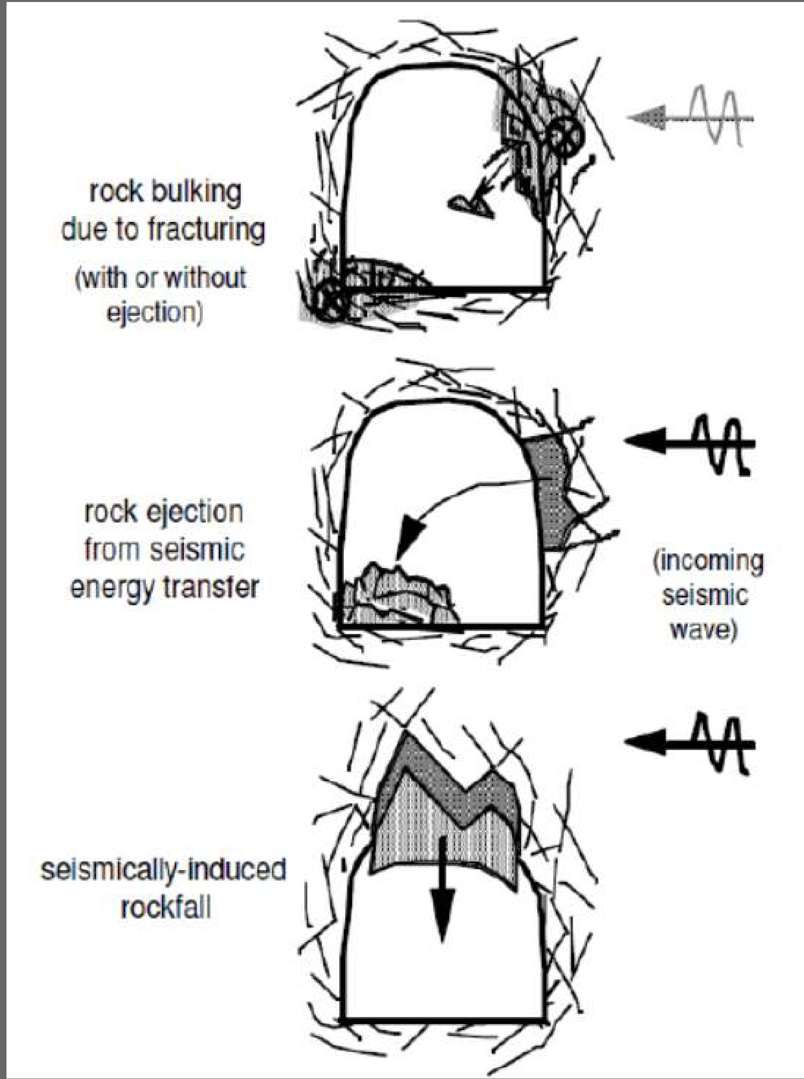
Rockburst damage mechanisms (dynamic failure modes)

1. Static stress fracturing or strainbursting due to tangential straining

2. Rock ejection by momentum transfer from remote seismic or from high bulking deformation rate during strainburst

3. Shakedown with stand-up time reductions



[3]

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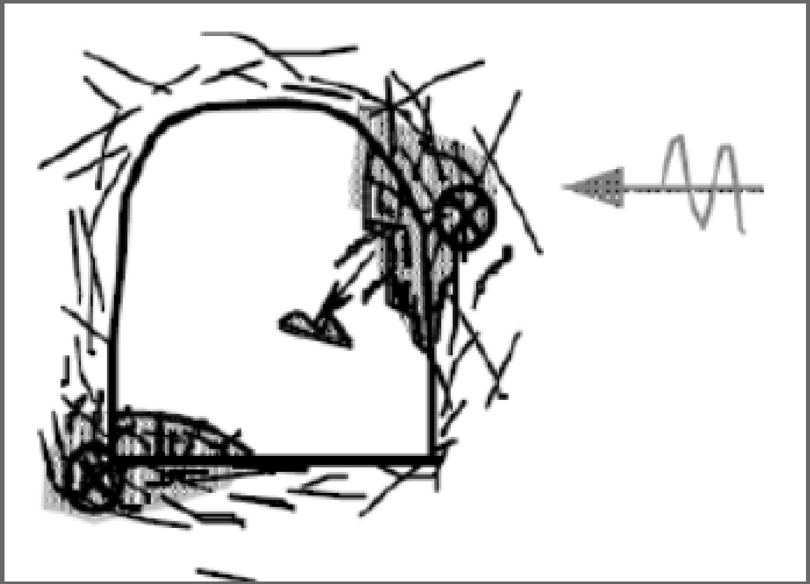
1. Static stress fracturing or strainbursting due to tangential straining

This failure mode is dominated by stored strain energy, the Loading System Stiffness (LSS) and the in situ stress field

It is associated with rock mass bulking that causes large static and dynamic deformations near the excavations, which are largely defined by the depth of failure and the mining-induced tangential strain.



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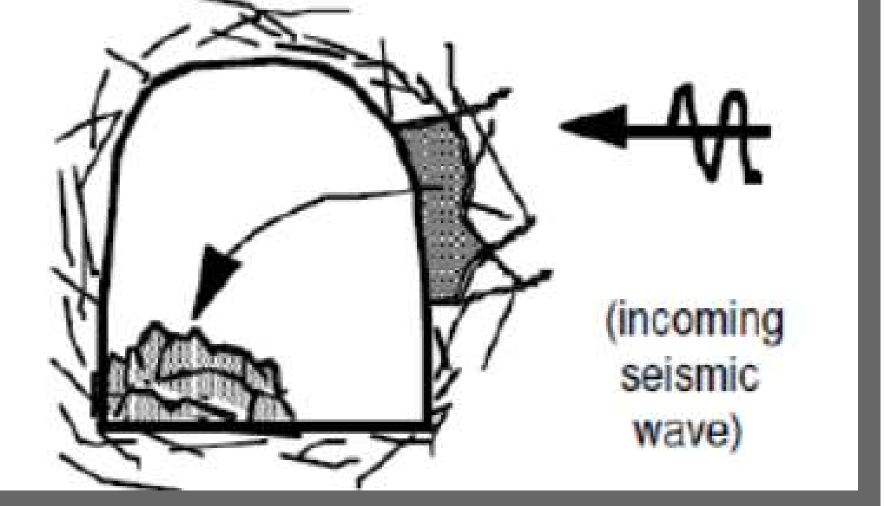
2. Rock ejection by momentum transfer from remote seismic sources or from high bulking deformation rate during strainburst

Failure mode is dominated by energy transmitted from remote seismic sources and the fracture rate due to strainbursting



Example of severe event with failure of support in andesitic rock. Probably combined 1-2 mechanism (Estimated released Energy 25-30kJ/m2)

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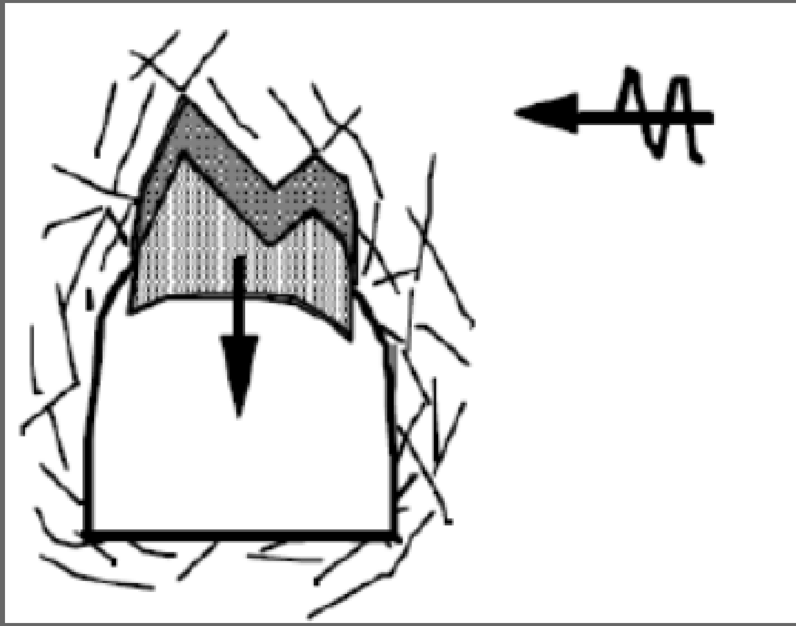
3. Shakedown with stand-up time reductions

This failure mode is dominated by rock quality, span, etc., and dynamic acceleration forces from a remote seismic event or other dynamic disturbances



Examples [1]

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Rockburst damage mechanisms and nature of the anticipated damage

Damage mechanism	Damage severity	Cause of rockburst damage	Thickness [m]	Weight [kN/m²]	Closure* [mm]	v_e [m/s]	Energy [kJ/m²]
Bulking without ejection	Minor	highly stressed rock with little excess stored strain energy	< 0.25	< 7	15	< 1.5	not critical
	Moderate		< 0.75	< 20	30	< 1.5	not critical
	Major		< 1.5	< 50	60	< 1.5	not critical
Bulking causing ejection	Minor	highly stressed rock with significant excess strain energy	< 0.25	< 7	50	1.5 to 3	not critical
	Moderate		< 0.75	< 20	150	1.5 to 3	2 to 10
	Major		< 1.5	< 50	300	1.5 to 3	5 to 25
Ejection by remote seismic event	Minor	seismic energy transfer to jointed or broken rock	< 0.25	< 7	< 150	> 3	3 to 10
	Moderate		< 0.75	< 20	< 300	> 3	10 to 20
	Major		< 1.5	< 50	> 300	> 3	20 to 50
Rockfall	Minor	inadequate strength, forces increased by seismic acceleration	< 0.25	$< 7g/(a+g)$	na	na	na
	Moderate		< 0.75	$<20g/(a+g)$	na	na	na
	Major		< 1.5	$<50g/(a+g)$	na	na	na

v_e is the velocity of displaced or ejected rock; a and g are seismic and gravitational accelerations

* closure expected with an effective support system

[3]

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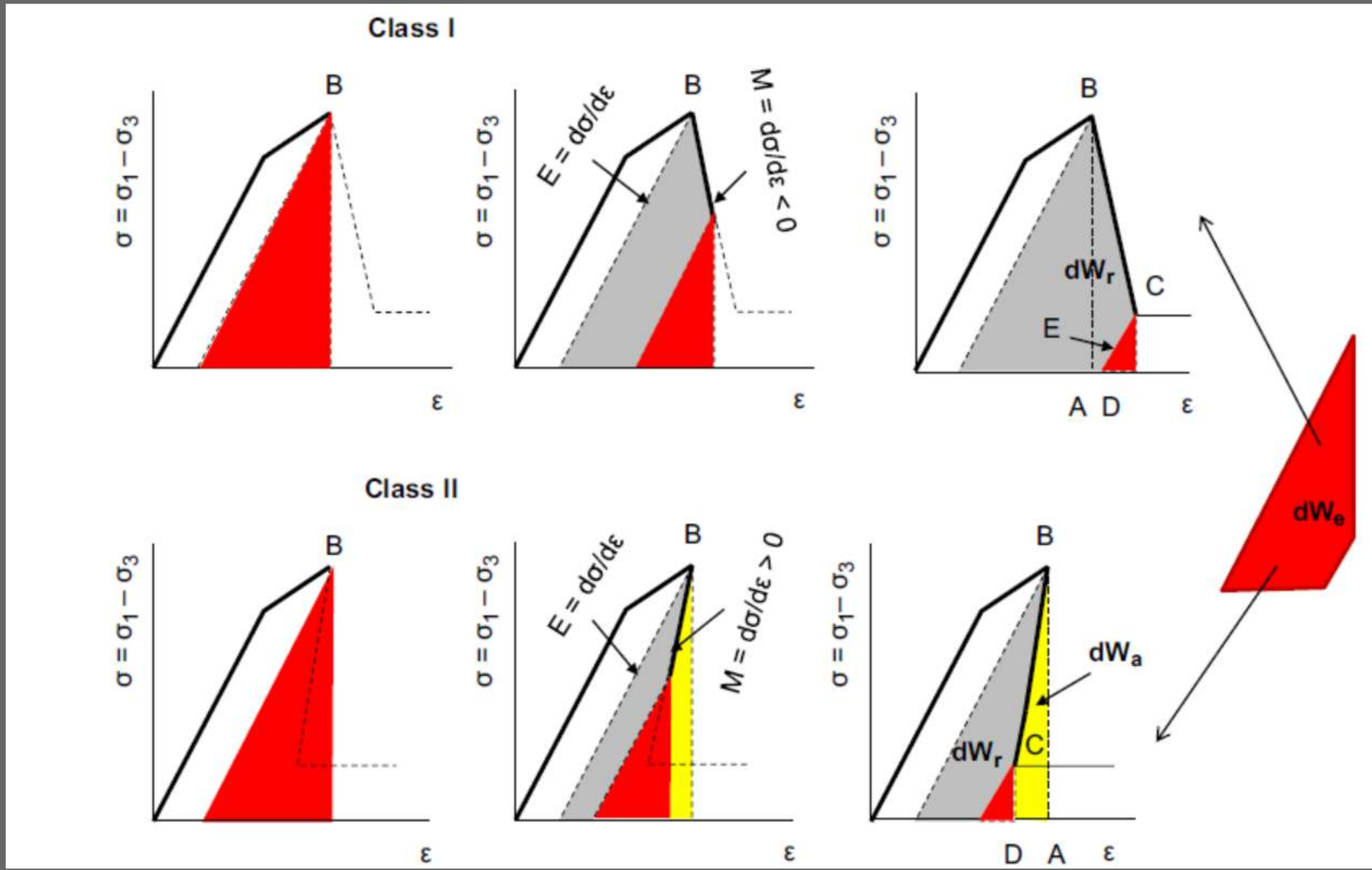
Strainburst Susceptibility - Rock mass quality - Intrinsic brittleness*	- Failure (brittle)
Strainburst Potential (SBP) + High tangential stress	- Stress concentration - Deconfinement
Strainburst Severity (SBS) - Burst volume - Relative brittleness* (→LSS) - Consumed energy at failure (→DP) - Volume increase (bulking)	- Energy storage - Rapid release - Volume
LSS=Loading System Stiffness (mine) DP =Deformation Potential *Tarasov and Potvin, 2013 [28] [1] modified	Rockburst mechanics components [9]

Brittle failure
Intrinsic Brittleness: →Elastic/Post-peak modulus ratio (E/M)



[29]

Gray area: rupture energy **dWr=post-peak rupture energy**
Red area: elastic energy **dWe=elastic energy withdrawn during post-peak**
Yellow area: excess energy **dWa=post-peak released energy**

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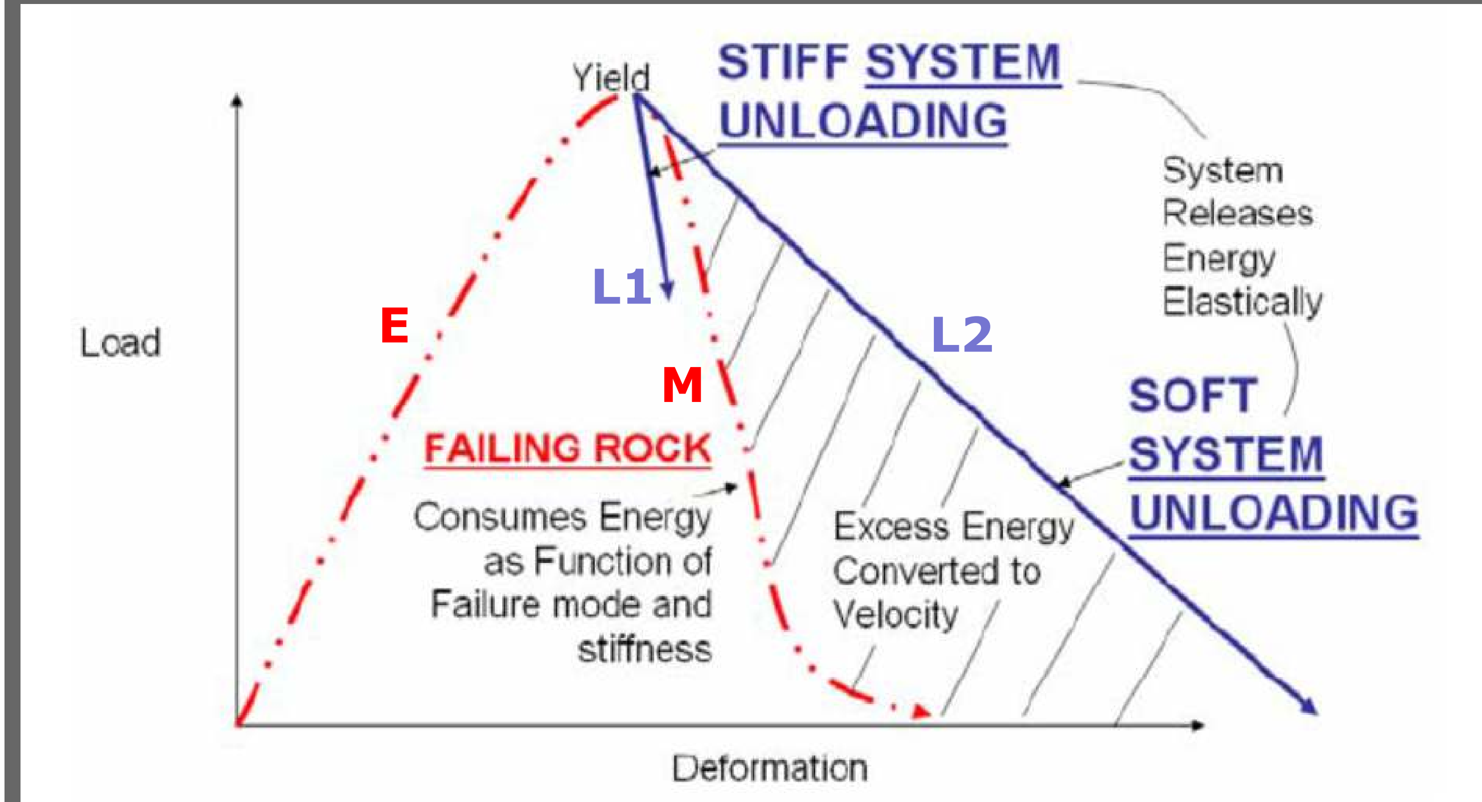
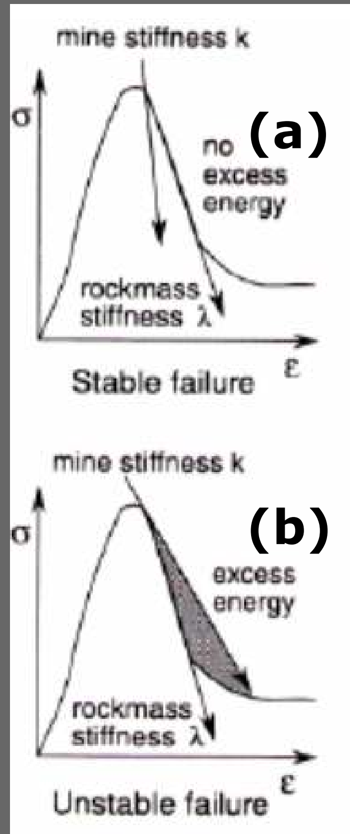
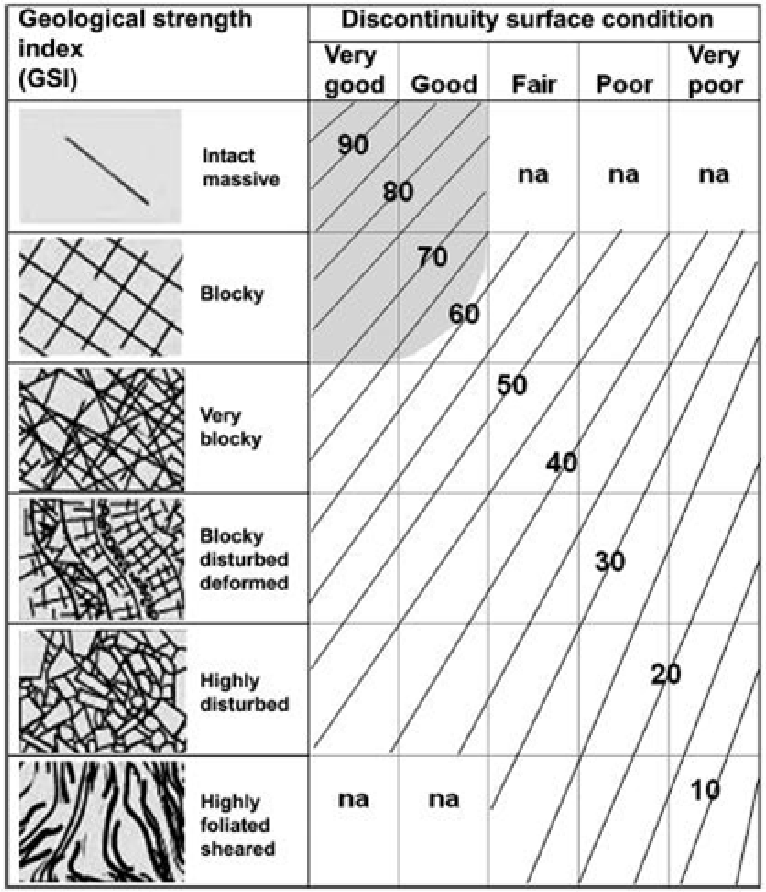
Brittle failure

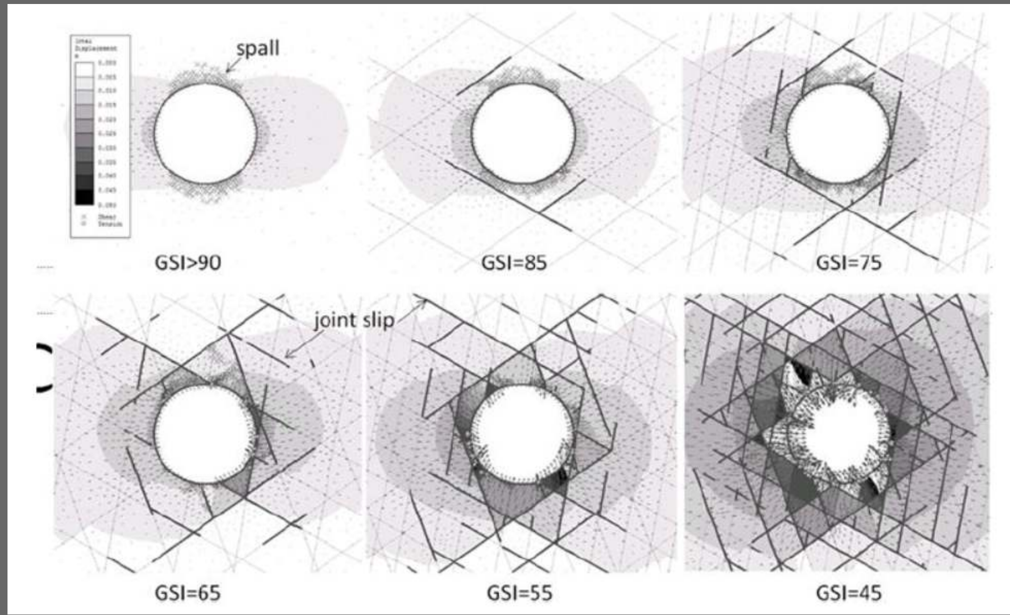
Relative Brittleness: → unloading rock (M) and system (L) modulus





The lower the LSS is or the softer the mine stiffness is, the higher is the energy input from the surrounding rock mass and then the Deformation Potential (DP)





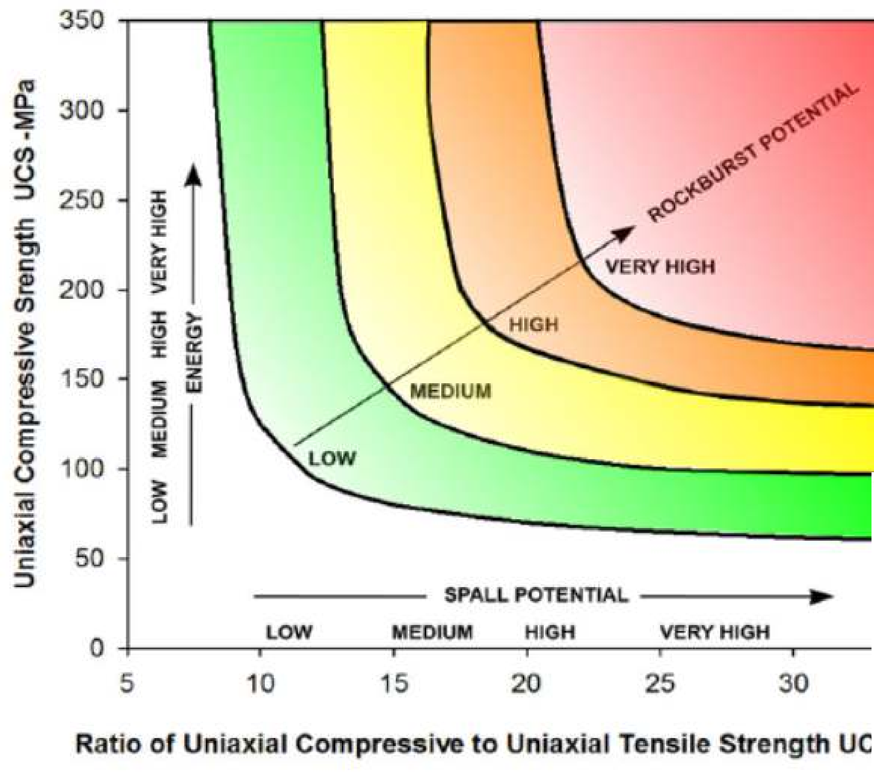
Guidelines for analysing rock failure as shearing or spalling based on GSI and the ratio of compressive to tensile strength (→strainburst susceptibility)

