Itasca Constitutive Model for Advanced Strain Softening
IMASS

Background and Applied Examples

Séance technique du CFMR 27 Mai 2021
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Agenda

I. Brief introduction to strain-softening constitutive models

II. Theory of *IMASS*

III. Examples

IV. Questions and answer session

Details about *IMASS* at www.itascainternational.com/software/imass

Ghazvinian, Ehsan & Garza-Cruz, T & Bouzeran, Lauriane & Fuenzalida, M & Cheng, Zhao & Cancino, Christian & Pierce, M. (2020). Theory and Implementation of the Itasca Constitutive Model for Advanced Strain Softening (IMASS).

Introduction

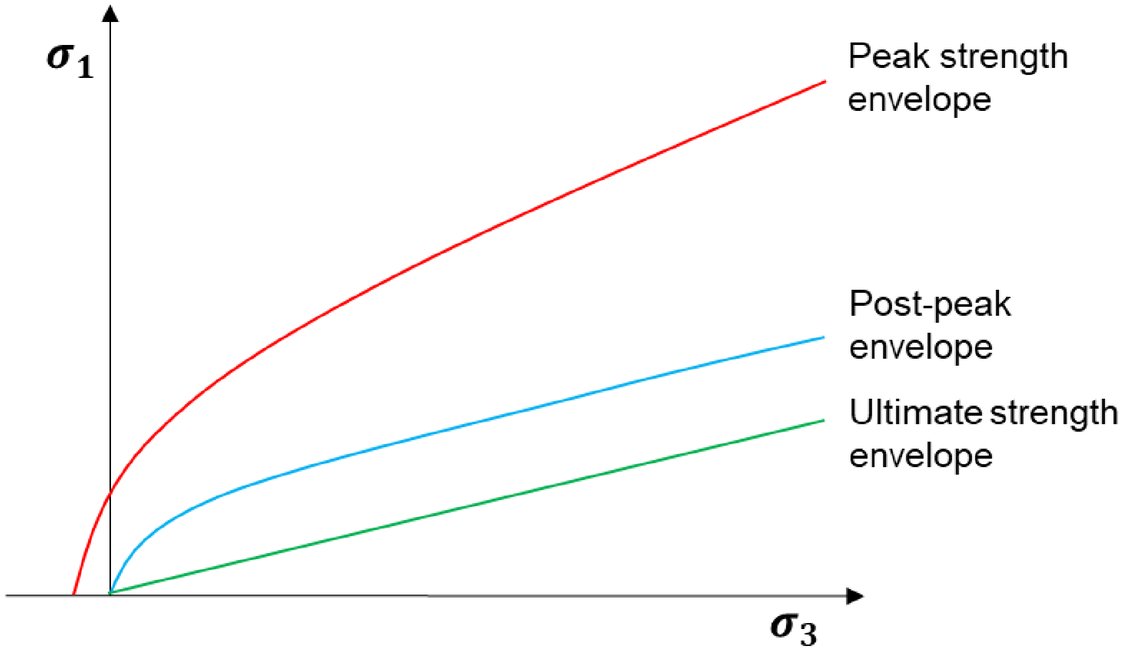
A numerical model that represents the damage around an excavation, slope or caving process must account for the **progressive failure and disintegration of the rock mass from an intact/jointed condition to a bulked material**. Four critical factors that control the overall behavior of the rock mass matrix during this process are:

- Cohesion and Tension Weakening and Frictional Strengthening
- Post Peak Brittleness
- Modulus Softening
- Dilatational Behavior

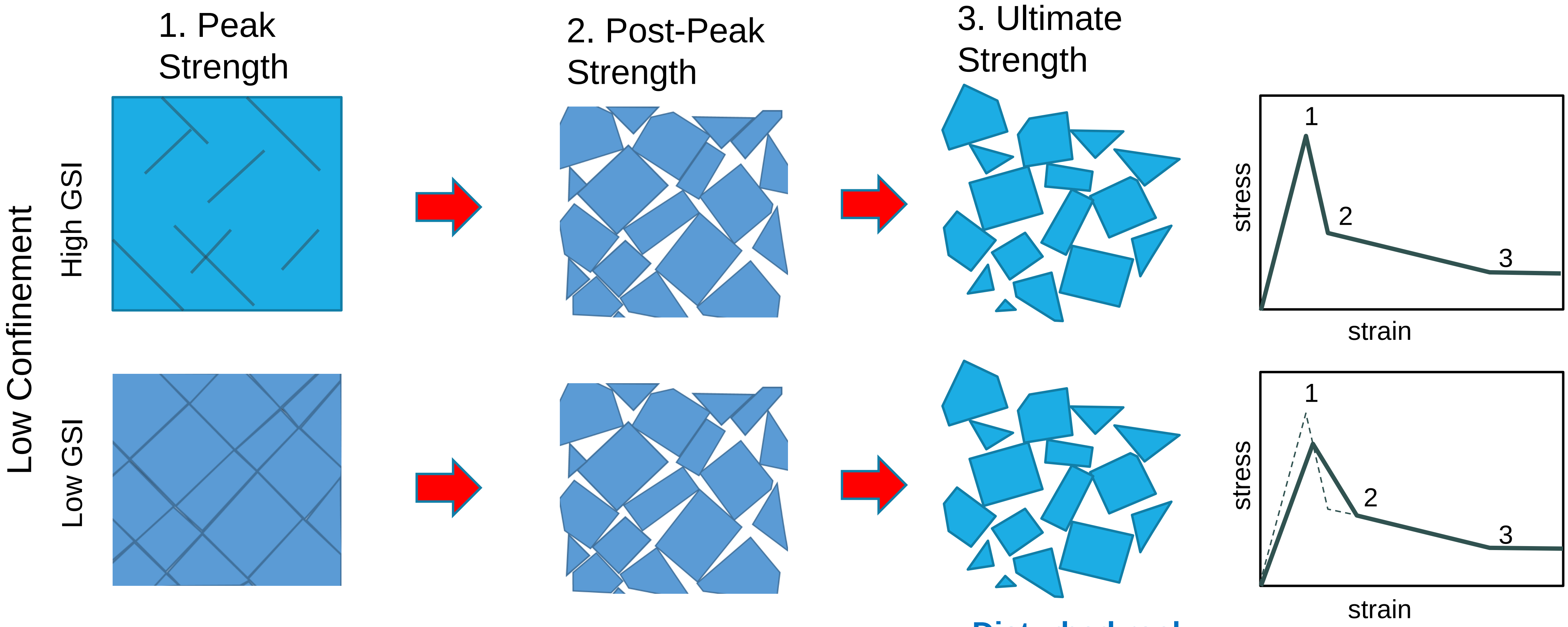
This overall process – loading the rock mass to its peak strength, followed by a post-peak reduction in strength to some residual level with increasing strain – often is termed a “strain-softening” process and is the result of strain-dependent material properties.