BI (Brittle Index)	GSI < 55	GSI = 55 to 65	GSI = 65 to 80	GSI > 80
UCS/T < 8	SHEAR	SHEAR	SHEAR	SHEAR
UCS/T = 9 to 15	SHEAR	SHEAR	SHEAR/SPALL	SPALL/SHEAR
UCS/T = 15 to 20	SHEAR	SHEAR/SPALL	SPALL/SHEAR	SPALL
UCS/T > 20	SHEAR	SHEAR/SPALL	SPALL	SPALL

[6]

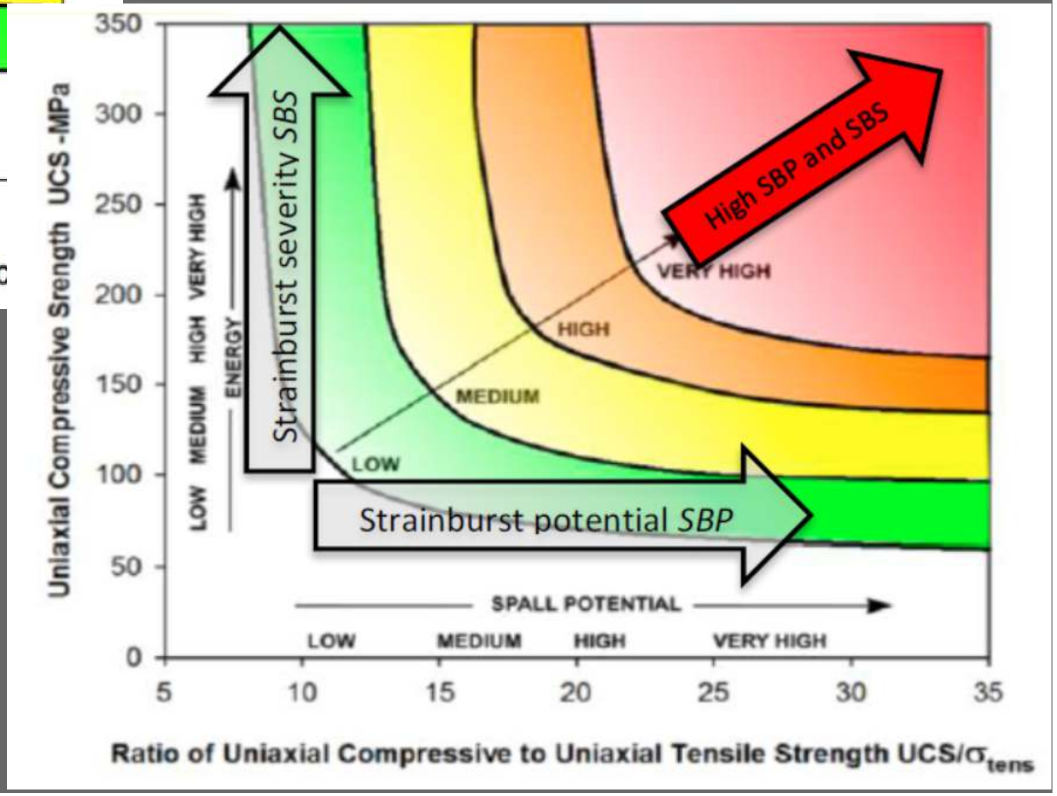
[6,9]

Rockburst failure mode potential indicator



Modification proposed by [1]
Rkb Potential and Severity
(only for stiff environment)

→



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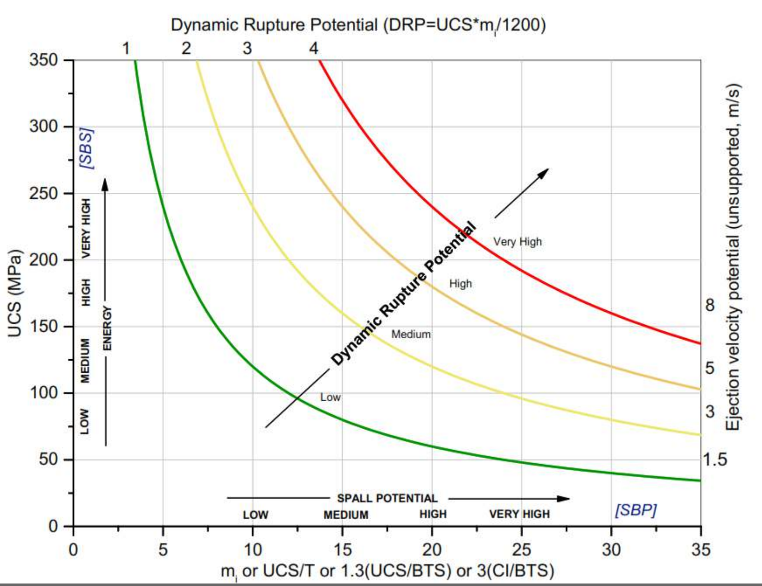
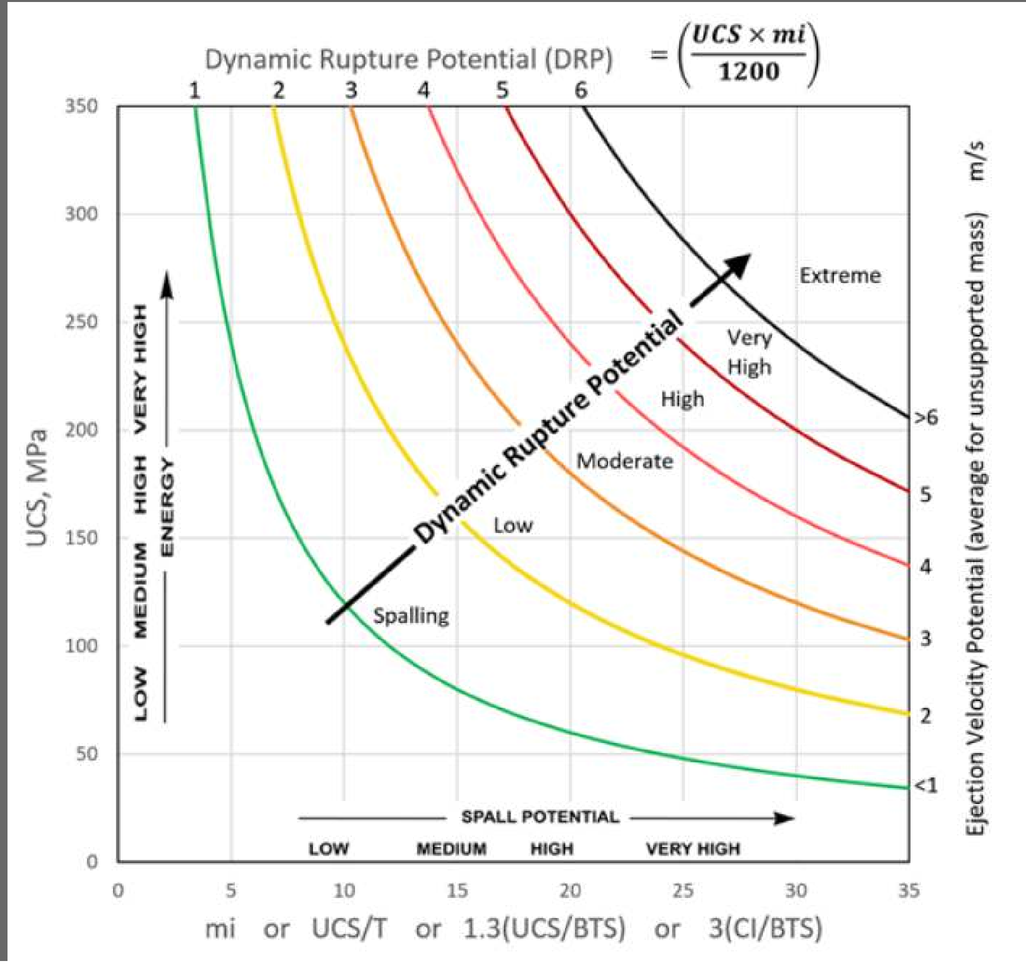


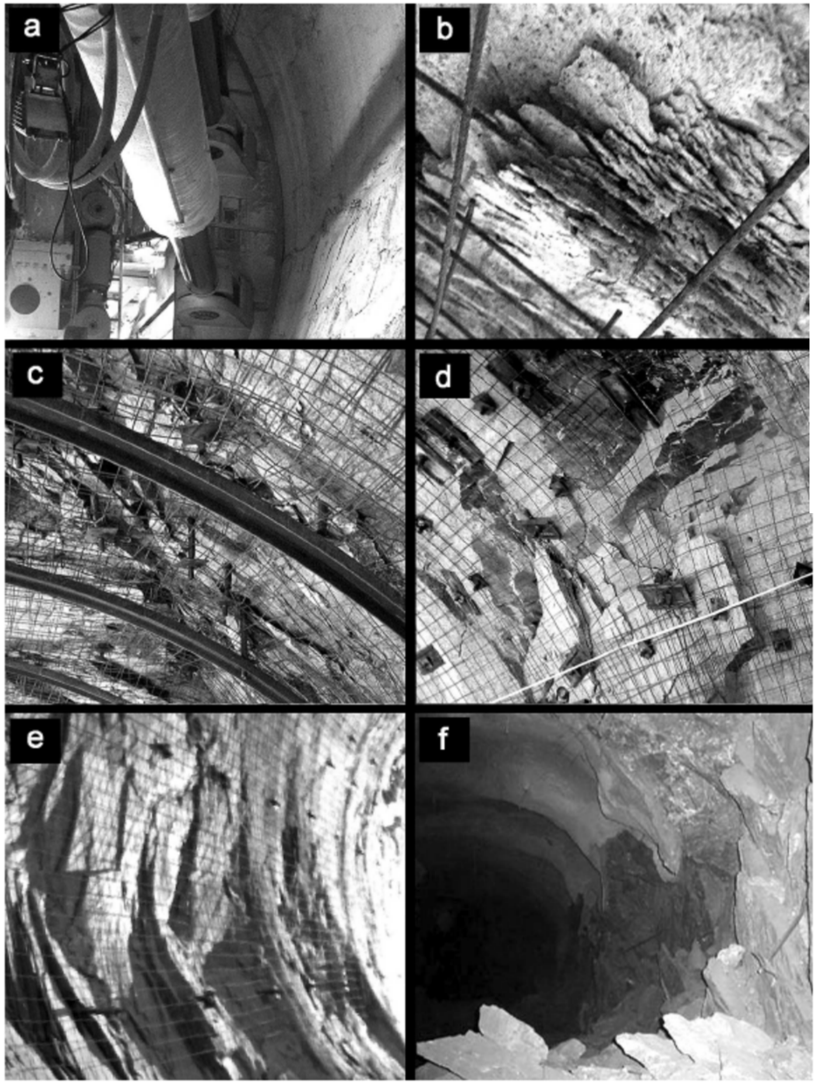
←Update version [10] and Proposed Ejection Velocity assessment [27]

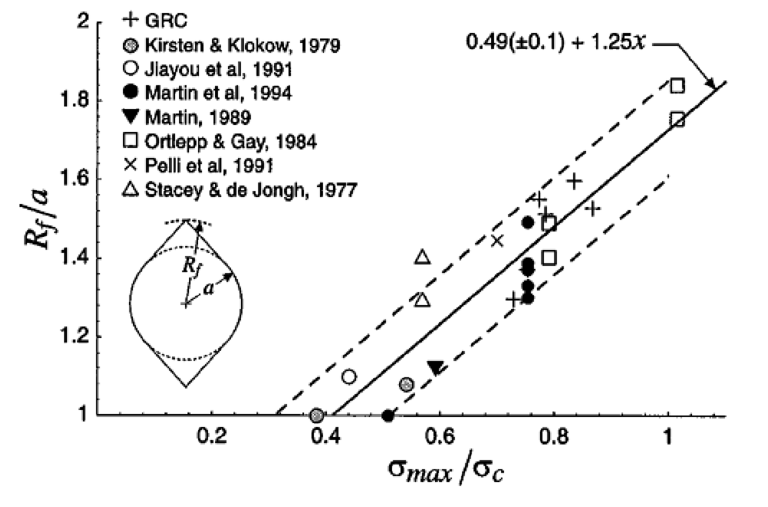
Published version Diederichs, 2017 [10] ↓



Futher evolution of the Rockburst failure mode potential indicator:

- **Definition of Dynamic Rupture Potential (DRP)**
- **DRP correlated to rock block Ejection Velocity potential**





Martin et al., 1999 [20]

The Depth of brittle failure is related to the

Damage Index (DI) or Stress Level (SL)

expressed by ratio

σ_{max}/UCS

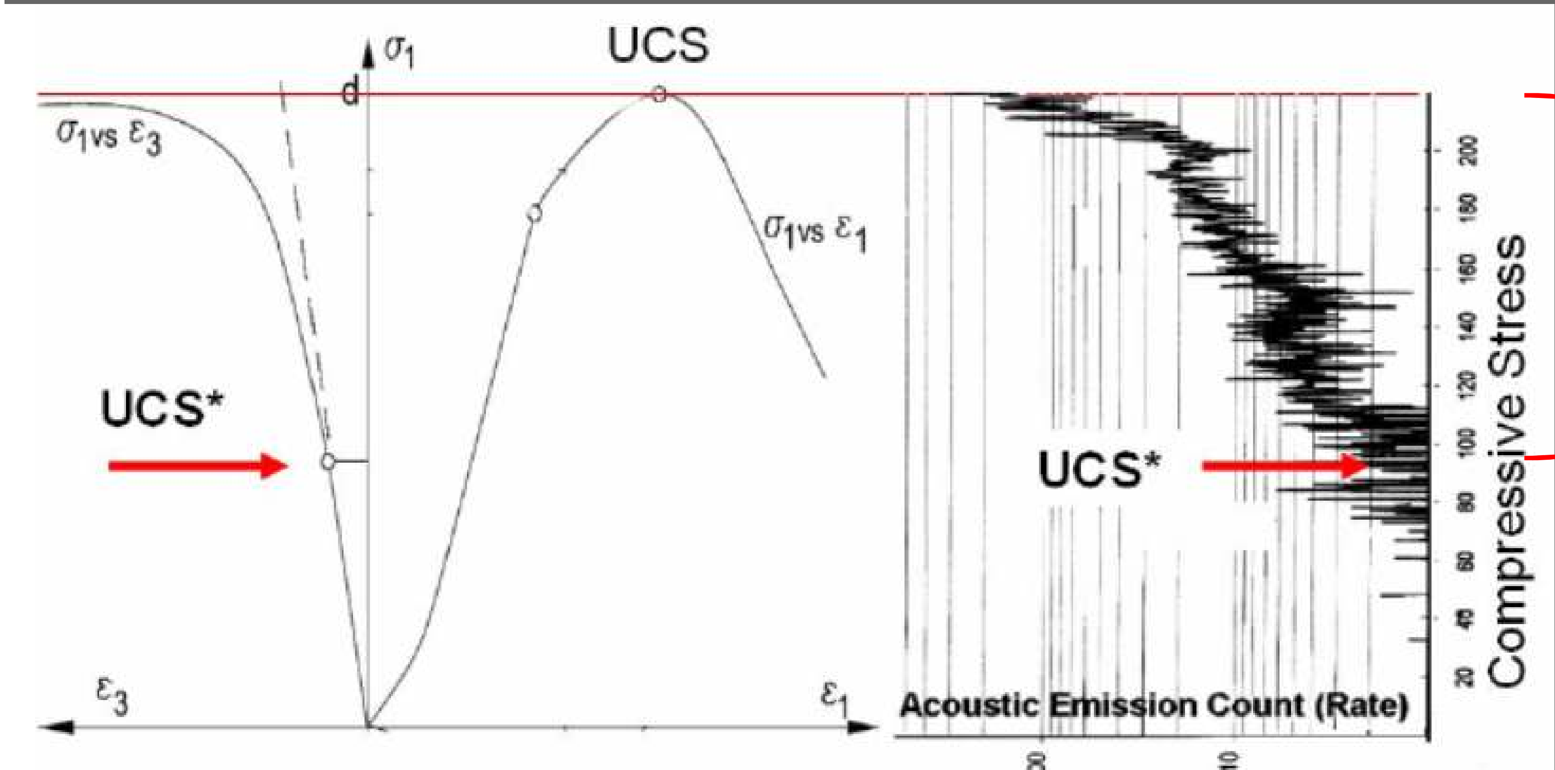
σ_{max}/CI

Crack Initiation Threshold (→CI=UCS*) occurs when

$\sigma_{max} \approx$ 0.4-0.6 UCS

a→f=increasing levels of spall damage

[7,8]



The higher the difference, the higher the stored energy and then the potential for violent failure

Damage initiation (UCS*=CI) is taken as the first significant and sustained increase in Acoustic Emission rate after the initial flurry of events associated with crack closure

[6]

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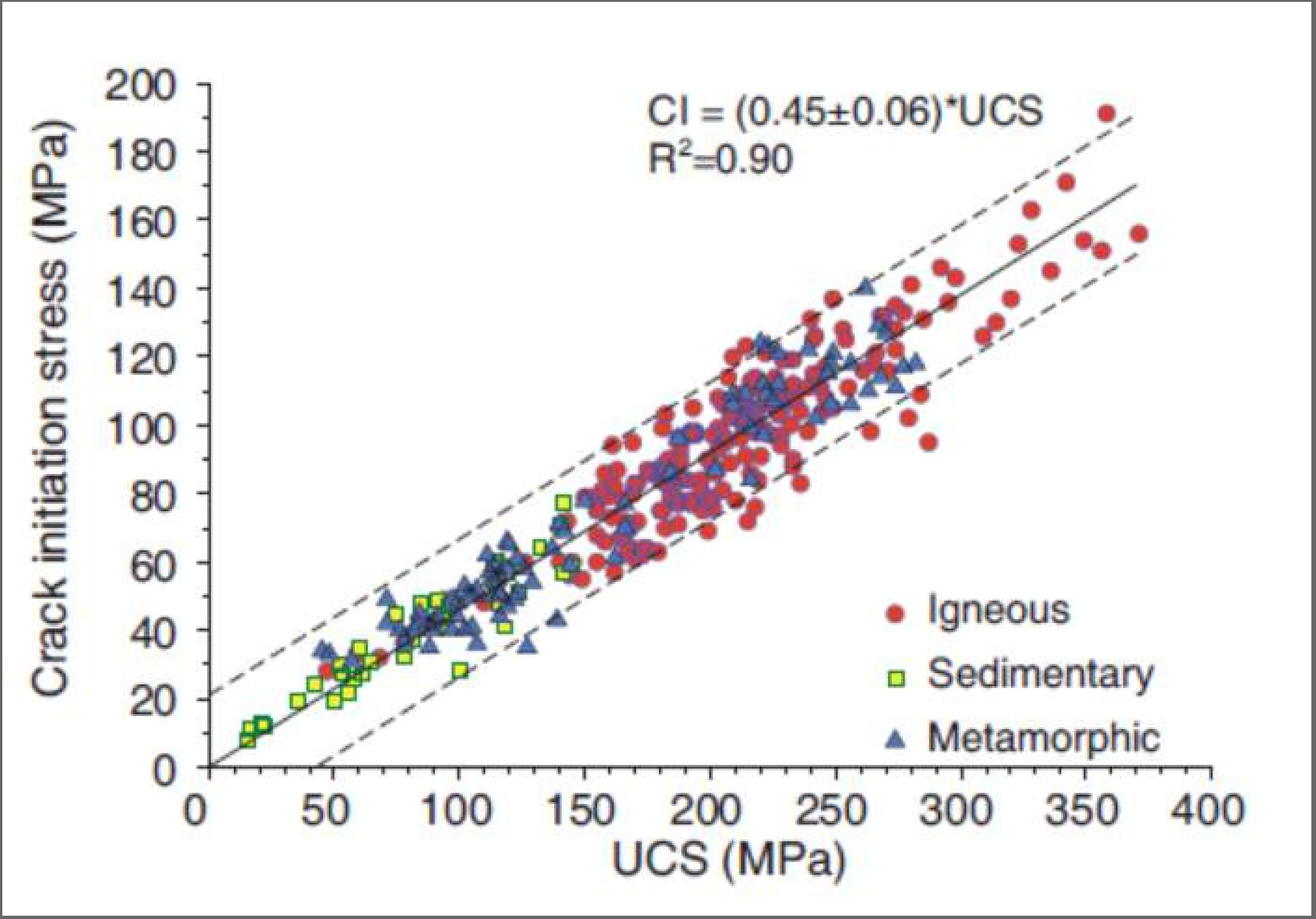
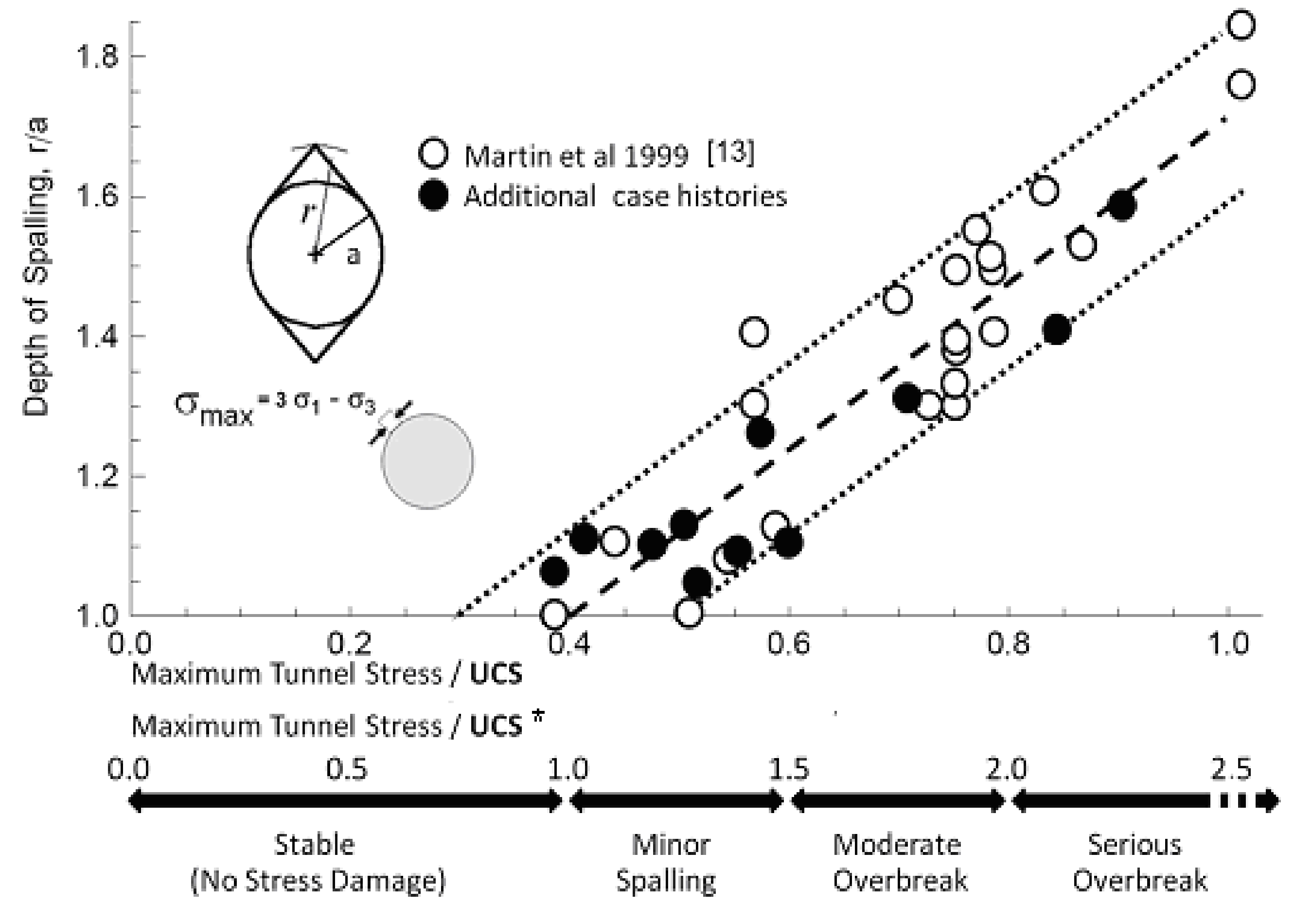


Relationship between UCS and CI for various rocks

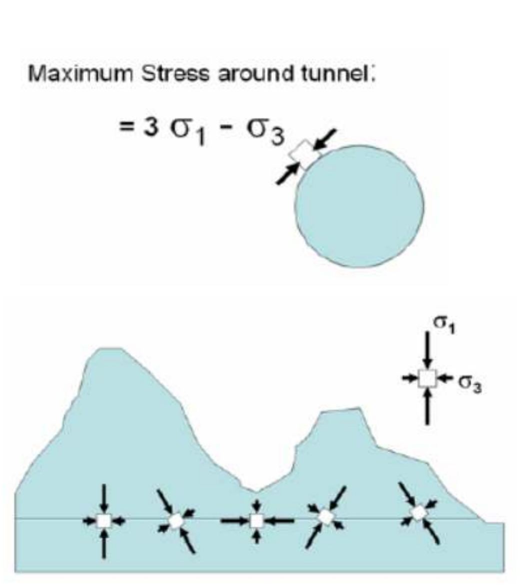
Nicksiar and Martin, 2013; modified by Hoek and Martin, 2014 [13]



$$\frac{r}{a} = 0.49 + 1.25\frac{\sigma_{max}}{UCS}$$

$$\frac{r}{a} = 0.5\left(\frac{\sigma_{max}}{CI} + 1\right)$$

$$for\ \sigma_{max} > CI$$



Empirical estimation tool for spalling depth

UCS* is the Crack Initiation threshold (CI)

[Moderate and Serious overbreak indicate strainburst potential]

[8]

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Moreover, it should be observed that estimation of Depth of Failure (DoF) refers to the maximum value and not to the medium value. zero d_f not plotted

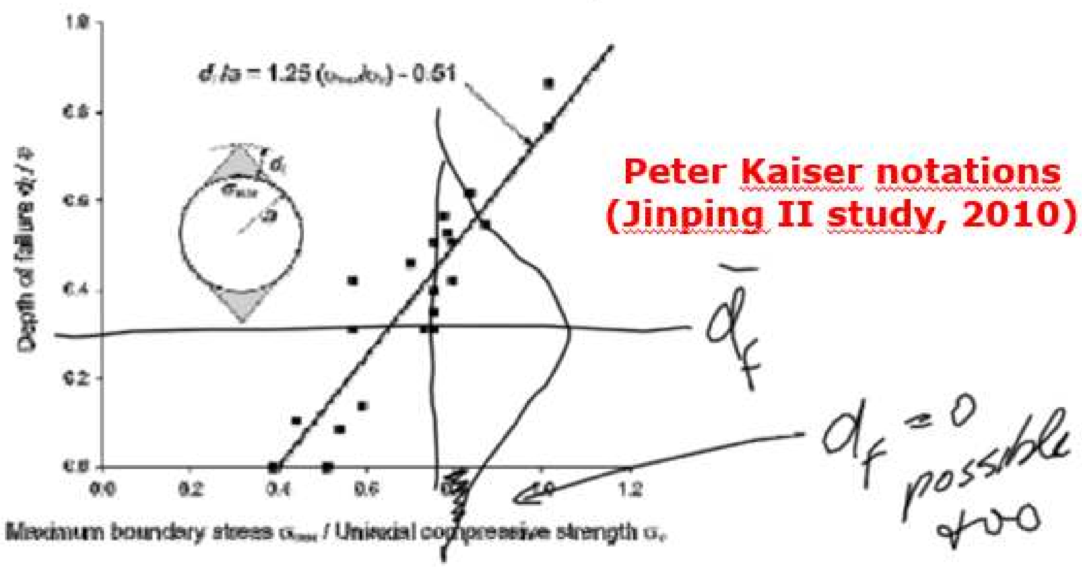

Figure 5: Empirical approach for DoF estimation (Martin et al, 1996).

Note that the Depth of Failures (DoF) reported in [20] refer mainly to no-violent events and max values for the stress levels (→high DoF does not necessary mean violent event with rock ejection).

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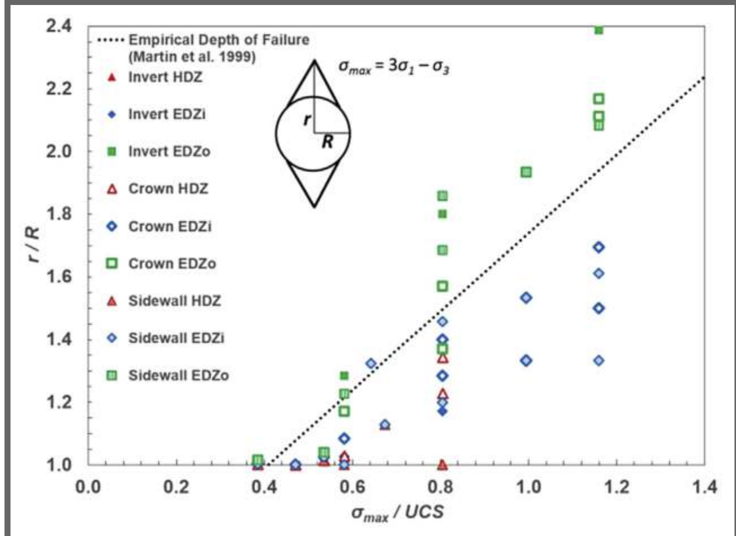
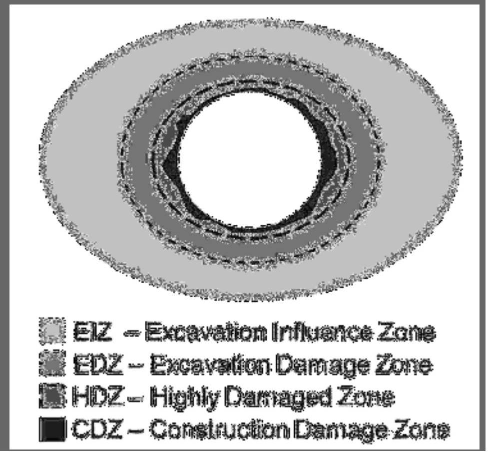
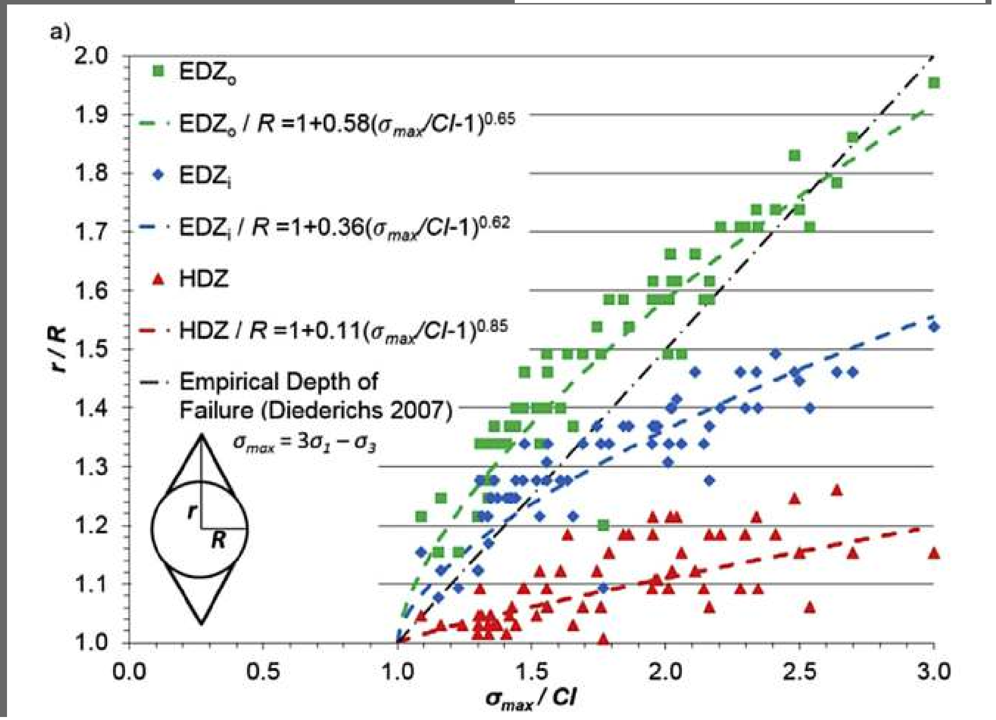
DoF line should coincide with the Inner Excavation Damage Zone EDZi (connected micro-fractures →visible damage)



←In situ-measurements of EDZ depths compared with Martin et al. equation for DoF.





Calculation example of damage zones for granitic rock.
Note that EDZi over-predict DoF for about σmax/CI>1.5.
EDZi is assumed to coincide with the Volumetric Strain Reversal.

Perras and Diederichs, 2016 [22]

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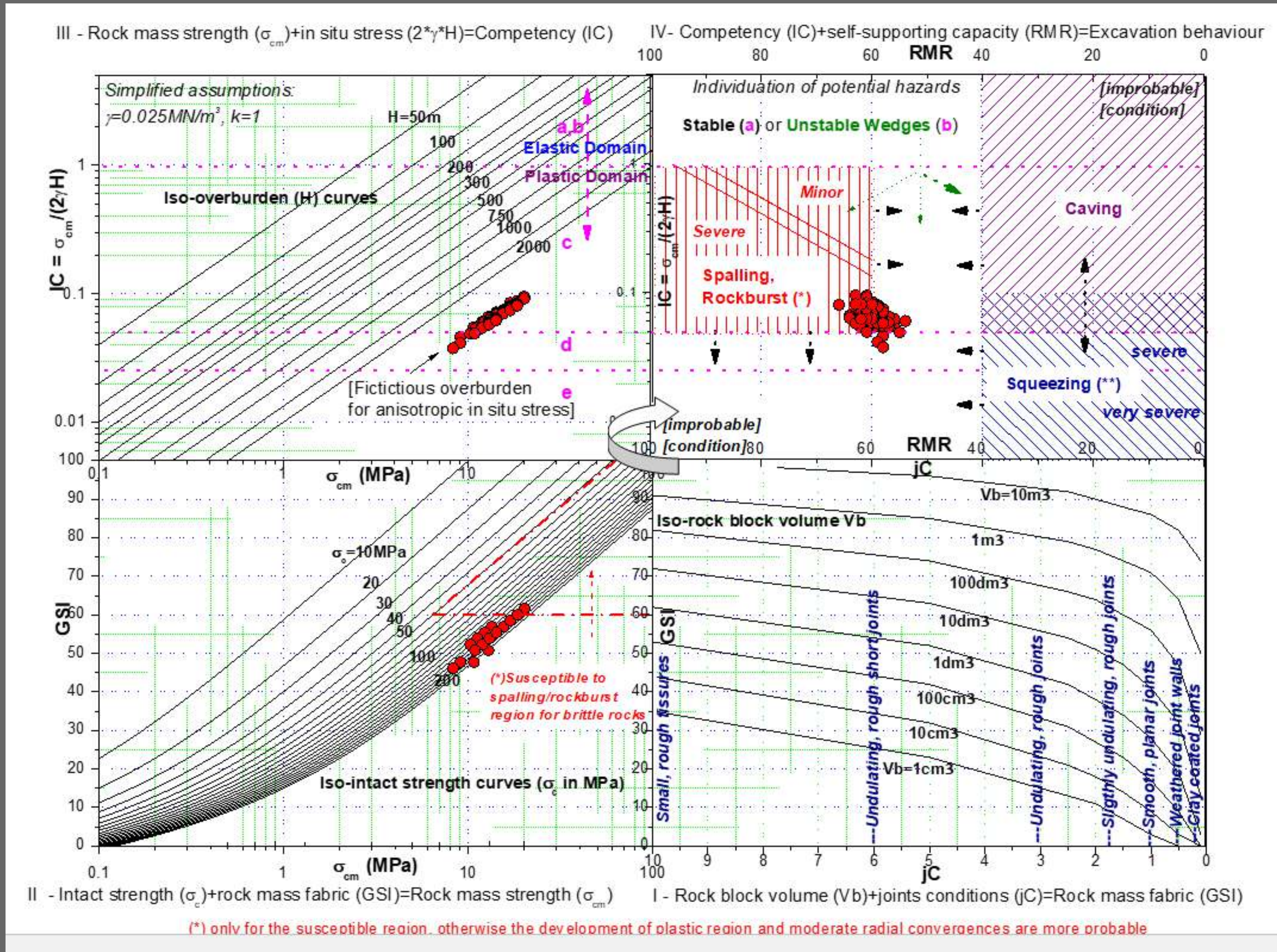

The same classification for spalling depth is applied in the GDE multiple graph

Russo, 2014 [26]

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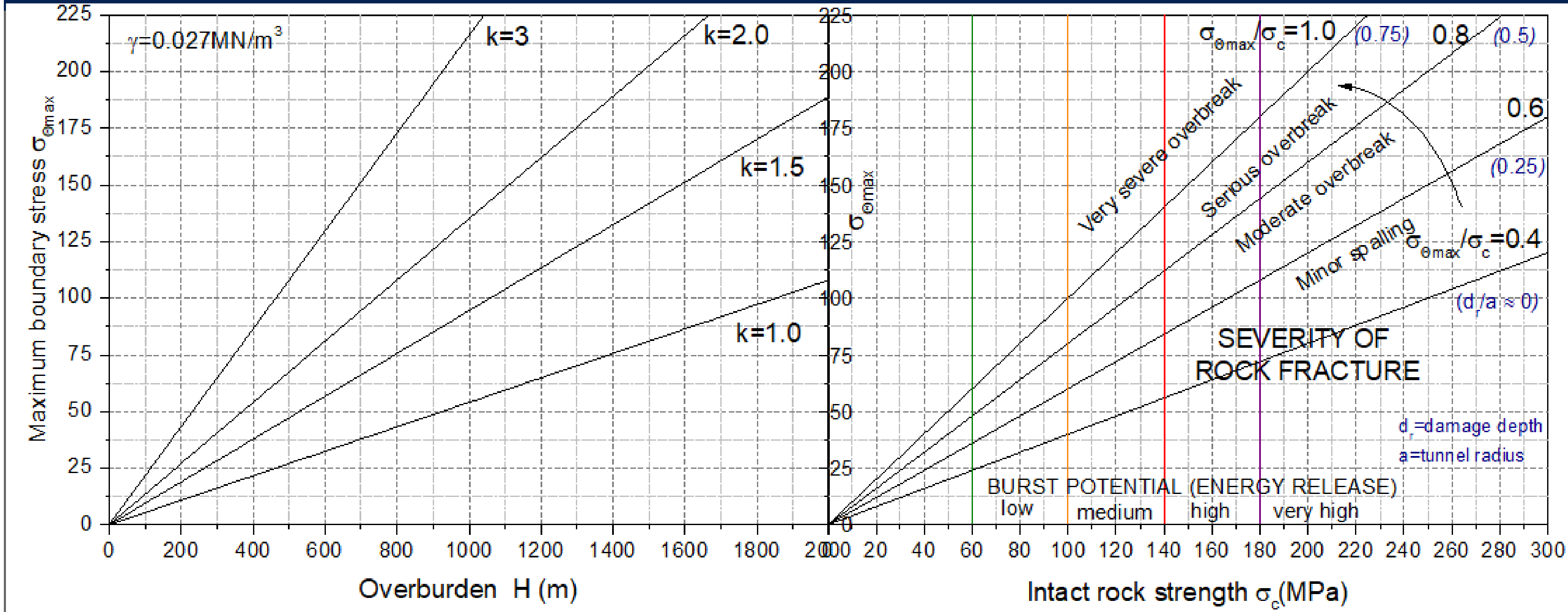
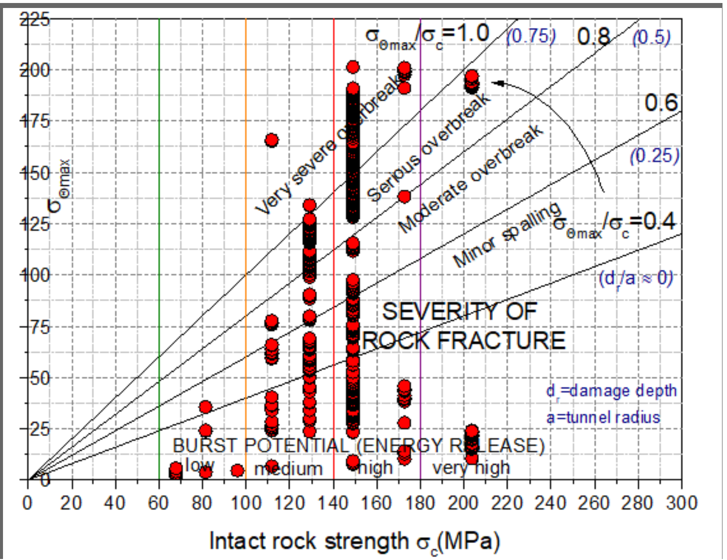


Chart for assessment of the severity of brittle rock failure [27]

Example of application



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Another example: The classification limits are a little different

Hoek, 2010 [12]

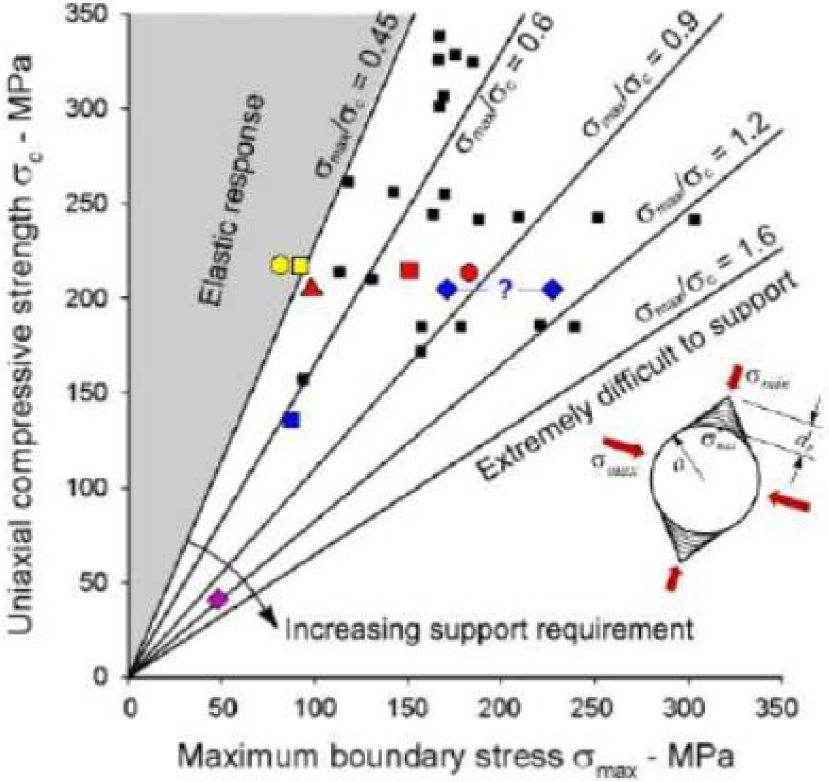
$\sigma_{max}/\sigma_c < 0.45$ $d_f/a = 0$
No spalling, stable - no support required

$\sigma_{max}/\sigma_c = 0.6$ $d_f/a \cong 0.25$
Minor spalling - spot rockbolts and mesh

$\sigma_{max}/\sigma_c = 0.9$ $d_f/a \cong 0.60$
Moderate spalling - pattern rockbolts and mesh and, in some cases, straps

$\sigma_{max}/\sigma_c = 1.2$ $d_f/a \cong 1.0$
Severe spalling - steel sets with rockbolts and mesh usually required

$\sigma_{max}/\sigma_c = 1.6$ $d_f/a \cong 1.5$
Stability of opening may be difficult to achieve - extreme support measures required



Legend:

- South African deep level mines
- AECL URL 240 level, Canada - Stable
- SKB Aspo tunnel, Sweden - Stable
- AECL URL 420 level, Canada - Moderate spalling
- SKB Aspo pillar, Sweden - Minor spalling
- Lötschberg tunnel, Switzerland - Moderate spalling
- Niagara Falls tunnel, Canada - Significant spalling
- Olmos tunnel, Peru - Severe spalling
- Gotthard tunnel, Switzerland - Minor spalling

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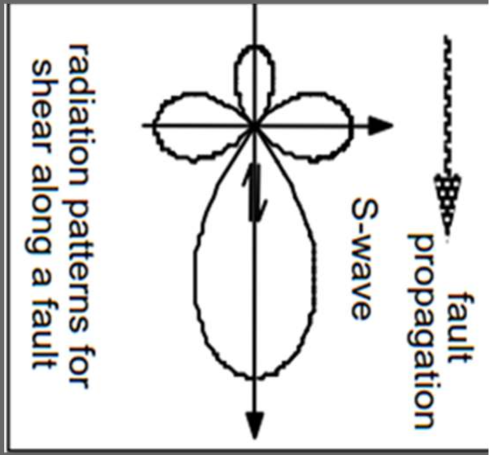
Dynamic ground stress → increase of DoF

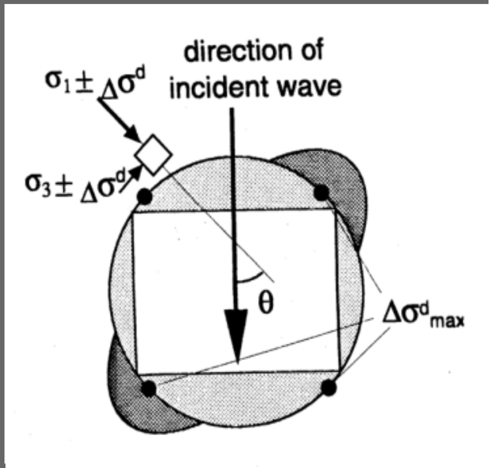
As remarked, a seismic event or blast may add an increment of dynamic stress that may trigger strainburst or increase the depth of stress fractured ground.

The dynamic stress pulse of the shear wave modifies principal stresses



$$\Delta\sigma_1^d = +\rho * ppv_s * Vs \text{ and } \Delta\sigma_3^d = -\rho * ppv_s * Vs$$

The max resulting tangential stress variation on circular excavation contour oscillates at each pulse



$$\Delta\sigma_{max} = \pm 4\rho * ppv_s * Vs$$

ρ = rock mass density

ppv_s (or PGV_s) = Peak particle (or Ground) Velocity of shear waves

Vs = shear waves propagation velocity

[3] Refer also to [1, 20] for Seismic source characteristics, Ground motion velocity/acceleration, etc.

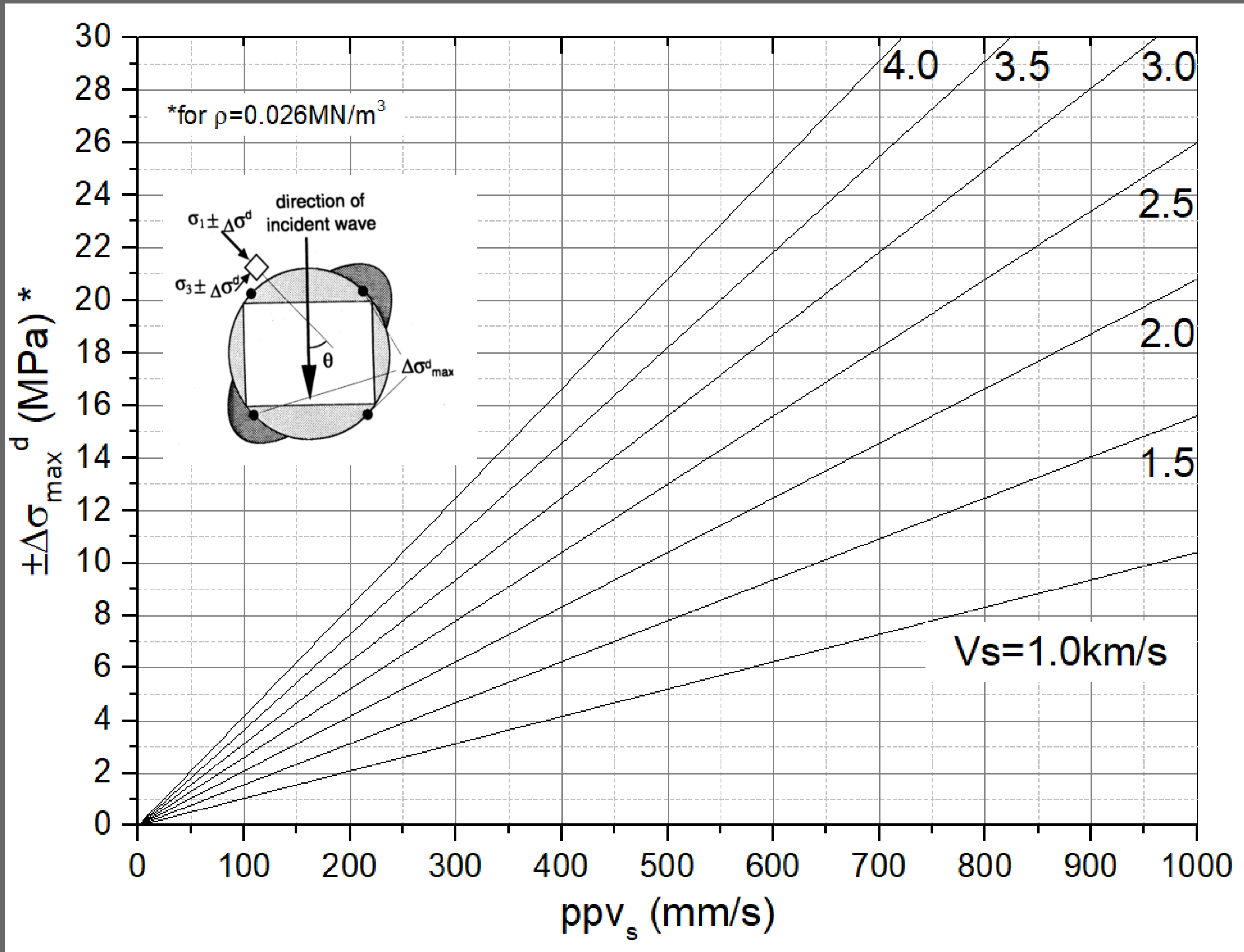


Chart for assessment of tangential stress variation for different ppv$_s$ and V$_s$ [27]

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Depth of Failure (d_f=DOF) increase for Dynamic ground stress

C1 for dynamic depth of failure determination; $C2 = SL_o C_1$ (Kaiser, 2006)

ppv [m/s]	C_1	Mean SL_o for $d_f = 0$
static	1.37	0.42
0.5	1.54 - 1.74	0.35
1	1.79 - 2.08	0.29
2	2.17 - 2.86	0.23
3	2.63 - 3.64	0.18

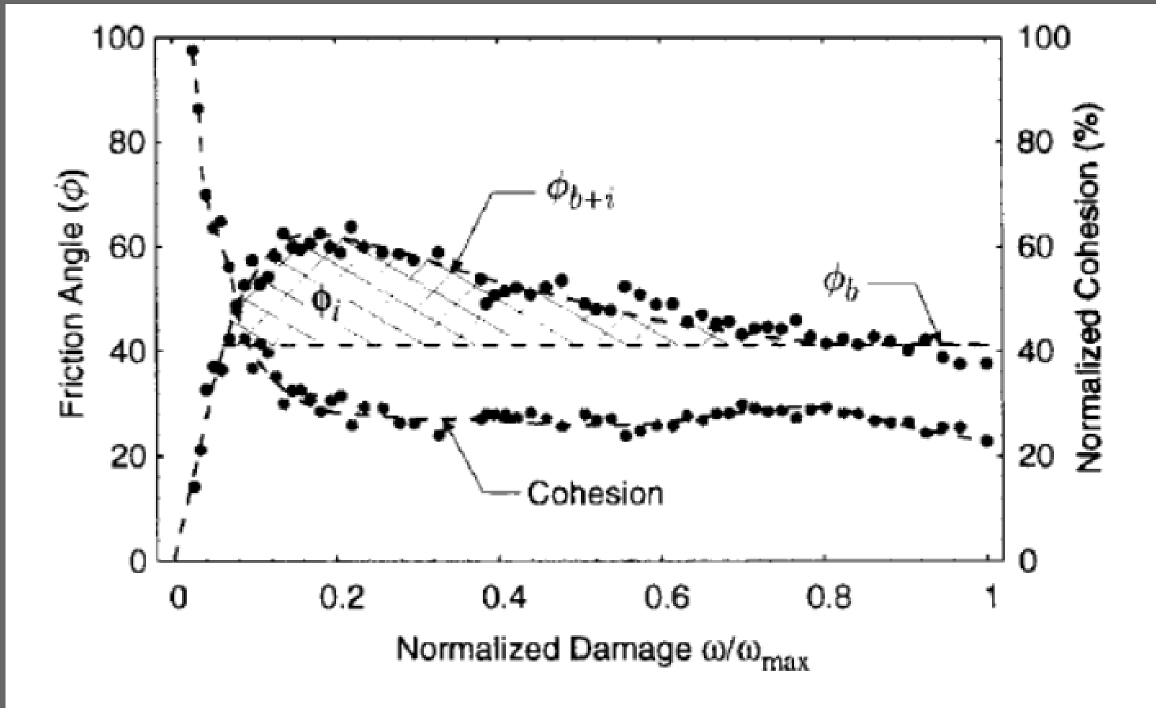
$$d_f/a = C1(\sigma_{max}/\sigma_c) - C2 = C1*SL - C2$$

For static condition on average C1=1.37 and C2=0.57 [15]

$$d_f/a = 1.37(\sigma_{max}/\sigma_c) - 0.57$$

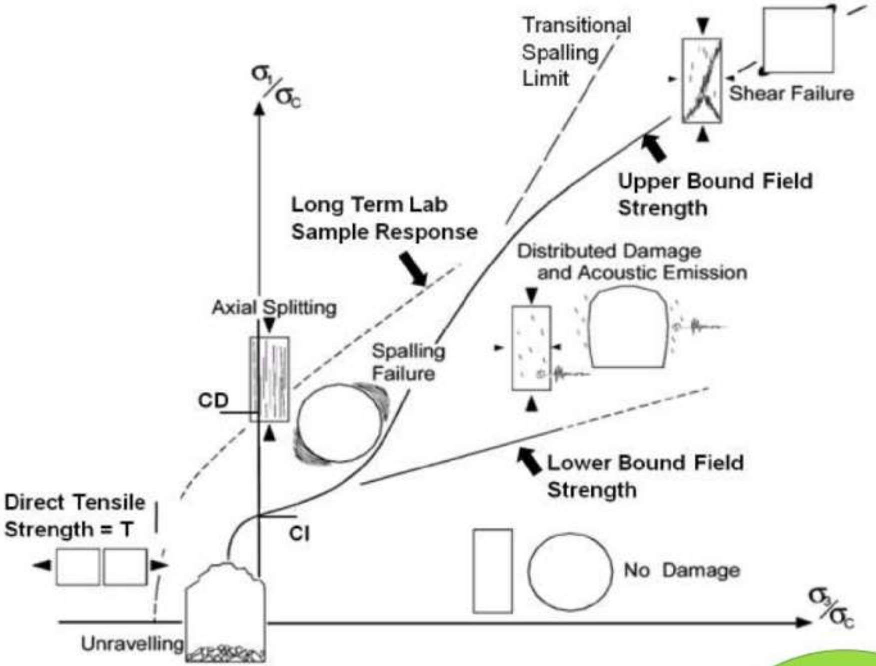
(SL=Stress Level=Damage Index)

Constitutive models for brittle yield simulation
Mohr-Coulomb "error"



In brittle rock the mobilization of the cohesive and frictional component is strain dependent. Cohesion mobilizes before than friction angle [ϕ_b and ϕ_i are residual and interlocking (dilation) component]→ "m=0 approach"

Martin, 1997 [19]



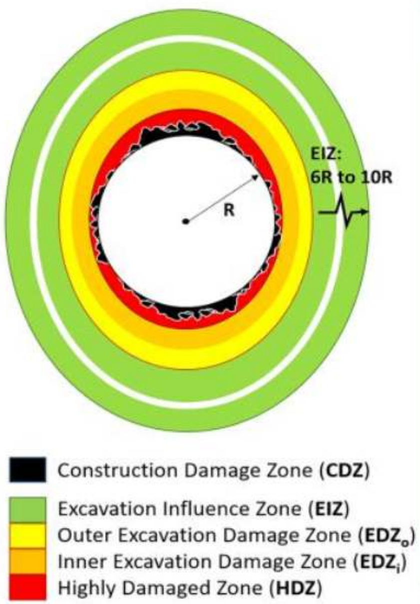
The composite strength envelope illustrating in principal stress space the zones of behaviour as bounded by the damage initiation threshold, the upper bound shear threshold (damage interaction), and the transitional spalling limit

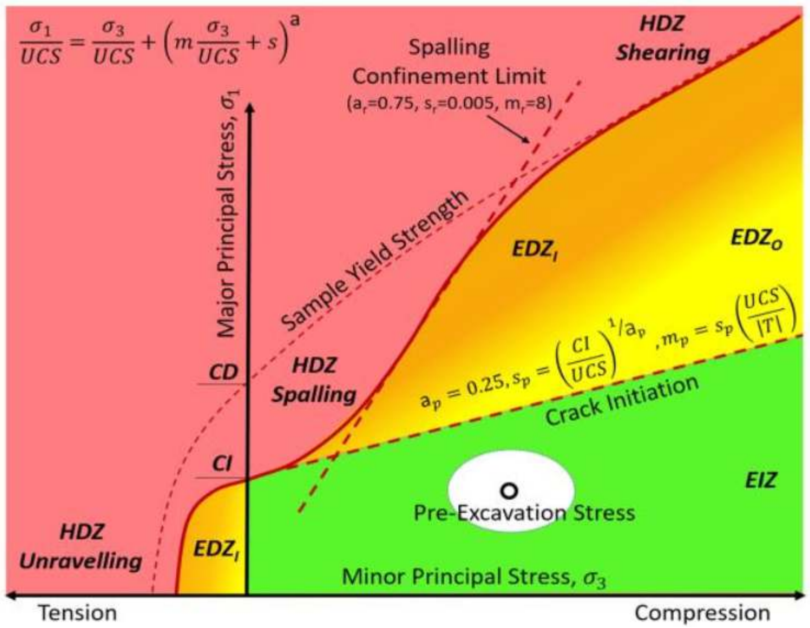
CI= Crack Damage Initiation threshold (usually 0.4÷0.6UCS)

transition→Spalling Limit Ratio
SLR = $\sigma1/\sigma3 \approx 10 \div 15$ or more

CD= Crack Damage Interaction threshold (usually 0.7÷0.9UCS)

[5, 10]





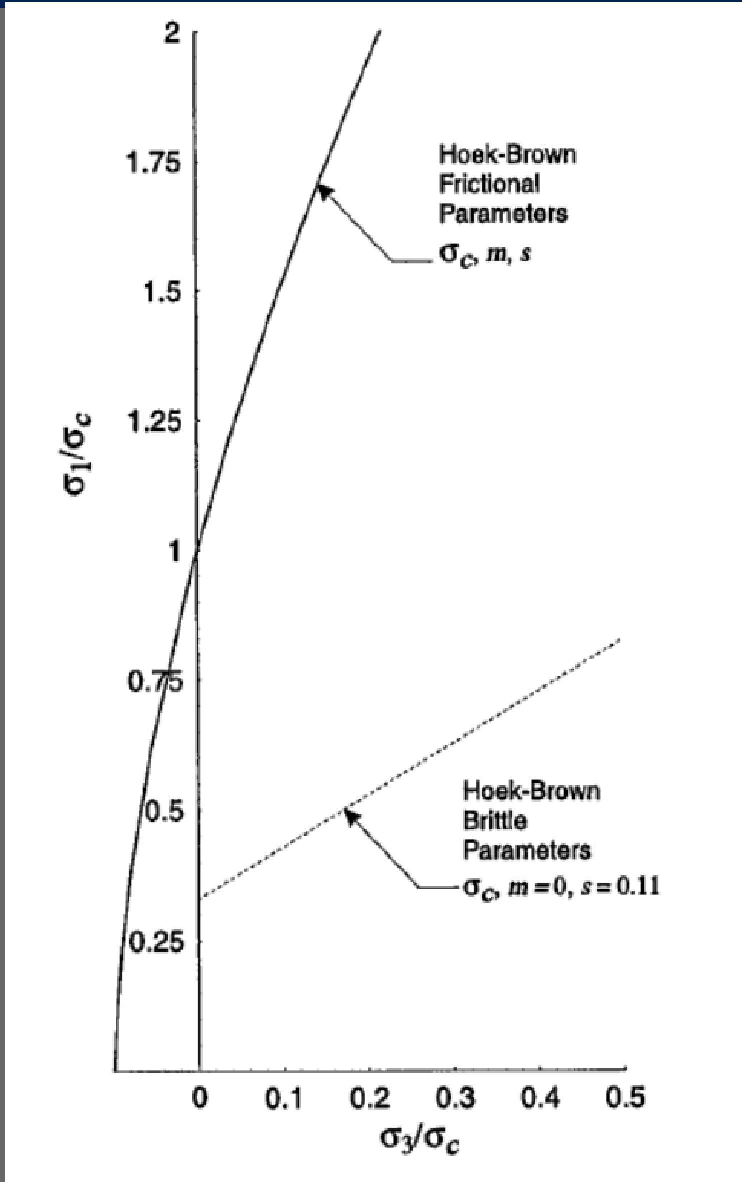
Numerical modelling: Elastic analysis: "m=0" approach

Simulation of brittle spalling behaviour by Hoek and Brown failure criterion
Hoek et al., 2002 [11]

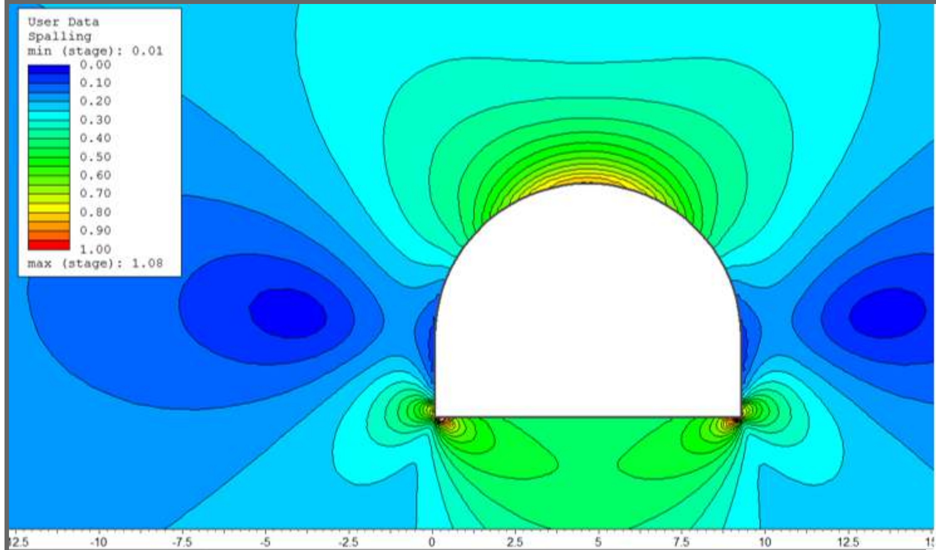
$$\sigma'_1 = \sigma'_3 + \sigma_c\left(m\frac{\sigma'_3}{\sigma_c} + s\right)^a$$

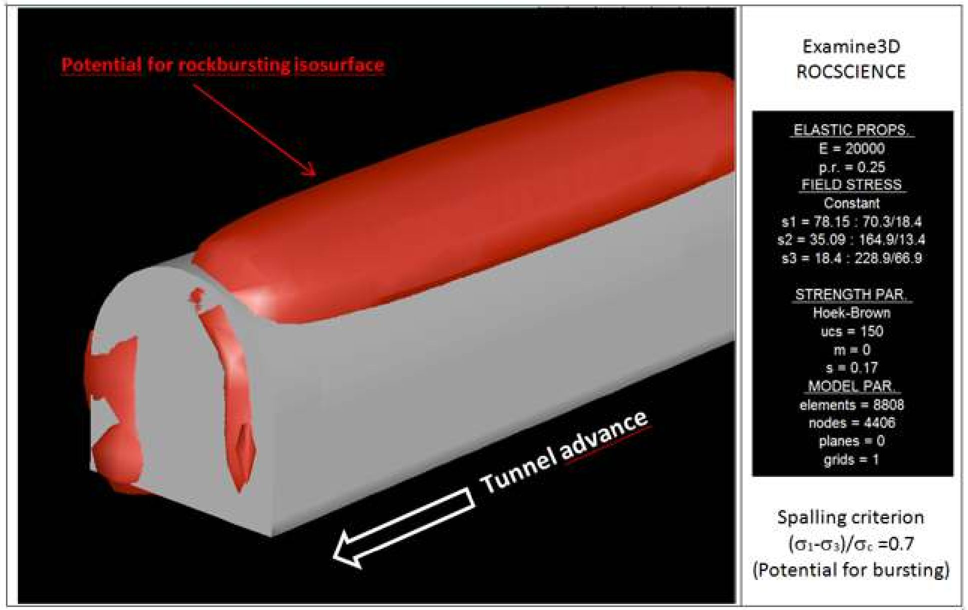
Hoek-Brown constants:
m=0
a=0.5
$s^{0.5}$=0.33 → s=0.11
($s^{0.5}$=0.41→ s=0.17 for Kaiser, 2016 [18]

$$\sigma_1 = \sigma_3 + \sqrt{s\sigma_c^2}$$

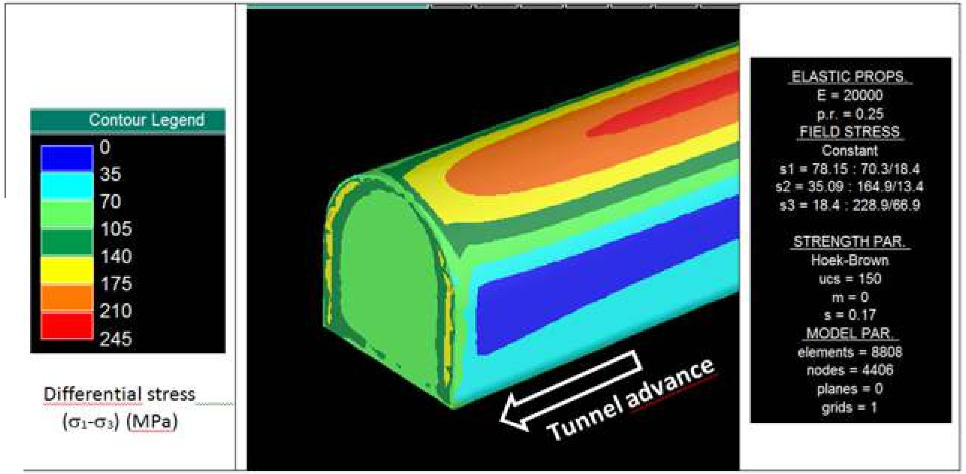


[20]





Examples of 2D-3D elastic (m=0 type) analyses by Rs2 and Examine3D (Rocscience): Differential stress and Spalling Criterion



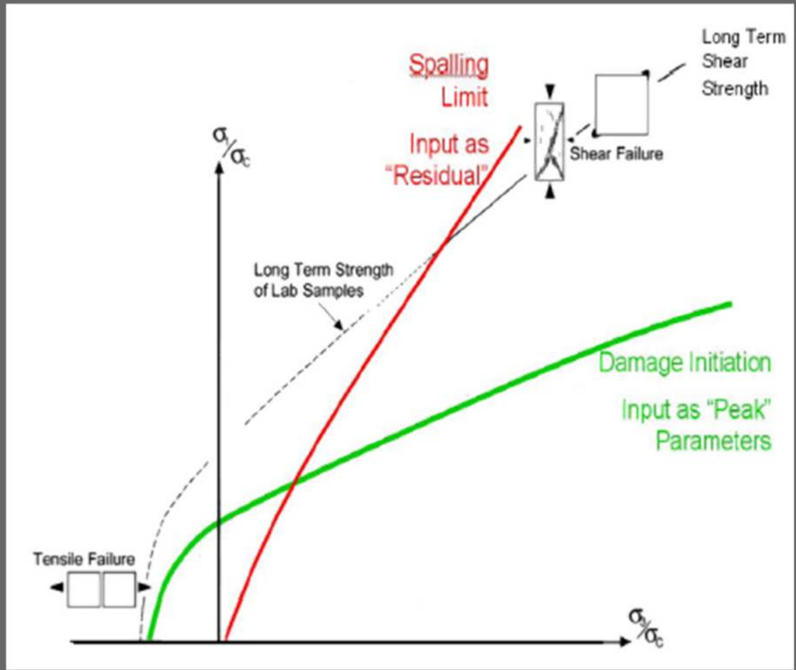
The **Spalling Criterion** (Castro et al, 1995, 1997) is given by:

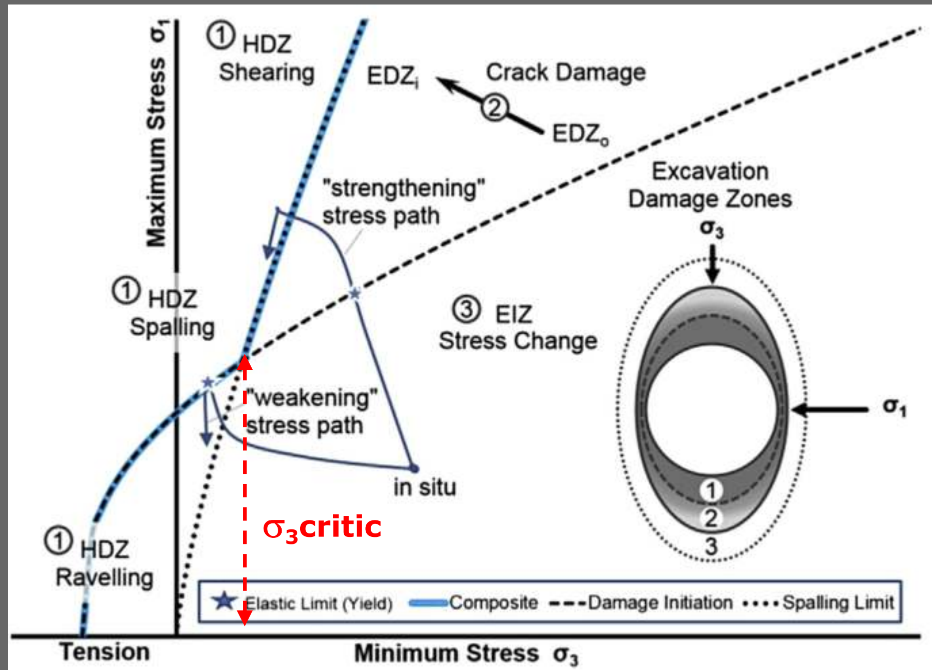
$$\frac{\sigma_1 - \sigma_3}{UCS}$$

As a general guideline, spalling criterion values of:

- 0.4 indicate damage initiation, beginning of fracturing
- 0.7 potential for rockburst (in particular strainburst) to occur

Numerical modelling: Elastic-plastic analysis
DISL (Damage Initiation Spalling Limit)





Simulation of brittle spalling behaviour by Hoek and Brown failure criterion [11]

Modelling method	Peak		Residual	
	Input parameter	Value/equation	Input parameter	Value/equation
DISL	a_p	0.25	a_r	0.75
	s_p	$\left(\frac{CI}{UCS}\right)^{1/a_p}$	s_r	0.001
p=peak r=residual	m_p	$s_p\left(\frac{UCS}{\lvert T \rvert}\right)$	m_r	6–12

$$\sigma'_1 = \sigma'_3 + \sigma_c\left(m\frac{\sigma'_3}{\sigma_c} + s\right)^a$$

[7, 22]

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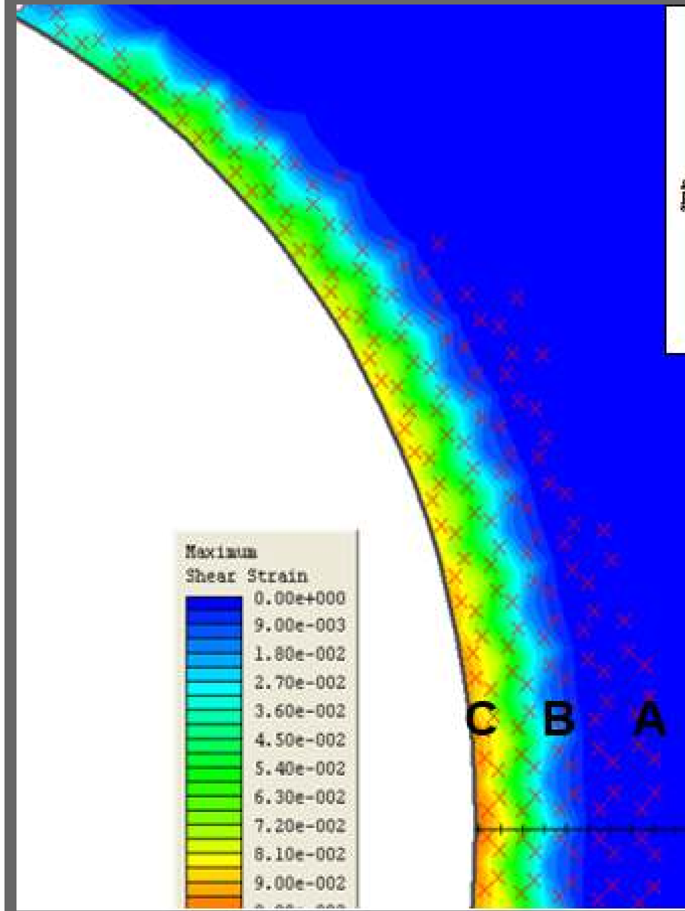
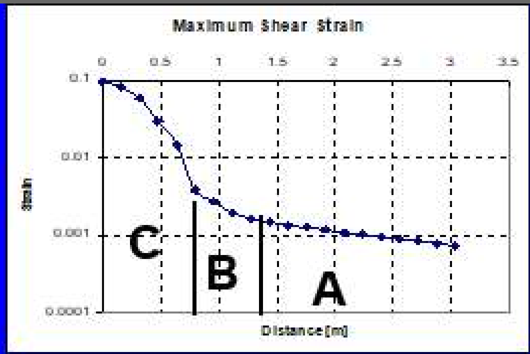


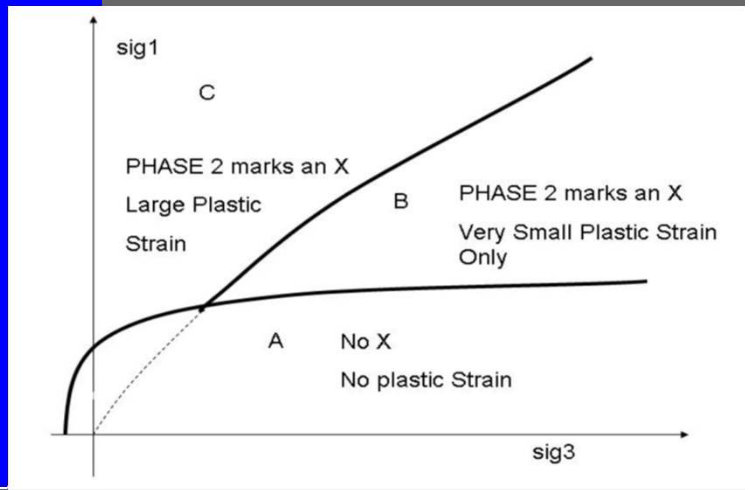


A = Elastic

B=Damaged (*"Yielded" in Phase2)*

C=Yielding and Failing

Note: B can fail if C is completely removed



Example of DISL application with distinction of damaged and yielding zone as a function of Maximum Shear Strain (PHASE 2=Rs2 Rocscience)

[6]

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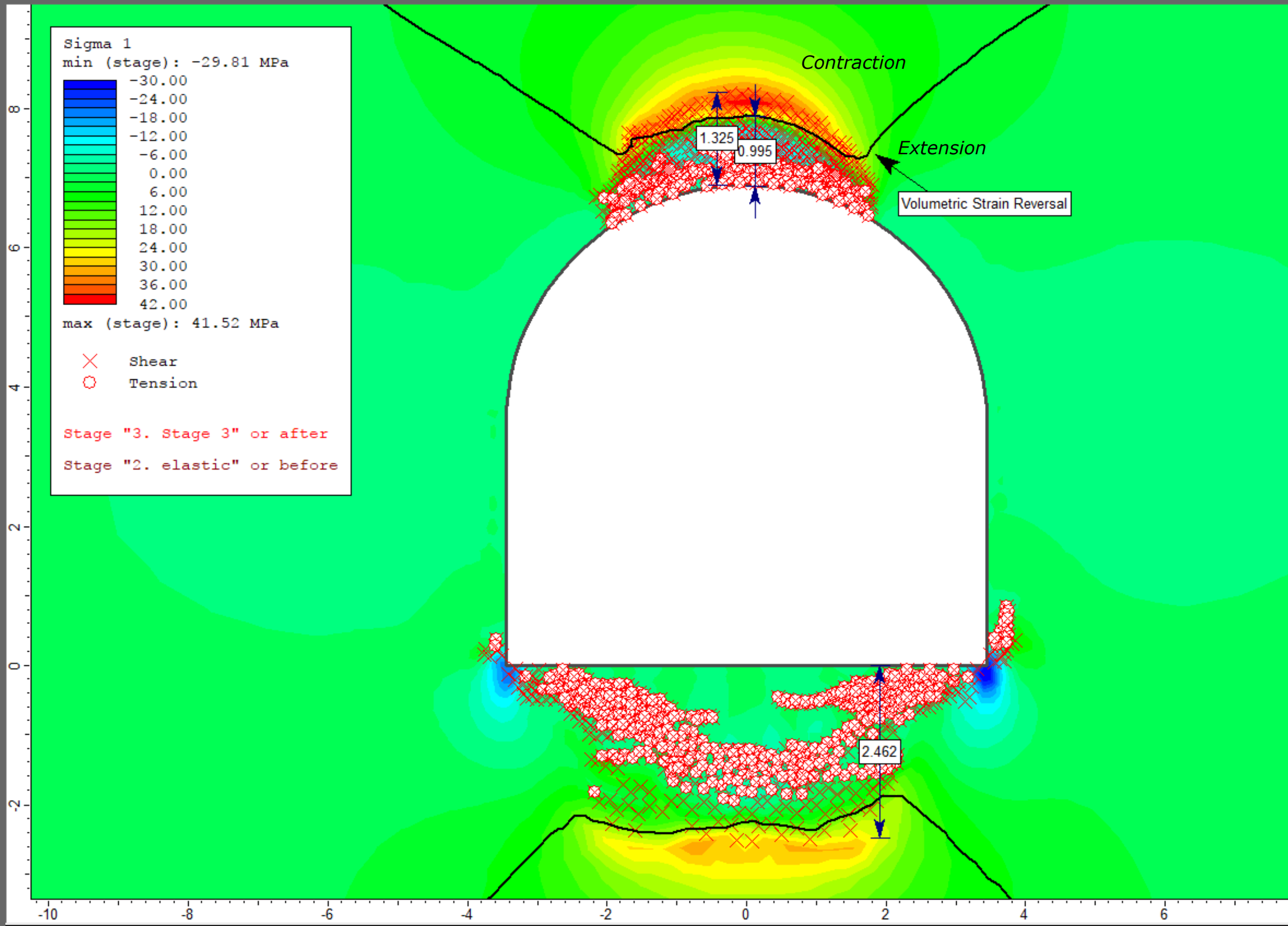

Example of DISL application in severe rockburst environment with indications of Yielding zone and Volumetric Strain Reversal (referable to Depth of Failure of Martin et al., 1999).

Case 1: equivalent-continuum modelling by Rs2 (Rocscience)

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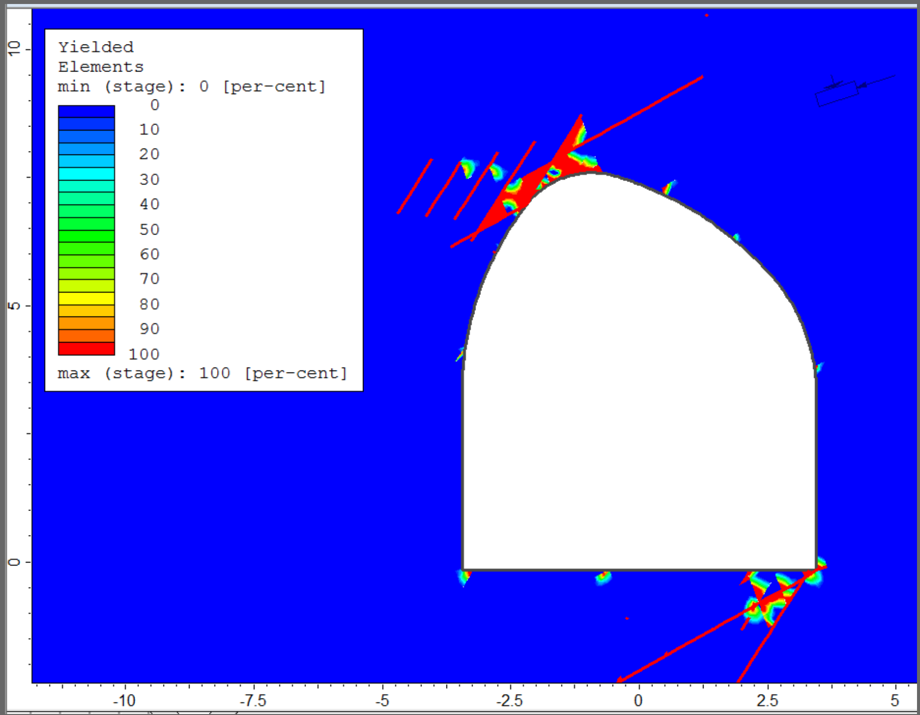

Example of DISL application in severe rockburst environment

Case 2: joint network modelling by Rs2

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Strain Energy

In terms of principal stresses the Strain Energy Density (SED) is calculated by the formula:

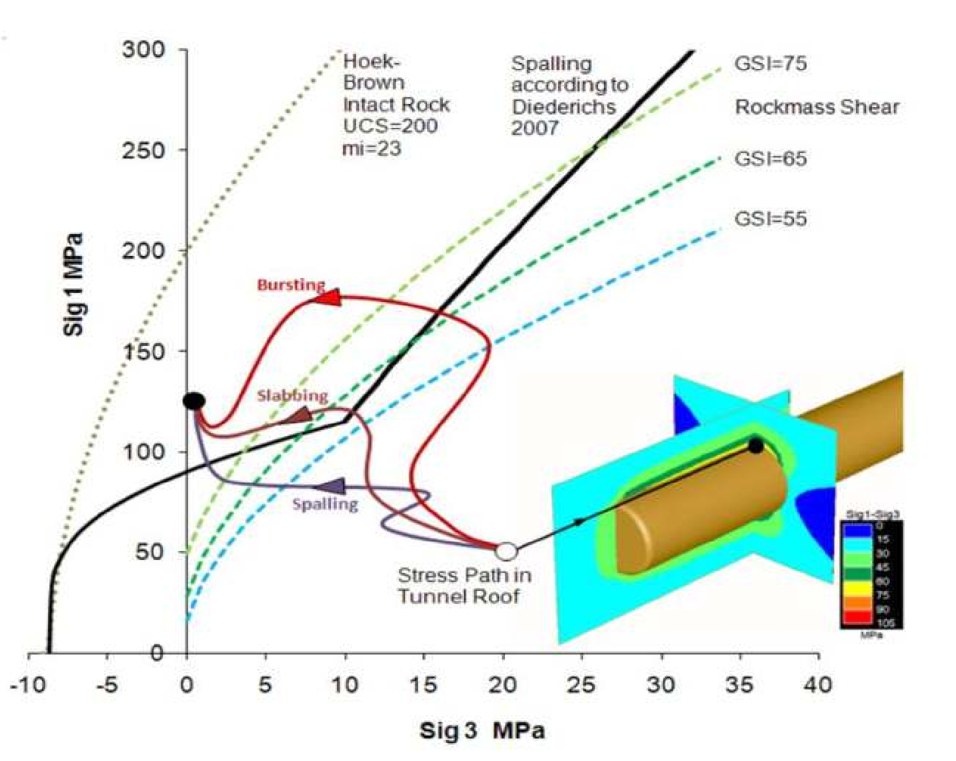
$$SED = [(\sigma 1^2+\sigma 2^2+\sigma 3^2)-2\nu(\sigma 1\sigma 2+\sigma 2\sigma 3+\sigma 3\sigma 1)]/(2E_y)$$

$\sigma 1,\sigma 2,\sigma 2$= Principal Stresses; ν=Poisson Ratio; E_y=Young Modulus

The stored strain energy can be consumed by process as rock fracturing or to be released in form of kinetic energy.

The severity of rockburst is essentially related to the amount of the energy in excess

Burst potential based on energy→ storage and release according to stress path [9]



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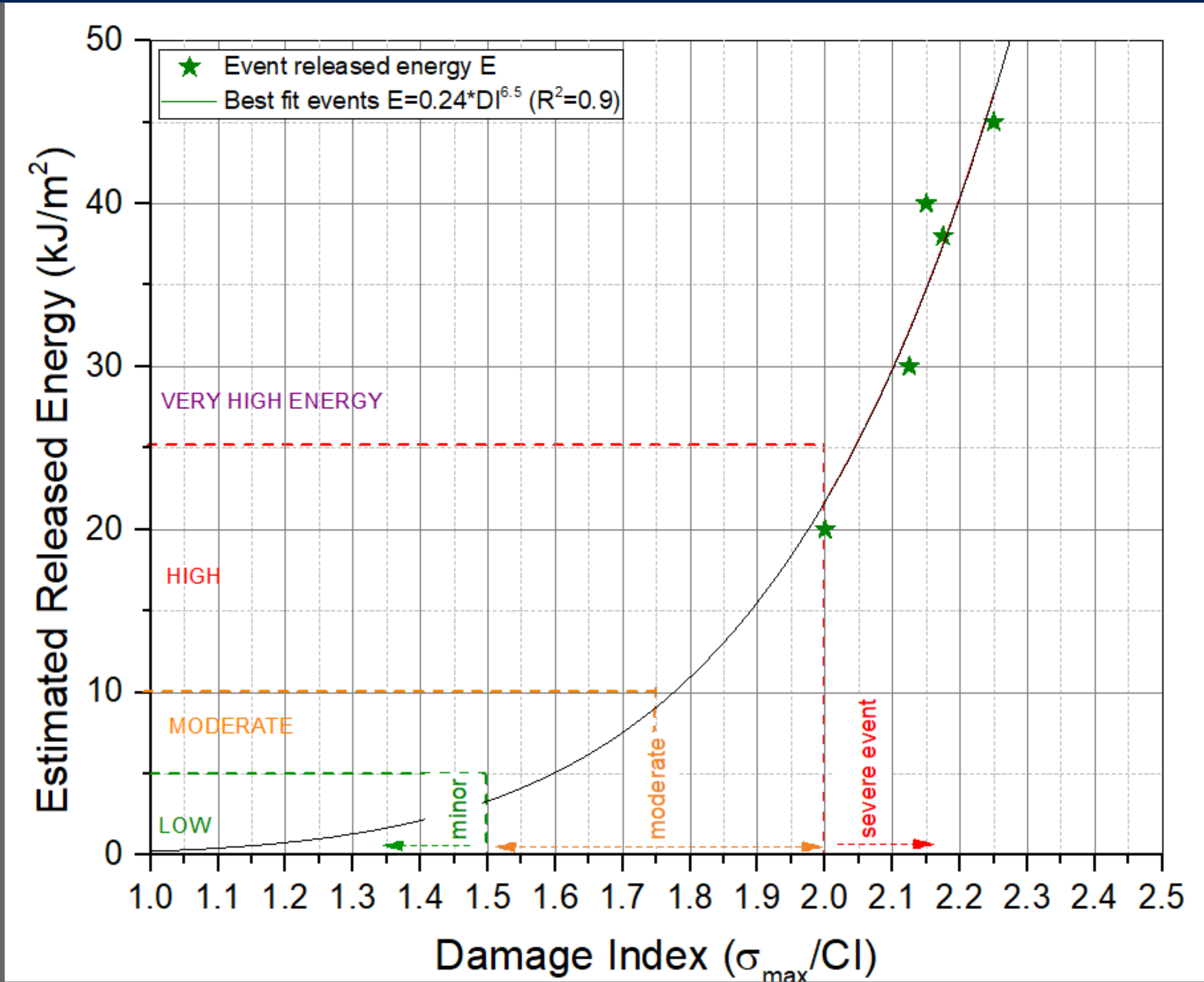

Example of relationship between Damage Index and estimated Released Energy of severe rkb events in Andesitic rocks

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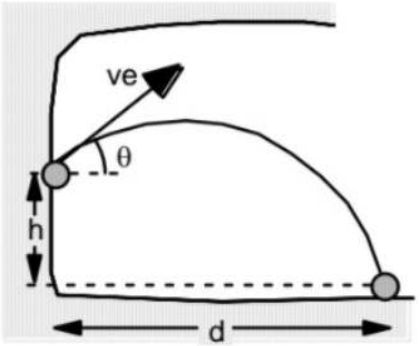


$$v_e = d \cdot \sqrt{\frac{g}{2\mathrm{h}\,cos^2\vartheta + sin2\vartheta}}$$

Where:

ϑ is the initial angle of motion measured upwards from the horizontal plane in degrees;

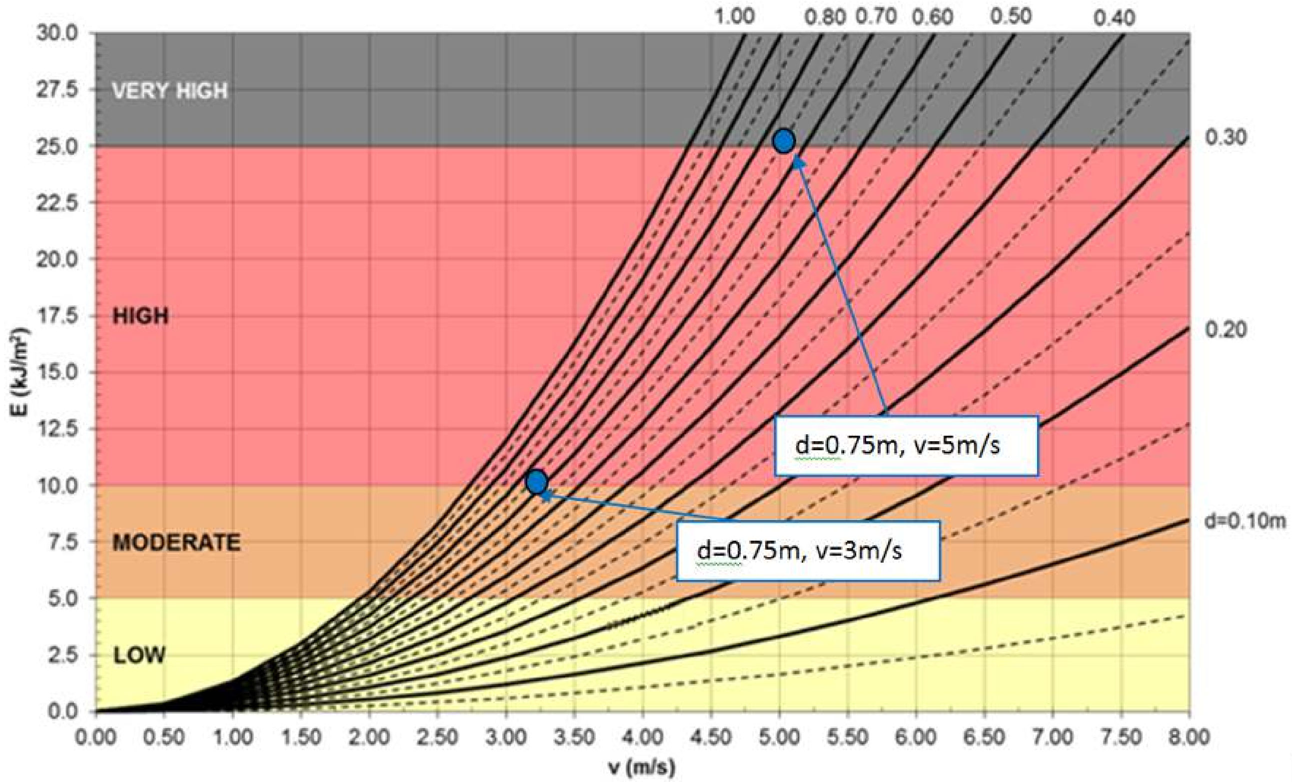
g is the gravitational acceleration.

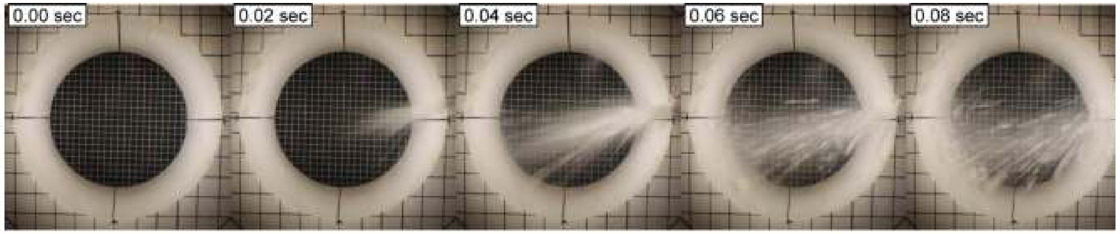
Trajectory of rock thrown during a rockburst (Tannant et al. 1993)

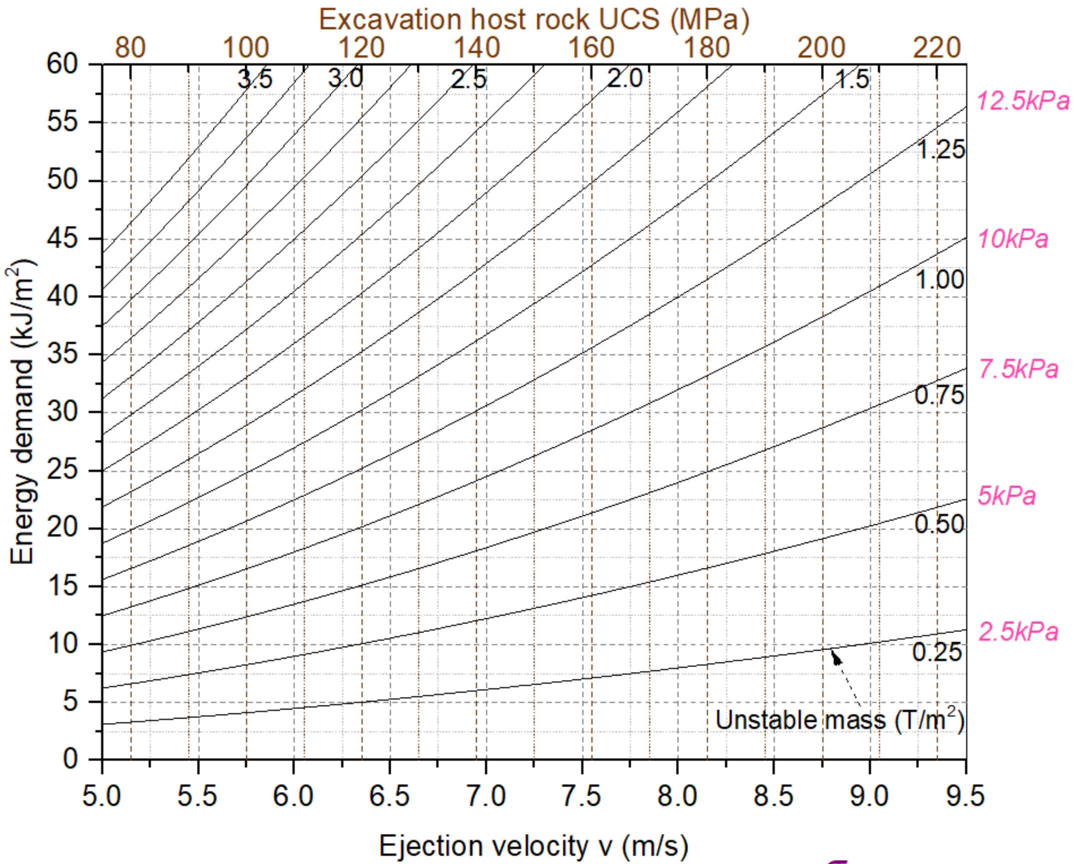
Ejection velocity

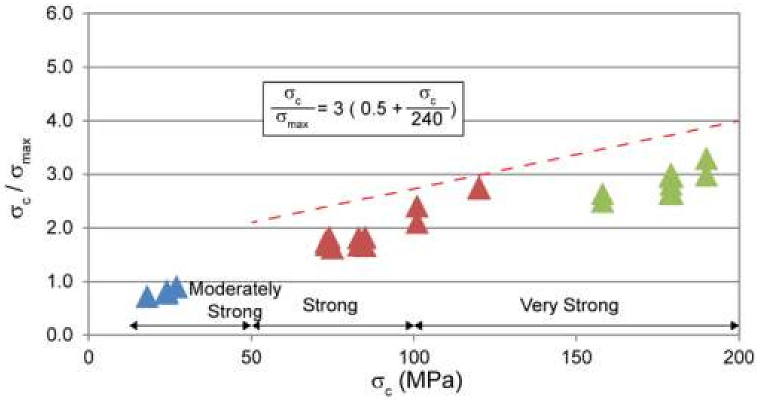
Kinetic Energy release

$$E_k = \frac{1}{2}mv^2$$









Ejection velocity and Energy demand

Based on laboratory tests, Villaescusa et al. 2016 [31] relate ejection velocity to intact rock strength (UCS).

The Energy demand is derived as a function of the potential Unstable mass.

[n.d.r.: Caution in estimating the ejection velocity is required for the reduced scale of tests!]

↑Chart derived according the cited Authors

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Hazard for brittle rock mass [a]	Minor spalling	Moderate overbreak	Severe overbreak	Very severe overbreak [c]
σ_{max}/UCS	0.4-0.6	0.6-0.8	0.8-1.0	>1.0
σ_{max}/CI	1.0-1.5	1.5-2.0	2.0-2.5	>2.5
DOF/a $_{(max)}$[b] (≈)	0.25	0.5	0.75	>0.75
Energy (kJ/m^2) (indicative for Bulking causing ejection)	<5 low	5-10 moderate	10-25 high	>25 v.high to extreme

[a]Diederichs, 2010;

[b]Martin et al.,1999: DOF/a=1.25σmax/UCS-0.51 with a=tunnel radius

[c]very sever overbreak class has been added with respect to the original formulation

Kinetic energy (kN/m^2)	Damage intensity
<5	Low
5 to 10	Moderate
10 to 25	High
25 to 50	Very high
> 50	Extreme

Proposed correlation between the Overbreak classification, the Depth of Failure (DOF=r-a) and the expected released Energy [26]

[3]→

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Rock mass bulking in brittle rocks

Extension fracture initiation/propagation and shear along joints lead to rock mass disintegration and rock mass bulking.
Bulking process is result of geometric block incompatibilities, leading to large volume increase. If the rock mass is supported, bulking can be restrained to smaller value.

Location and support condition	Average support load capacity [kN/m^2]	Recommended bulking factor (BF)	Severity of anticipated damage
Floor heave	0	30 ± 5 %	minor to moderate
		> 50 %	Major
Walls and backs	< 50	10 ± 3 %	minor to moderate
Light standard bolting and loose, light mesh			
Yielding support	< 200	5 ± 1 %	minor to major
Strong support with rock mass reinforcement	> 200	1.5 ± 0.5 %	minor to major

WD (Inelastic Wall Displacement)= DoF*BF [3]

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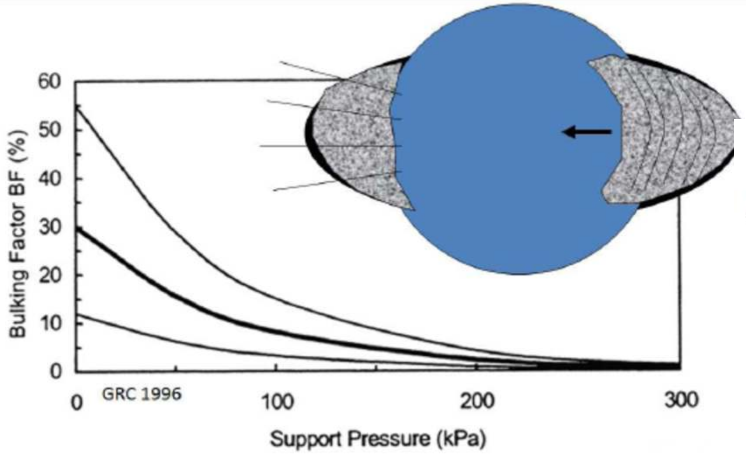
Additional equations for Bulking Factor [7,8,9]

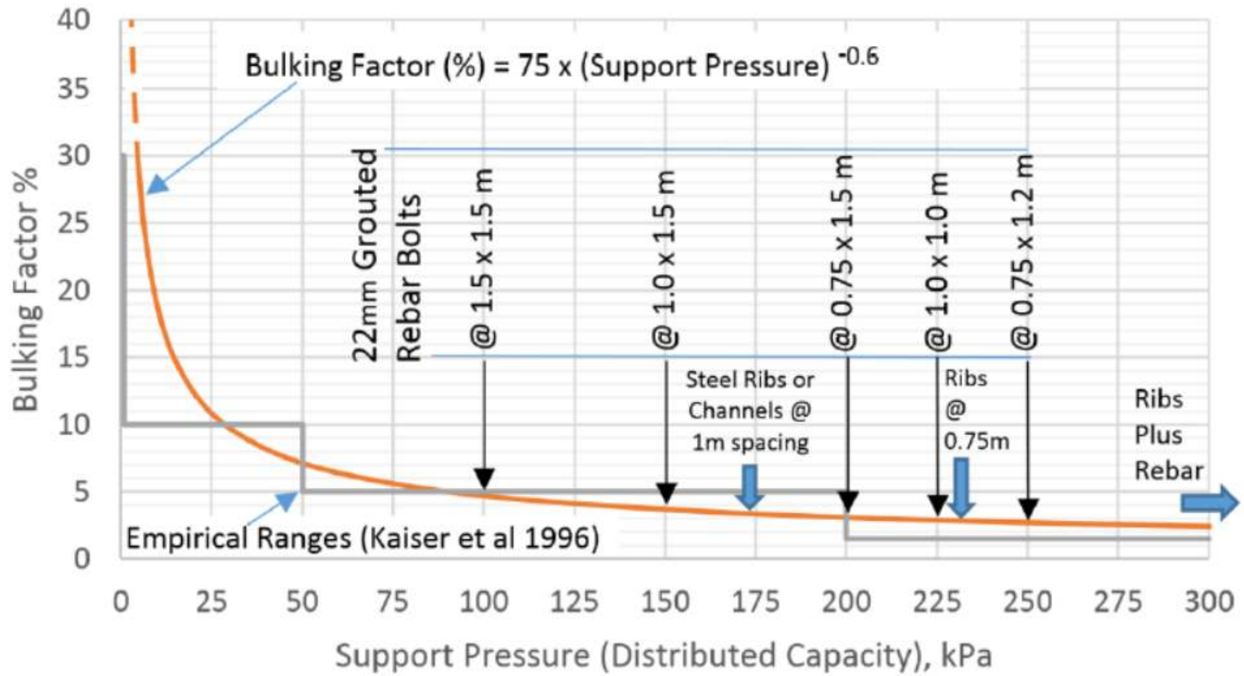


$$B.F. = 0.3e^{\left(\frac{-P}{70}\right)}$$

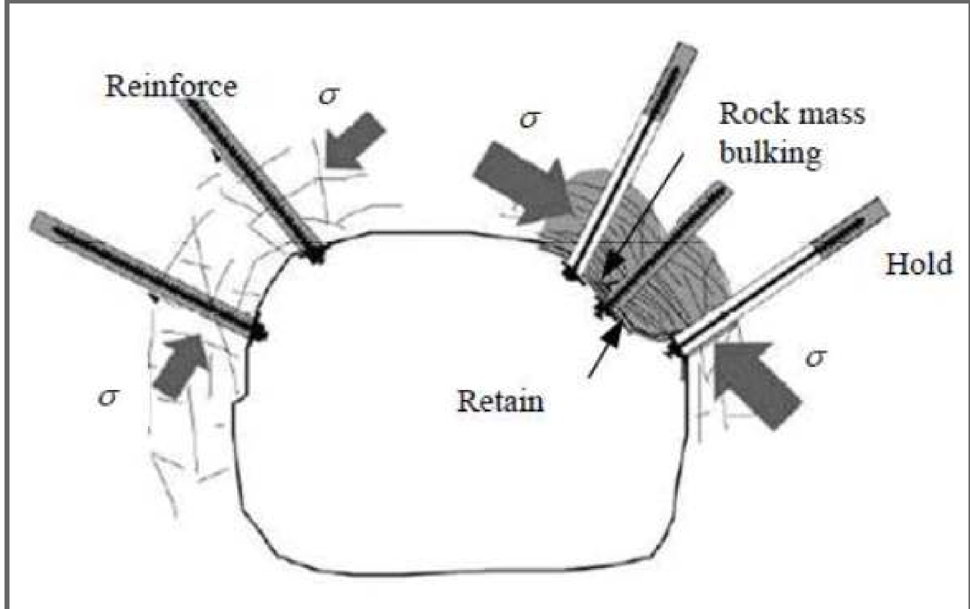
(P in kPa)

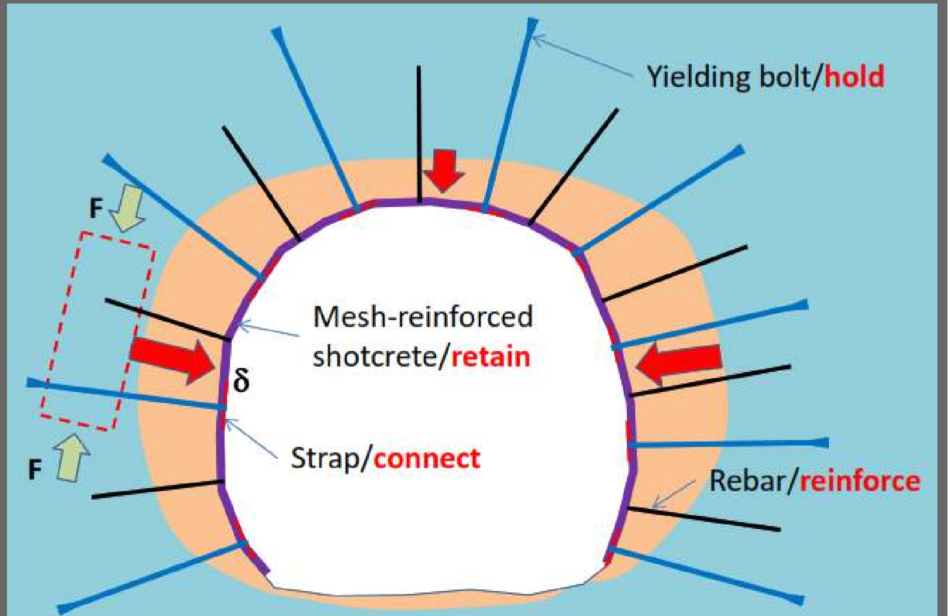
$$WD = DOF\left(0.3e^{-P/70}\right)$$

WD = wall displacement DOF = depth of failure P = support pressure

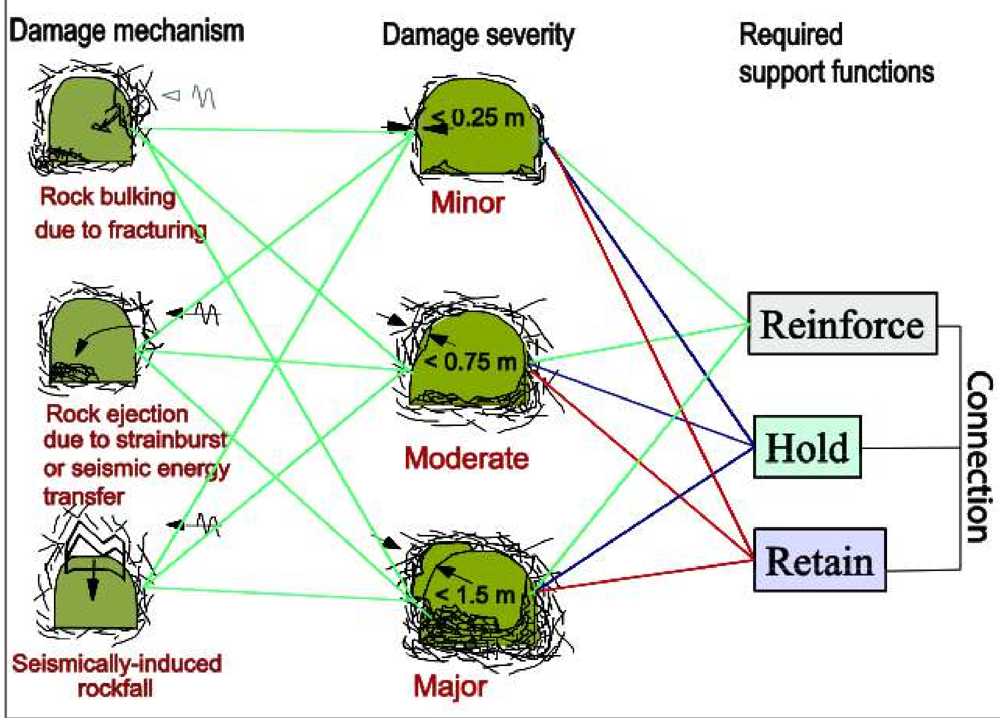


Support in burst prone ground
[1,3,18]

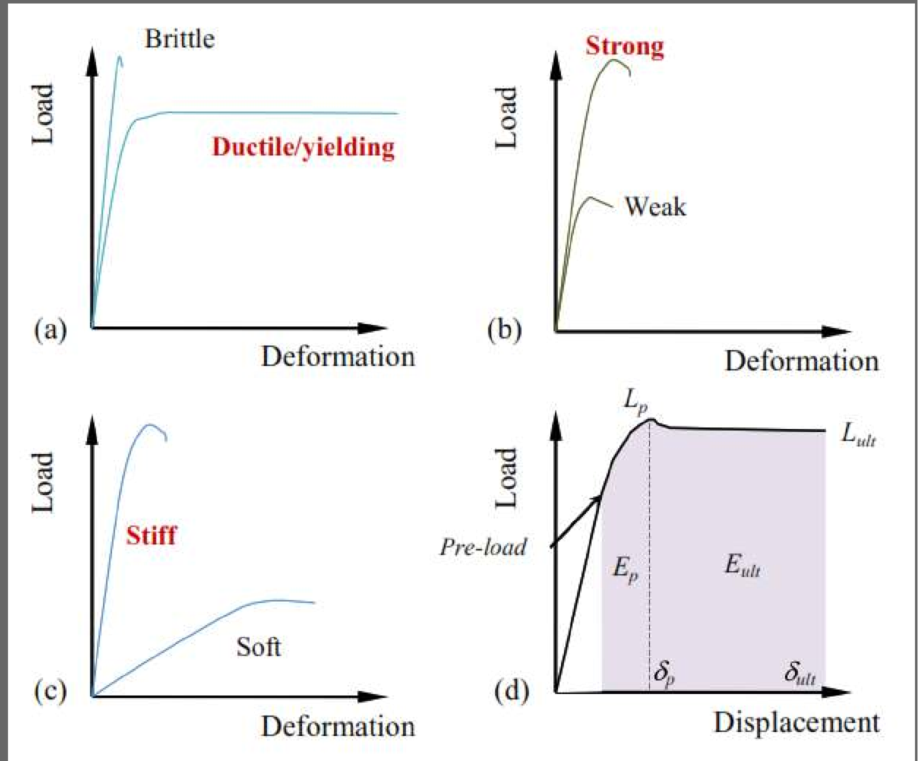




- Reinforce the rock mass to strengthen it and to control bulking;
- Retain broken rock to prevent fractured block failure and unraveling;
- Hold fractured blocks and securely tie back the retaining element(s) to stable ground.



All support functions are needed, with different contributions..



Optimal support system combines adequately the deformation properties and capacity of each basic component:
Reinforcement [bolts, cables,..] and Surface Support [(fiber-reinforced) Shotcrete , mesh,...]

[16]

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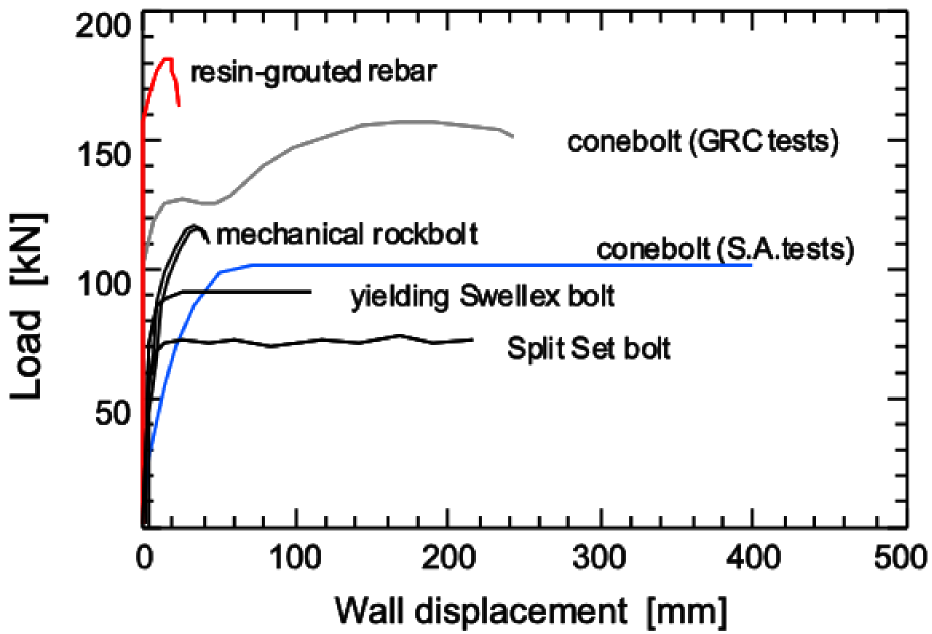
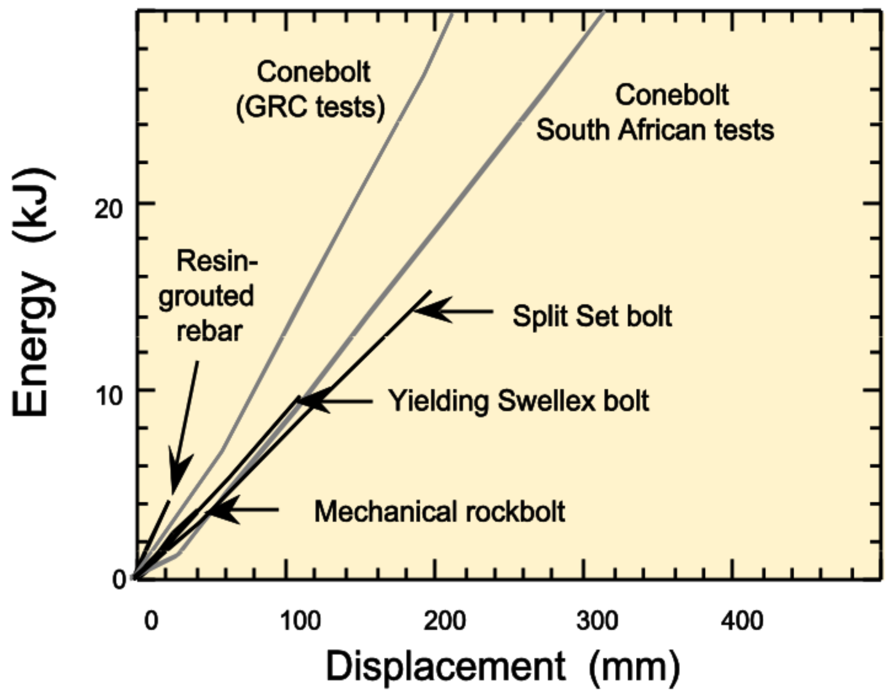


←Load-displacement curves

Reinforcing/Holding elements

Static energy absorbing capacity→



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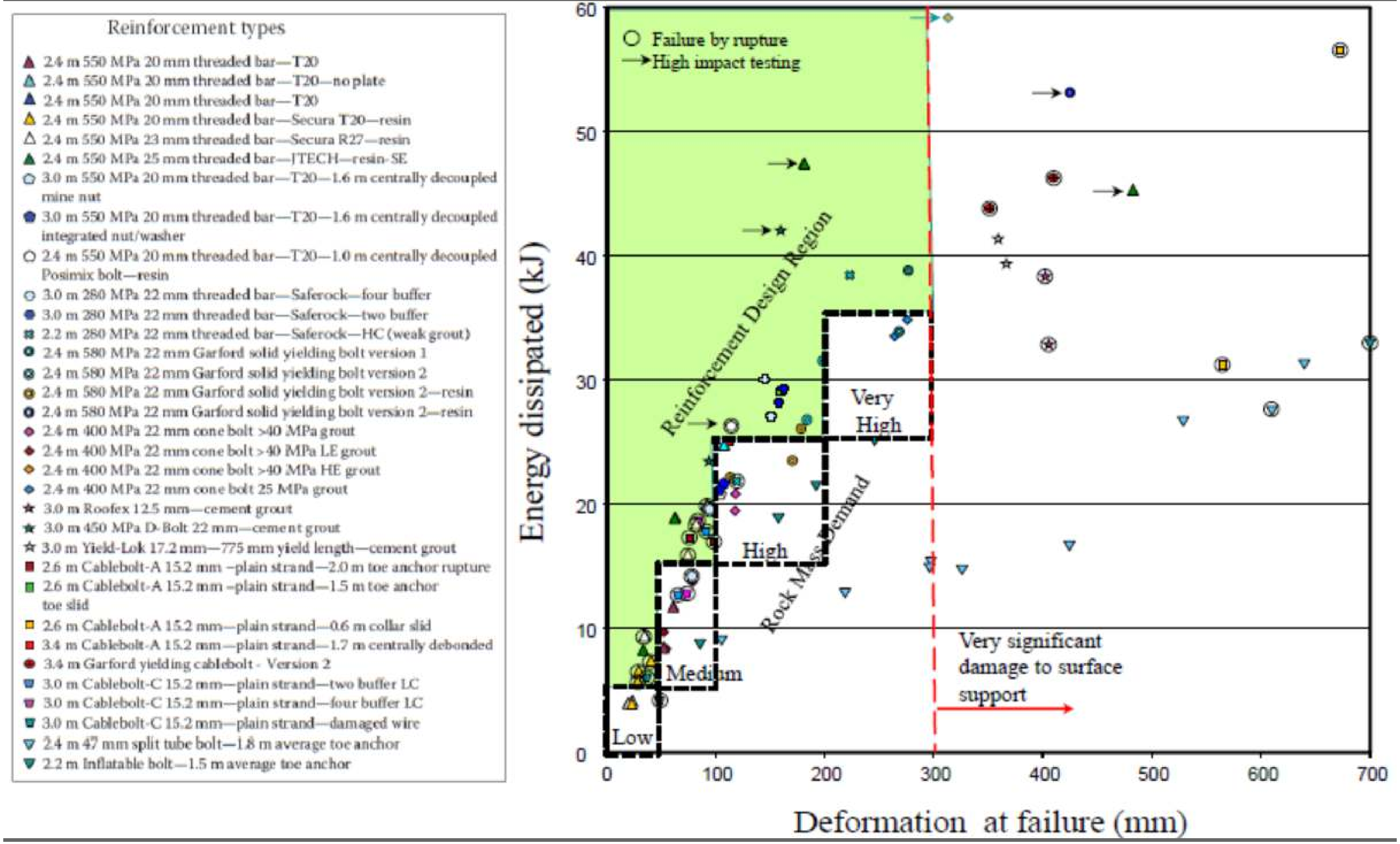
Energy Capacity of Reinforcement elements [30]



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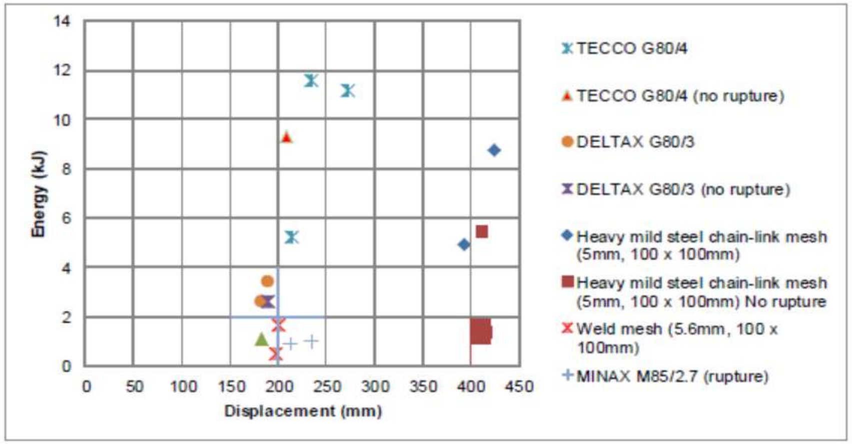
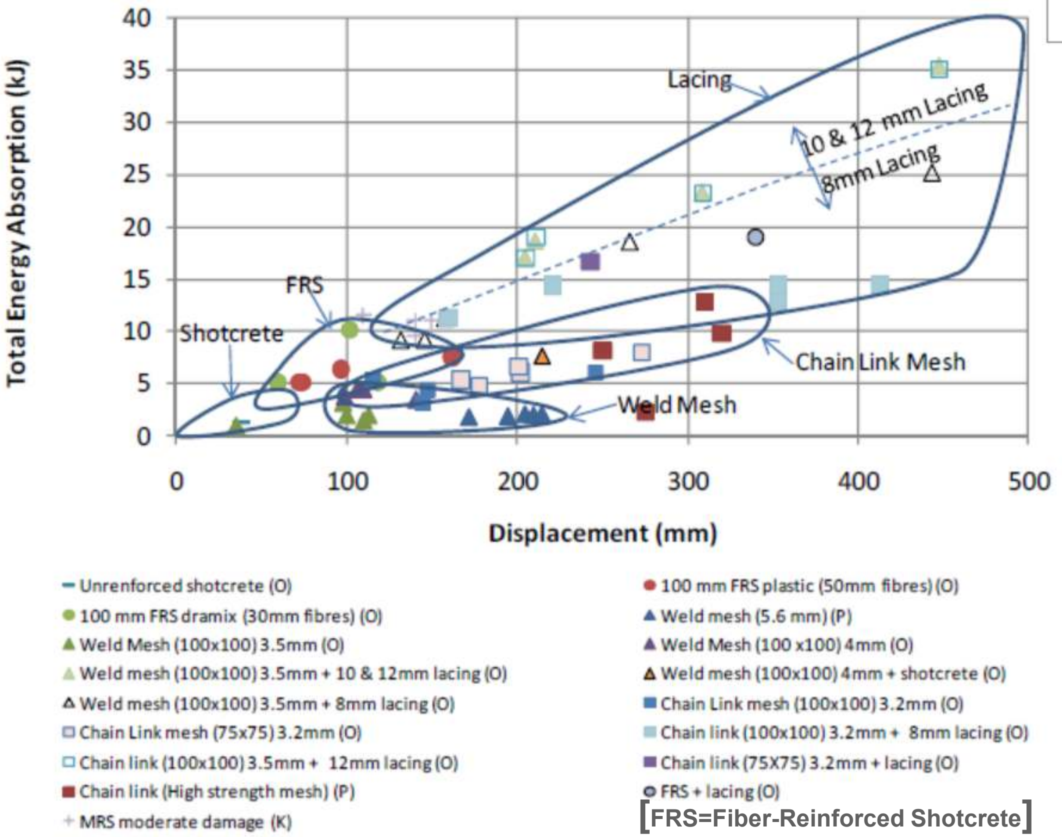
Energy Capacity of Surface support



↑**Steel mesh dynamic test results** [30]



[FRS=Fiber-Reinforced Shotcrete]

Potvin et al. 2010, [24]

Table 2.1 Rockburst damage mechanisms and nature of the anticipated damage

Damage mechanism	Damage severity	Cause of rockburst damage	Thickness [m]	Weight [kN/m²]	Closure* [mm]	v_e [m/s]	Energy [kJ/m²]
Bulking without ejection	Minor	highly stressed rock	< 0.25	< 7	15	< 1.5	not critical
	Moderate	with little excess	< 0.75	< 20	30	< 1.5	not critical
	Major	stored strain energy	< 1.5	< 50	60	< 1.5	not critical
Bulking causing ejection	Minor	highly stressed rock	< 0.25	< 7	50	1.5 to 3	not critical
	Moderate	with significant	< 0.75	< 20	150	1.5 to 3	2 to 10
	Major	excess strain energy	< 1.5	< 50	300	1.5 to 3	5 to 25
Ejection by remote seismic event	Minor	seismic energy	< 0.25				
	Moderate	transfer to	< 0.75				
	Major	jointed or broken rock	< 1.5				
Rockfall	Minor	inadequate strength,	< 0.25	< 7			
	Moderate	forces increased	< 0.75	<2			
	Major	by seismic acceleration	< 1.5	<5			

Table 2.5 Support systems appropriate for burst-prone ground

Mechanism	Damage severity	Load [kN/m²]	Displace. [mm]	Energy [kJ/m²]	Examples of suggested support systems *
Bulking without ejection	Minor	50	30	not critical	-mesh with rockbolts or grouted rebars (and shotcrete)
	Moderate	50	75	not critical	-mesh with rockbolts and grouted rebar (and shotcrete)
	Major	100	150	not critical	-mesh and shotcrete panels with yielding bolts and grouted rebars
Bulking causing ejection	Minor	50	100	not critical	-mesh with rockbolts and Split Set bolts (and shotcrete)
	Moderate	100	200	20	-mesh and shotcrete panels with rebars and yielding bolts
	Major	150	> 300	50	-mesh and shotcrete panels with strong yielding bolts and rebars (and lacing)
Ejection by remote seismic event	Minor	100	150	10	-reinforced shotcrete with rockbolts or Split Set bolts
	Moderate	150	300	30	-reinforced shotcrete panels with rockbolts and yielding bolts (and lacing)
	Major	150	> 300	> 50	-reinforced shotcrete panels with strong yielding bolts and rebars and lacing
Rockfall	Minor	100	na	na	-grouted rebars and shotcrete
	Moderate	150	na	na	-grouted rebars and plated cablebolts with mesh and straps or mesh-reinforced shotcrete
	Major	200	na	na	-as above plus higher density cable bolting
Limits (MPSL)		200	300	50	Maximum practical support limit

Example of suggested Support system (and Safety factor..) [3]

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Rock support capacity

In general, three Factor of Safety should be satisfied in Design

$$FS_{Load} = \frac{\text{Support Load Capacity}}{\text{Load Demand}} \;; \quad FS_{Disp} = \frac{\text{Support Displacement Capacity}}{\text{Displacement Demand}} \;; \quad FS_{Energy} = \frac{\text{Support Energy Capacity}}{\text{Energy Demand}}$$

Key factor: Capacity of the combined Support System

According to Potvin et al., 2010-2013 [24,25], the surface support (FRS and chain-link) could guarantee an additional safety margin or represent a potential "weakest link" depending if the support system, in function also of the bolt spacing, will be able to work on "serial" or "parallel", respectively.

Cala et al. ,2013 [2] remarked a redistribution of the energy in the different support elements variable in function of the stiffness of the surface component: typically for stiff conditions the reinforcement and surface support adsorbed 75% and 25% of the released energy, respectively.

In other tests [30] the reinforcement adsorbed 72 to 93% of the released energy.

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GDE design approach applied in Rockburst environment

	Rockburst Energy Demand	Reinforcement Capacity	Surface Support Capacity
	E_D	$\geq 2E_D$	$\geq E_D$
Example	High Energy (Severe Event)	n.2 orders of high capacity grouted elements	n.2 FRS+high capacity chain link mesh layers

Basic Safety statement: Automatized support installation without any workers exposure

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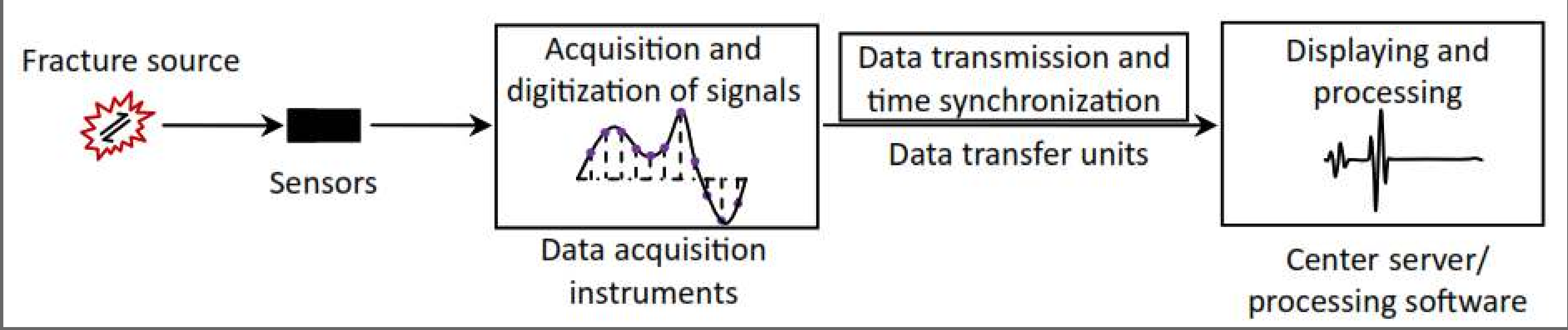
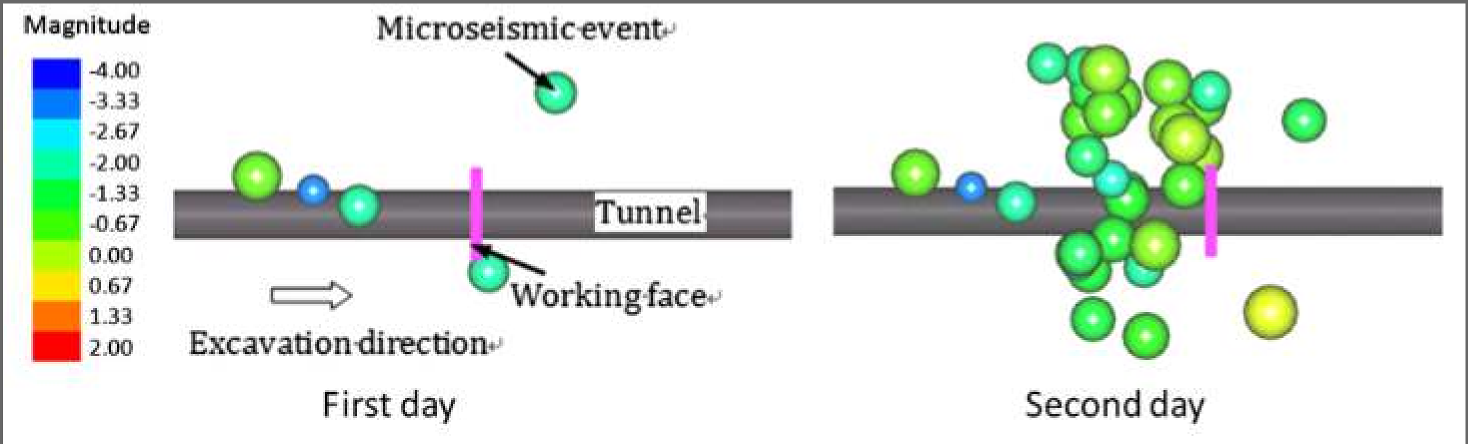
Outline of Microseismic Monitoring

Seismic monitoring enables the quantification of exposure to seismicity and provides a logistical tool in prevention, control and prediction of rockburst (from Mendecki et al., 1999).





[14]

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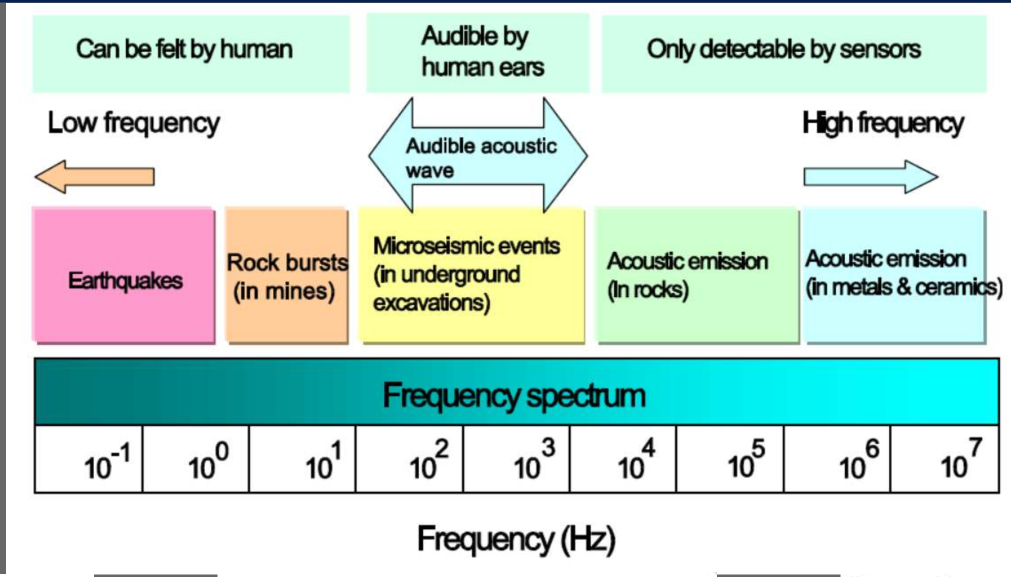
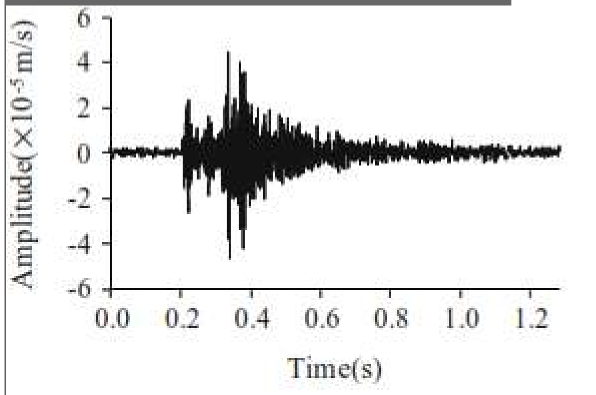
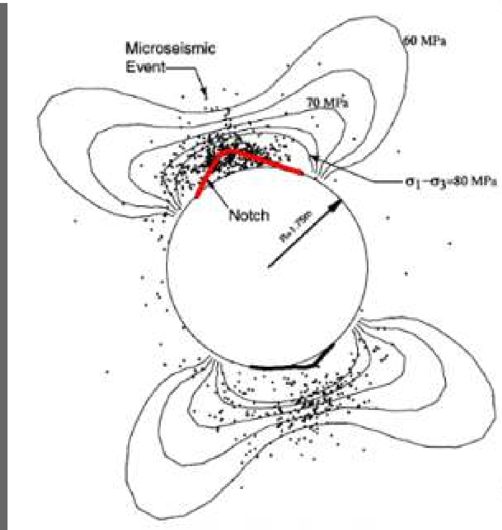
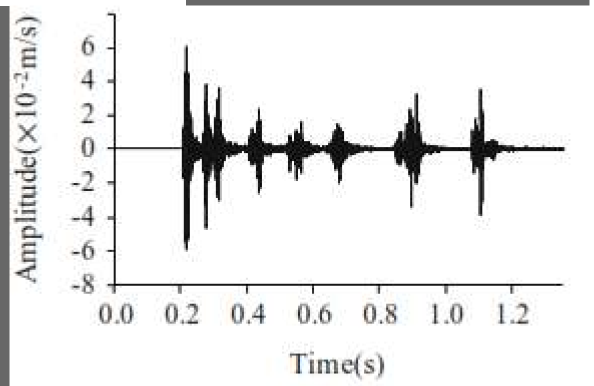


Cai et al.,2007, reported in [1]



Rock fracturing
<1s
10-3000Hz
10^{-2}-10^{-7} m/s





Blasting
>1s
100-500Hz
10^{-2}-10^{-3} m/s

Examples for typical time domain waveforms of microseismic signals in tunnels ISRM, 2016 [14]

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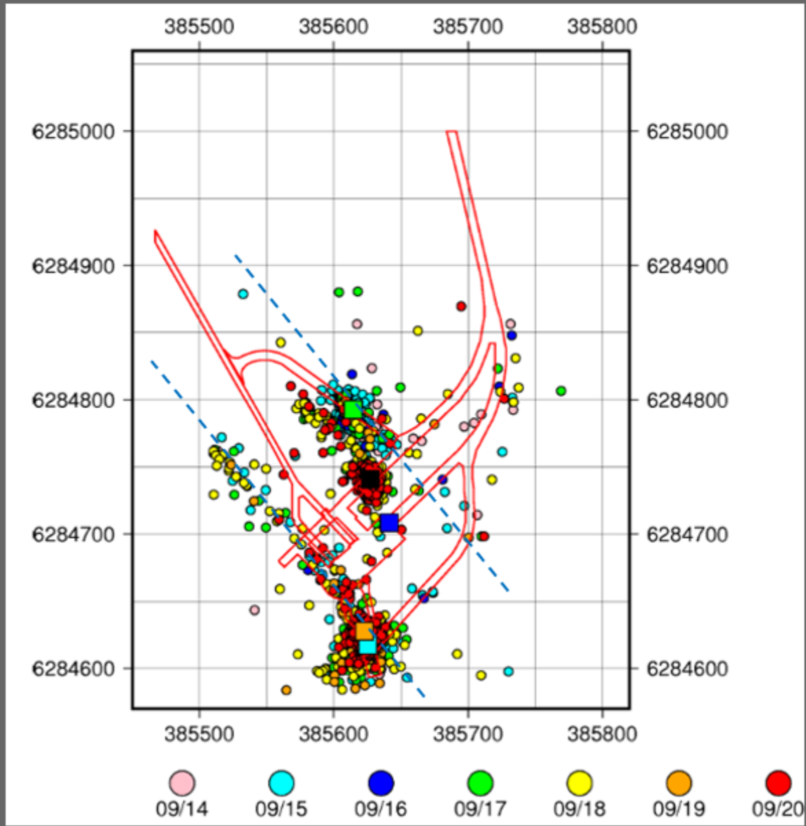


Example of seismic monitoring weekly report for tunnels of Hydroelectric project in Andean region showing the concentration of events (M_w=-3÷1)

Dotted lines remark some hypothesis of preferential alignment of events along main shear zones, while square symbols are tunnel faces in advancement.

An insight on a presumably Seismically triggered strainburst occurrence is shown in the following.

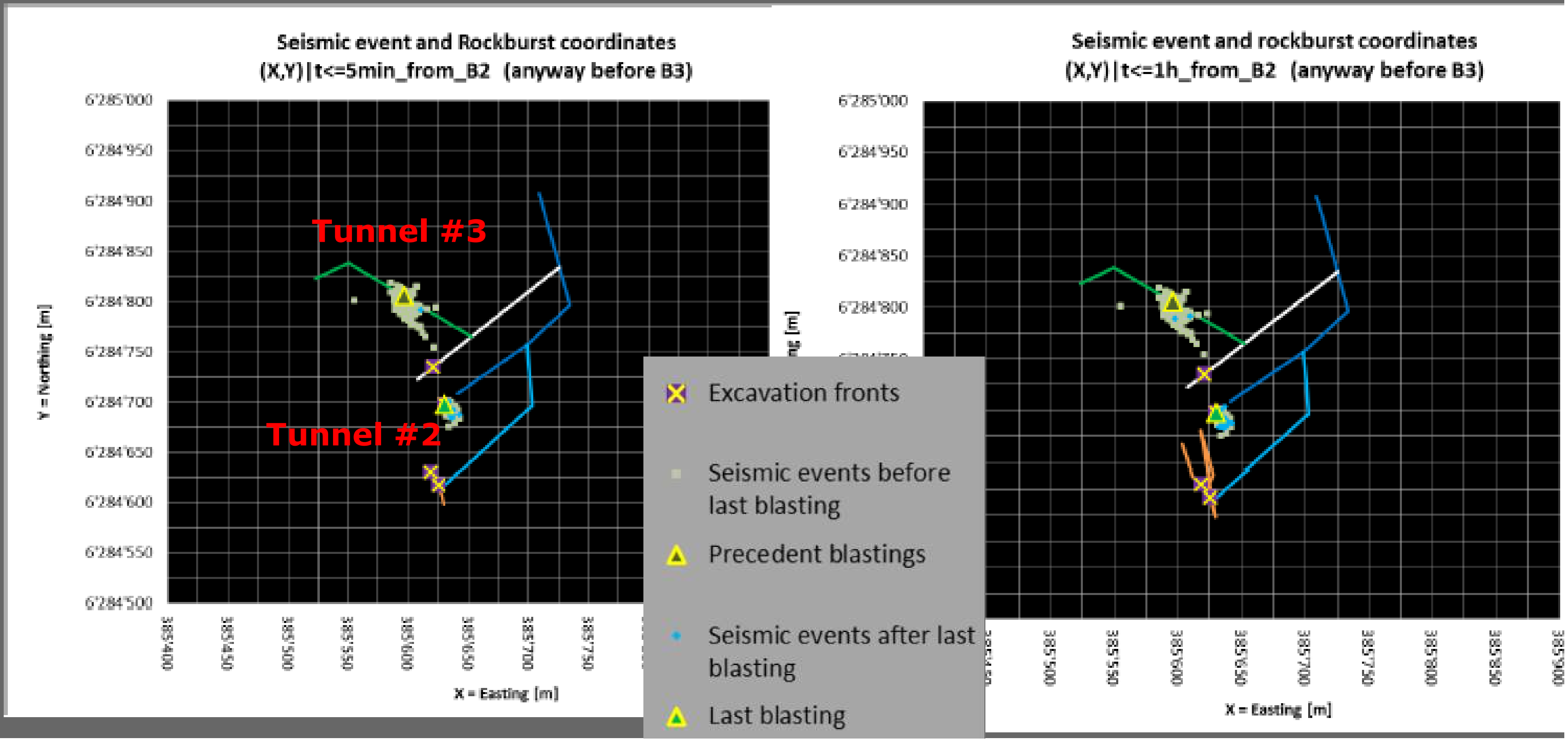
The analysis* focus on the time lapse between two blastings (B2 and B3) in tunnels #2 and #3 (distance ≈ 100m)

B2=h7:20 (day 1)

***** *Elaborated by Carlo Chiesa***

B3=h19:00 (day 2)

[Note: previous blasting in #3= h2:05 (day1): Some related seismicity still measured in #2 and #3 at B2 time]



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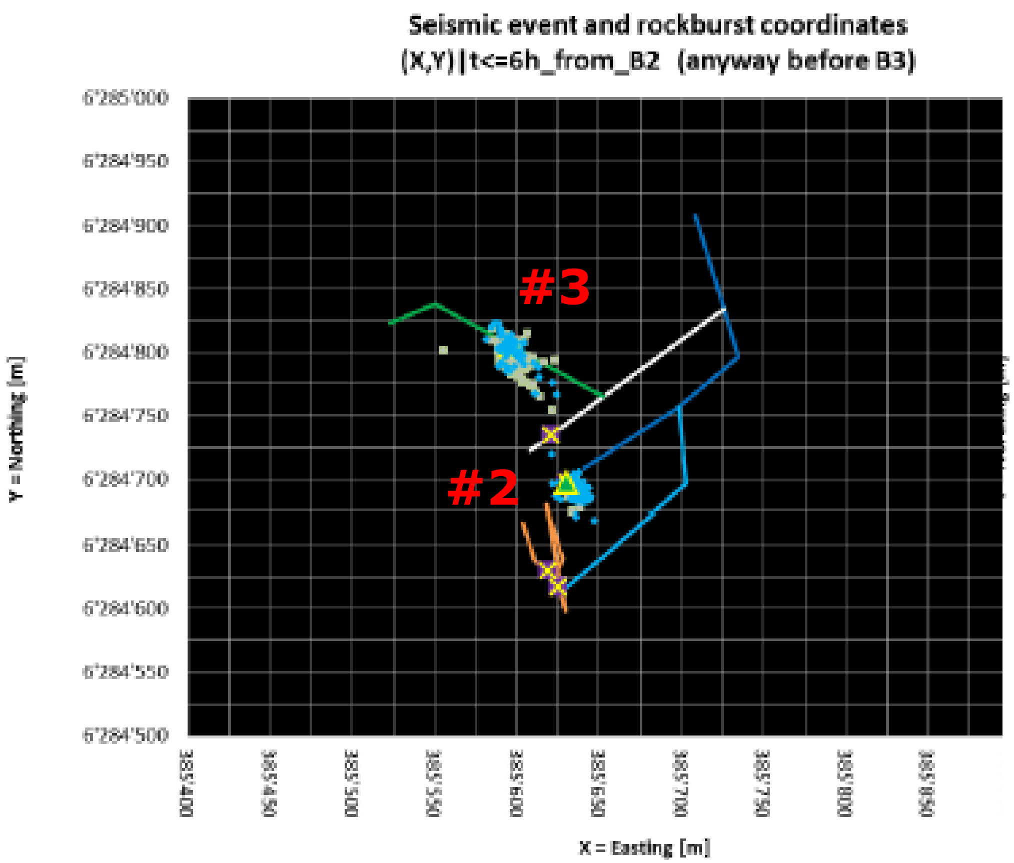

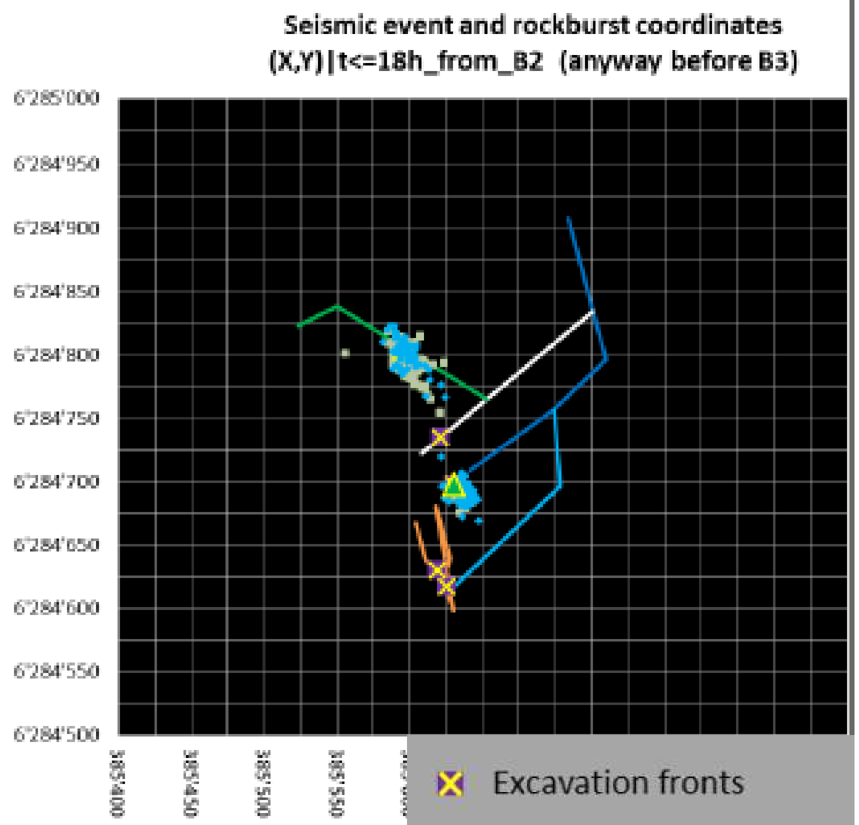

- Excavation fronts
- Seismic events before last blasting
- Precedent blastings
- Seismic events after last blasting
- Last blasting

Note (sky-blue points) some new seismicity between tunnels and increase around Tunnel #3 (previous blast was in #2)

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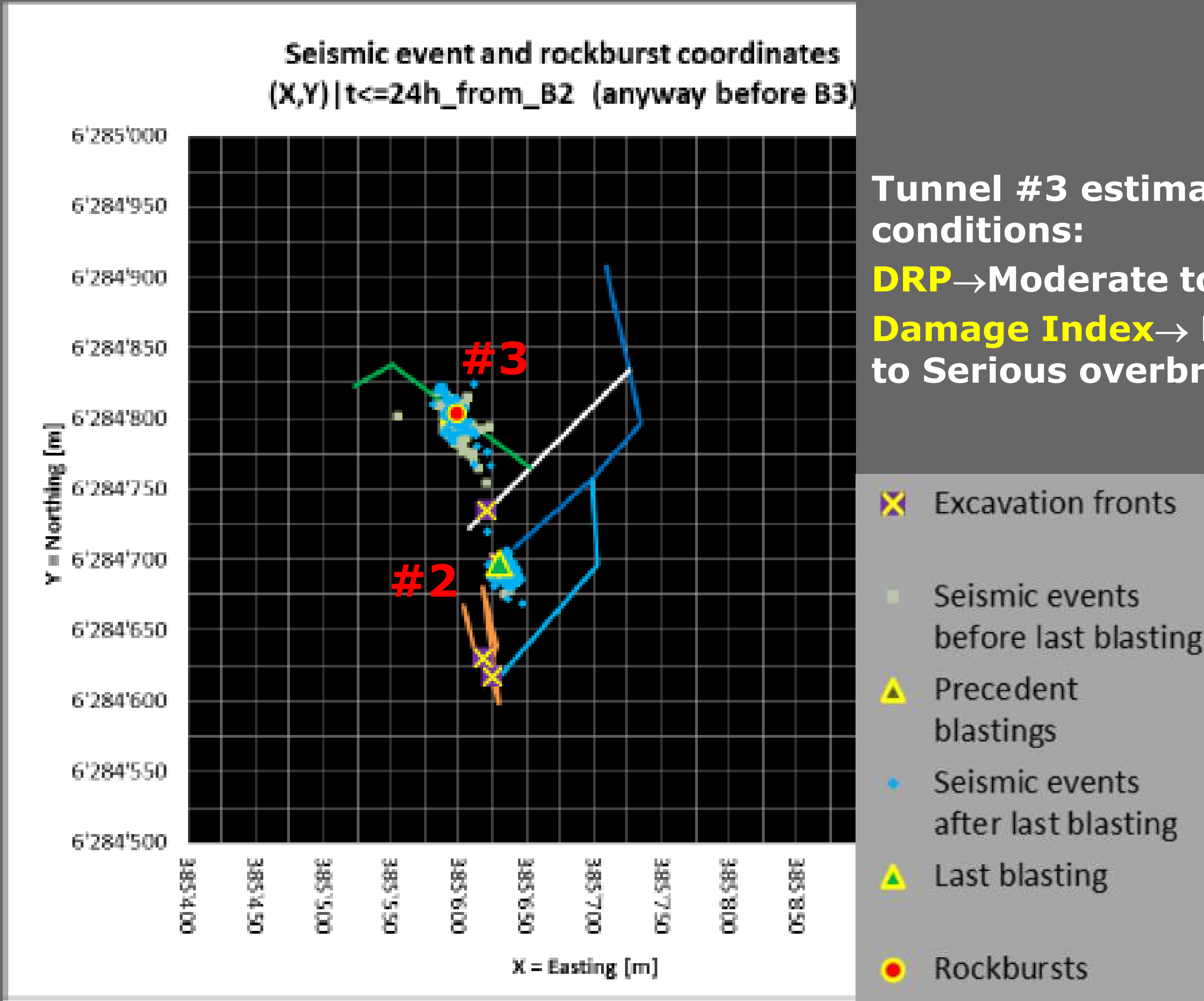

Tunnel #3 estimated conditions:

DRP→Moderate to High

Damage Index→ Moderate to Serious overbreak

Severe rockburst occurrence in tunnel #3

(after 19h from B2 and 24h from previous blast in #3)

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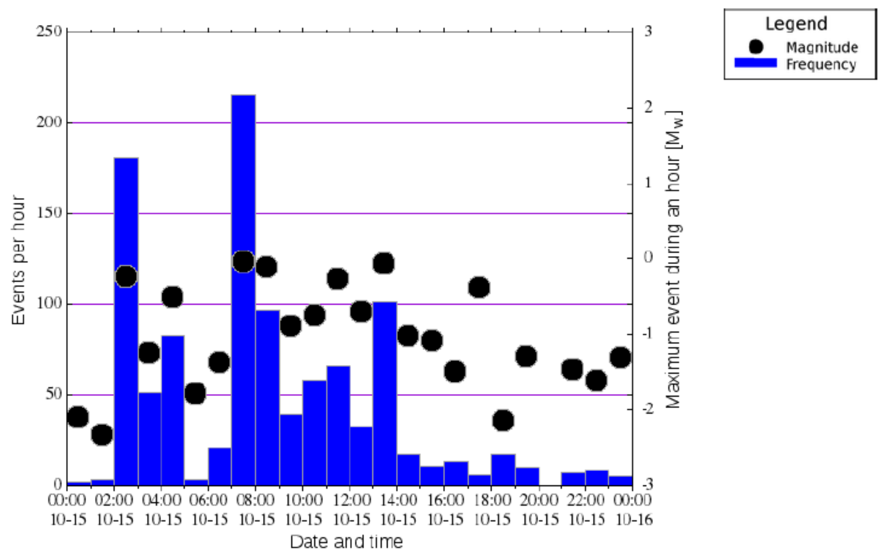
Seismic rate (events per hour) and max Moment Magnitude (M_w) event after B2.

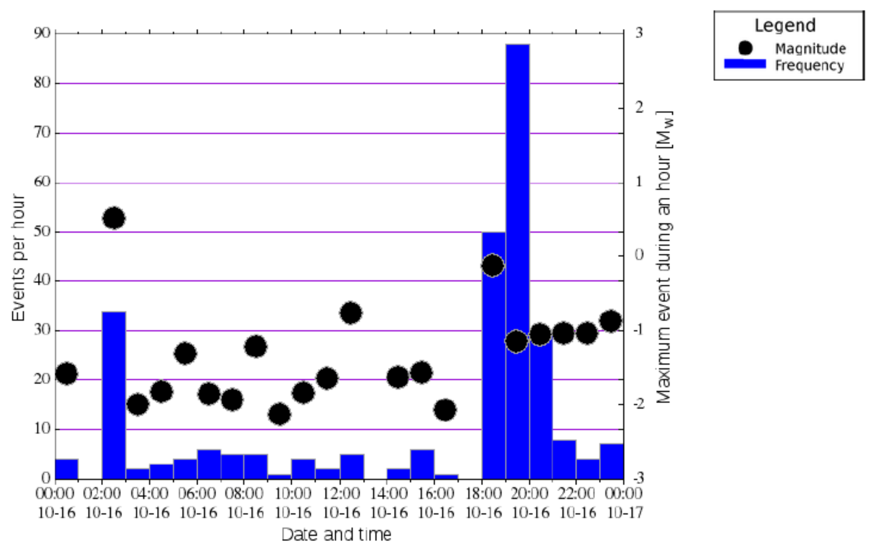
[$Mw=(2/3)\log_{10}(Mo)-6$ and Mo=Seismic Moment=$\mu A \Delta u$

μ=rock mass rigidity, A=fault area; Δu=slip displacement]

Seismic activity during the day



Seismic activity during the day



Previous Blasting B1 (15/10 – 2:05 – tunnel #3)

Blasting B2 (15/10 – 7:20 – tunnel #2)

RKB (16/10 – 2:10 – tunnel #3)

Blasting B3 (16/10 – 19:00 – tunnel #3)

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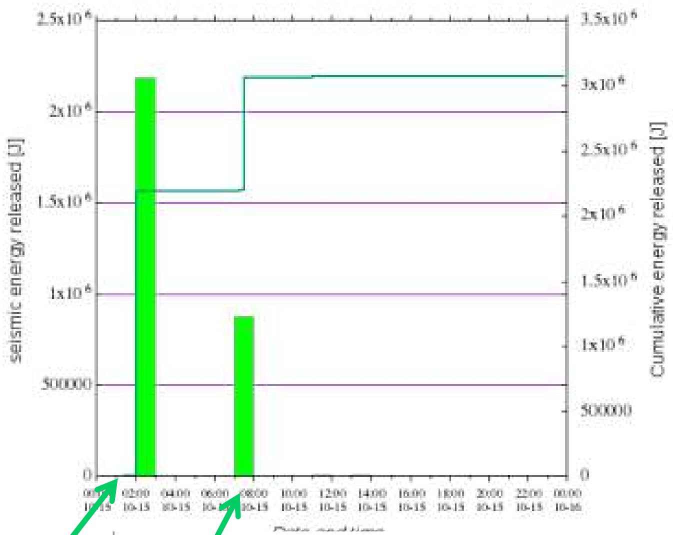
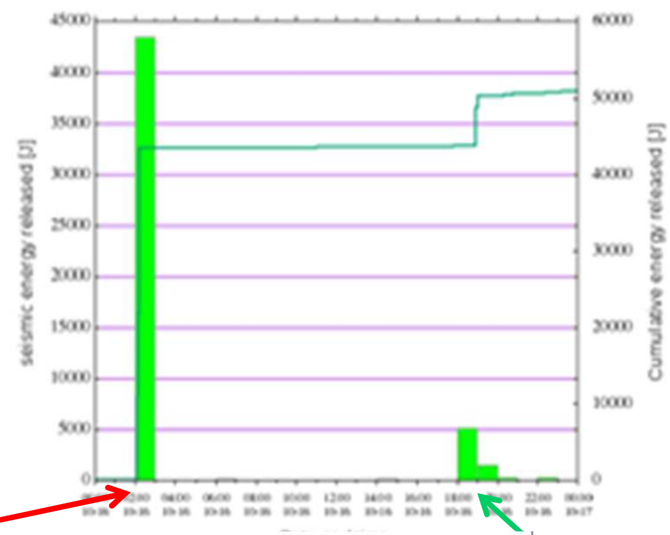
Seismic energy released



Seismic energy released



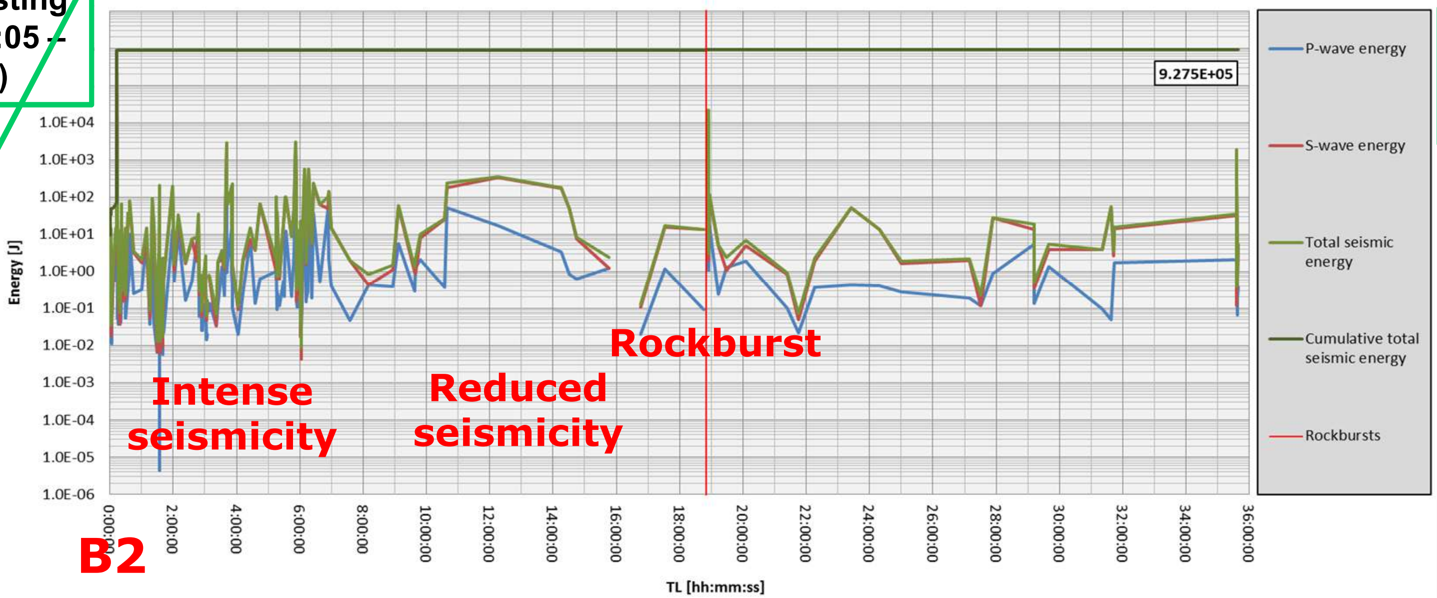
RKB (16/10 – 2:10 – tunnel #3)

Previous Blasting B1 (15/10 – 2:05 – tunnel #3)

B2 (15/10 – 7:20 – tunnel #2)

B3 (16/10 – 19:00 – tunnel #3)

Seismic event energy from B2 to B3



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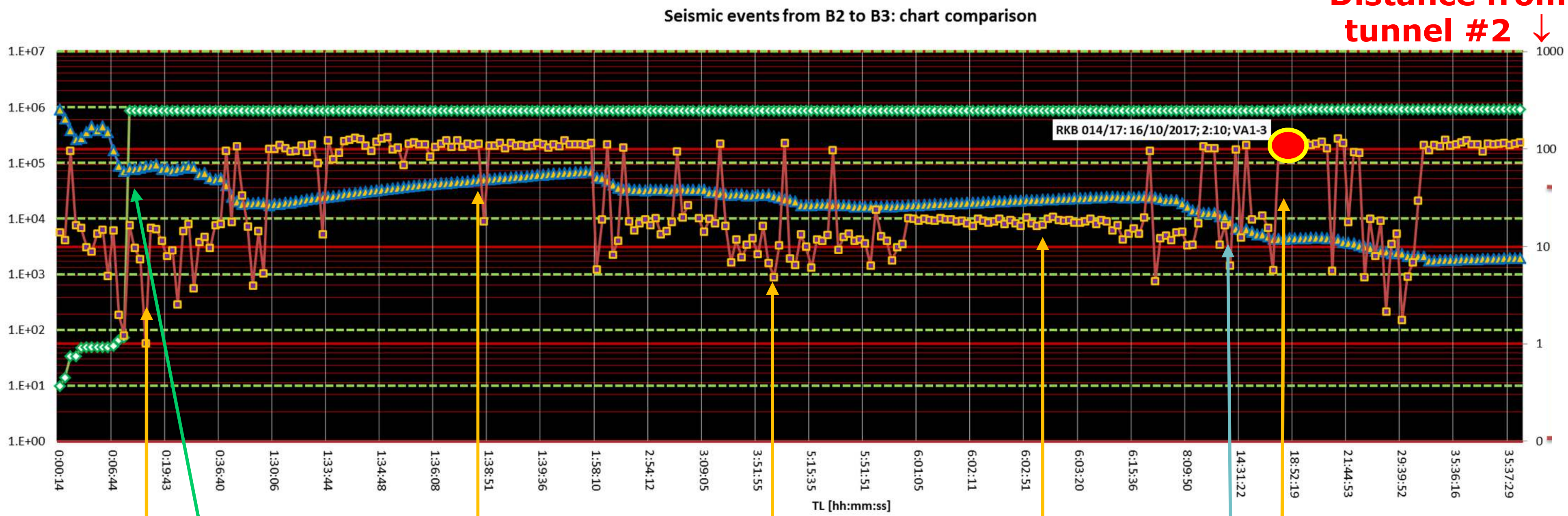
Distance from tunnel #2 ↓



>Events close #2 → **>Events close #3** → **>Events close #2 [& #3]** → **>Events close #2** → **>Events close #3 & #2**

t_{B2}=1h (Time after B2) | **t_{B2}=2h** | **t_{B2}=5h** | **t_{B2}=6h** | **t_{B2}=19h Rockburst in #3**

Cumulative total seismic energy [left axis: J]

Seismic event distance respect to last blasting [right axis: m]

Seismic event rate [right axis: n.ev./h]

Local increment after B2 and then minor variation

Very high after B2 Reduce before Rkb

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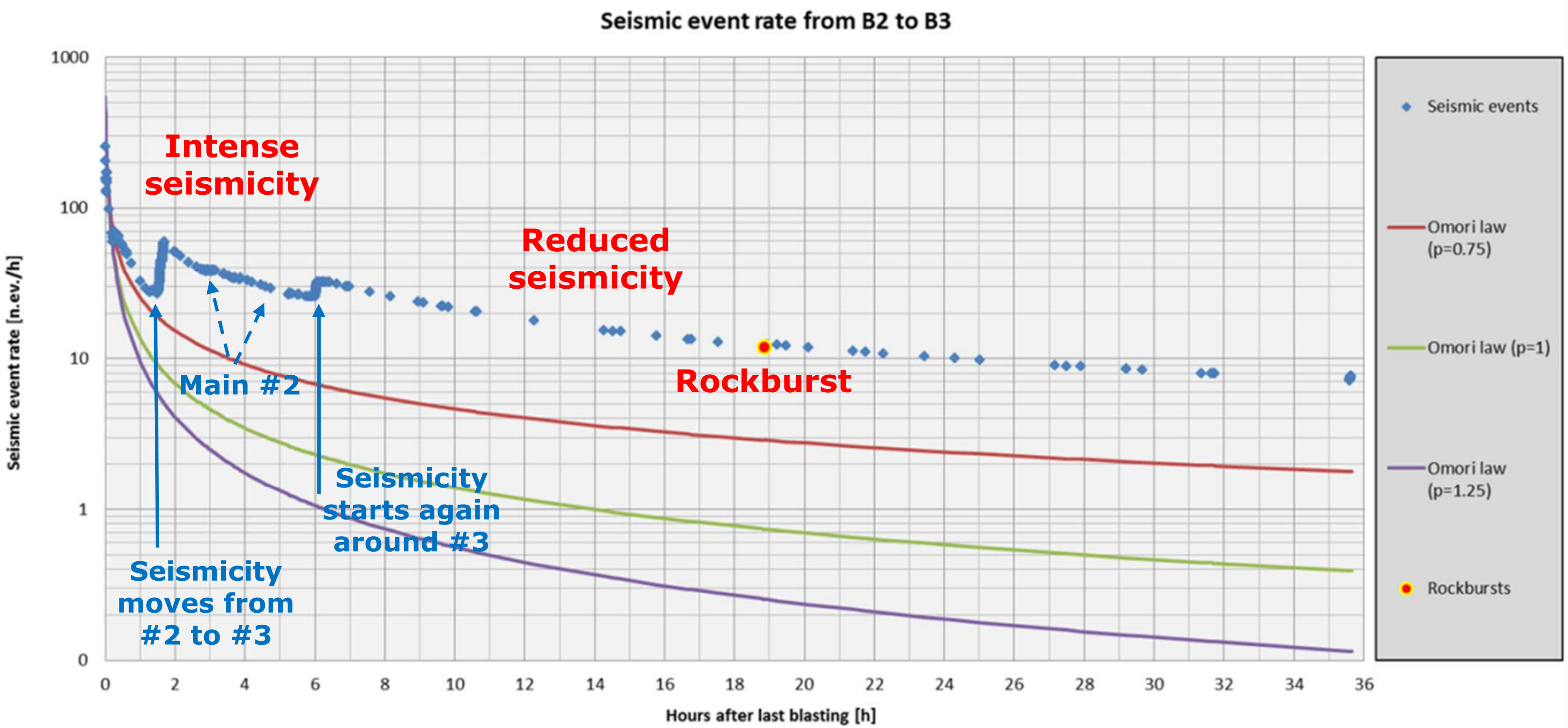
Seismic event rate after B2 and comparative Omori decay laws



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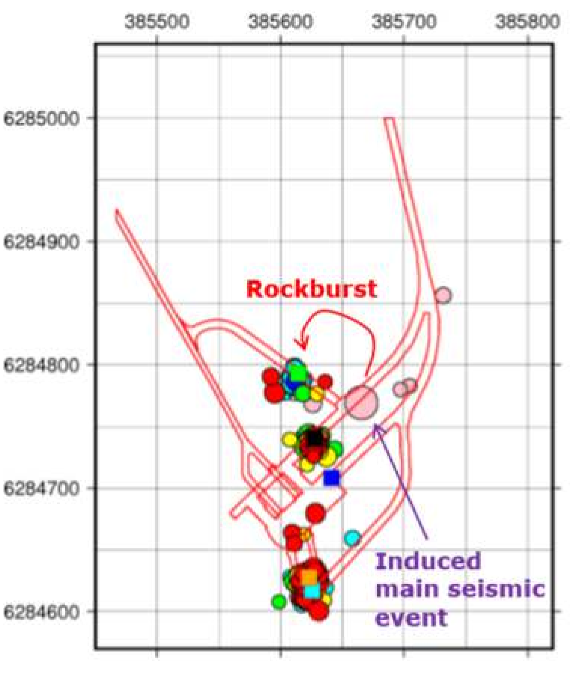
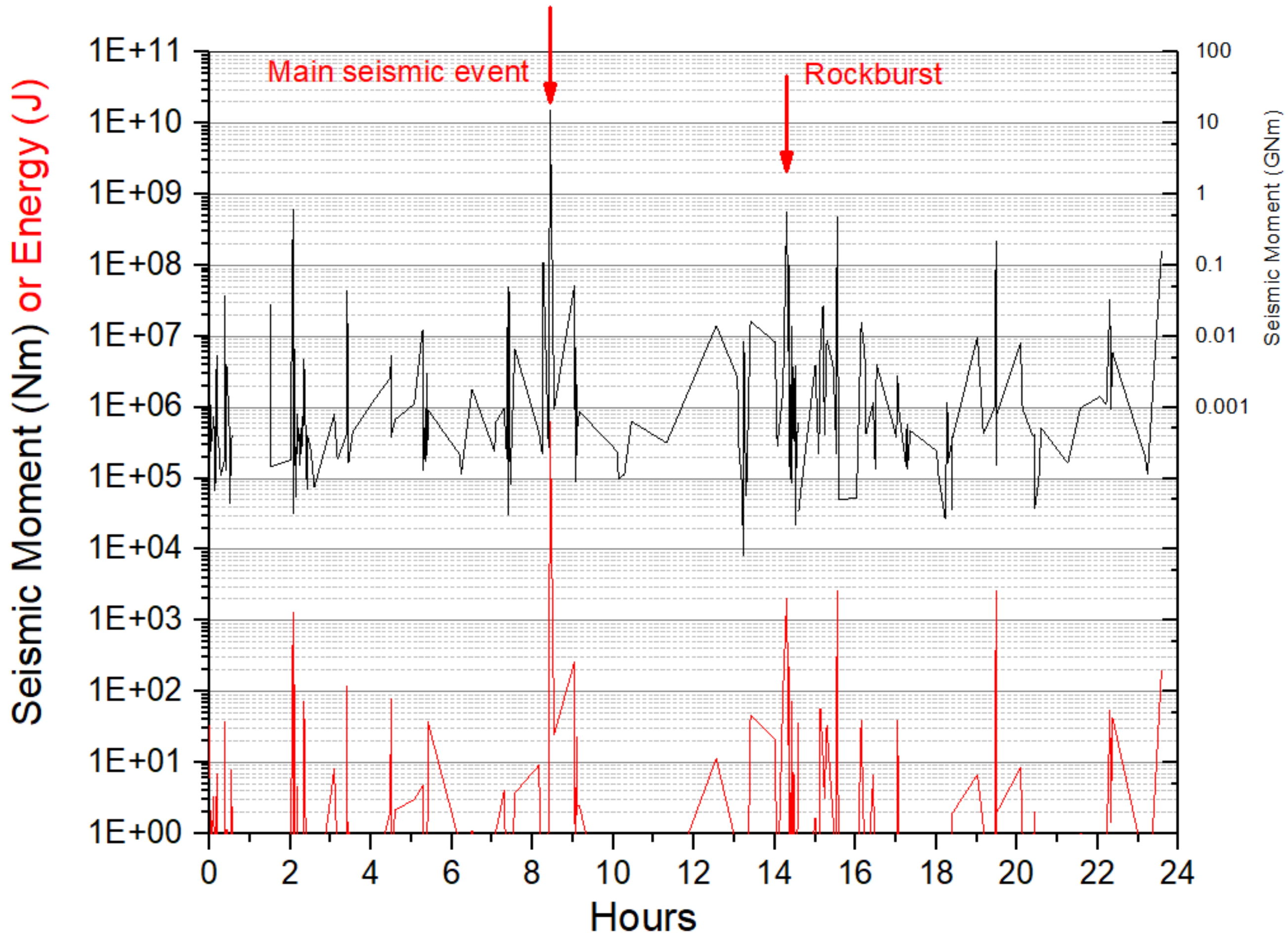
Other example with induced main seismic event, successive seismicity reduction (E and Mo) and final rockburst occurrence





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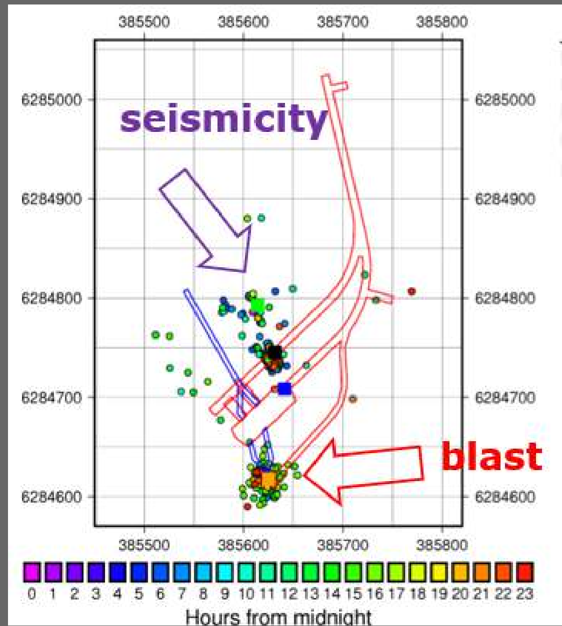
Conclusive Remarks

- Blasting induces seismicity in the surrounding rock mass and local geo-conditions may **increase** the radiated energy, eventually resulting in strainburst in other tunnel.
- Seismicity from successive blastings, in the same or different tunnels, may **overlap/interfere**, so increasing the probability of triggering strainburst
- Some **drop of energy** after main seismic event is frequently observed before strainburst (see also [13, 20])



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Thank you for your attention!

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