IMASS constitutive model

- The Itasca Constitutive Model for Advanced Strain Softening *(IMASS)* is a successor to the original *CaveHoek* constitutive model (first appearing in 2010)
- In terms of strength envelopes, *CaveHoek* is characterized by two bounding yield surfaces (peak and residual)
- After many successful projects and new discoveries about brittle rock behavior, a new strain softening model has been created (Itasca Model for Advanced Strain Softening)
- *IMASS* contains two softening (residual) yield surfaces



Damage and disturbance in *IMASS*



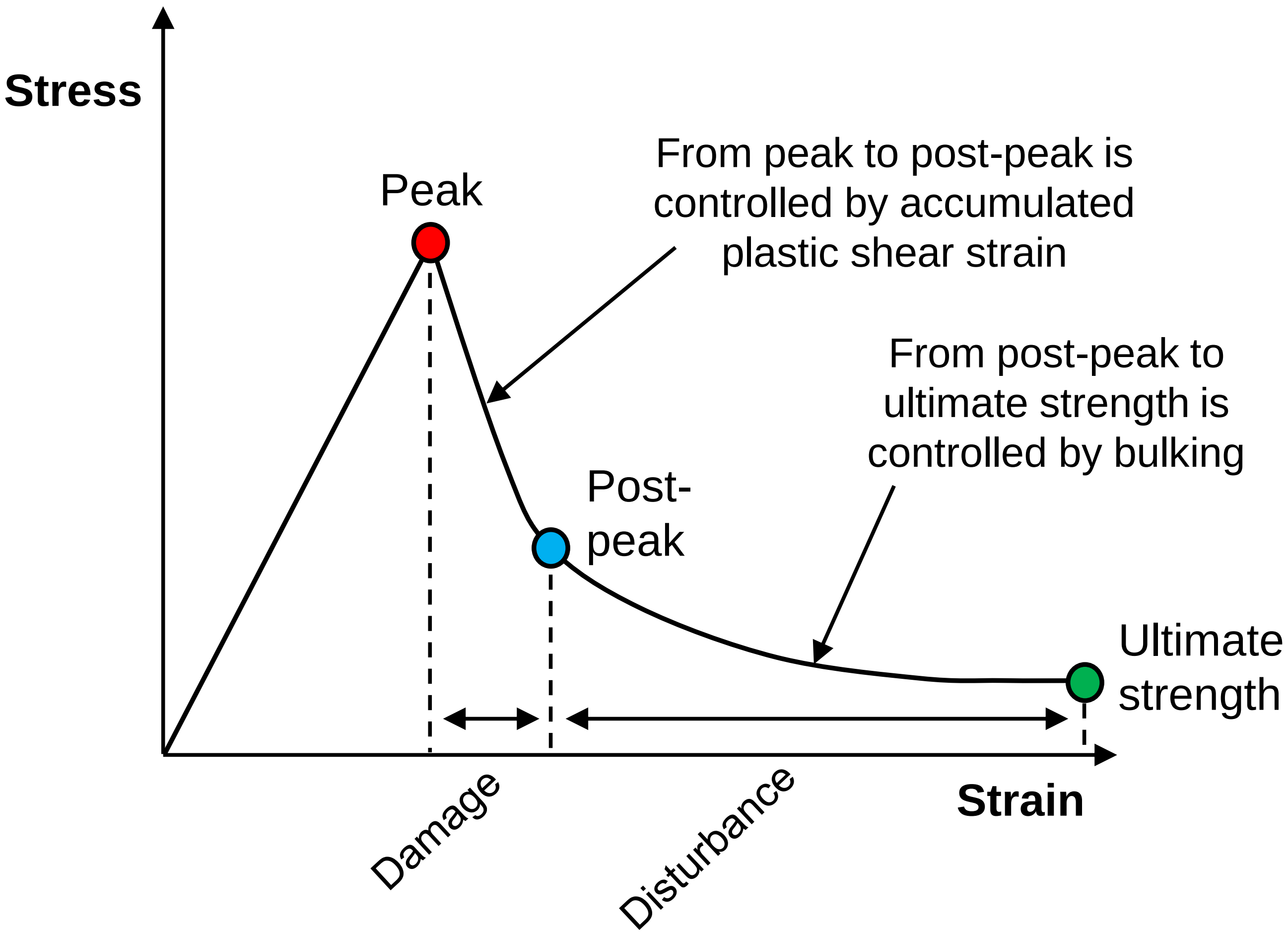
Damaged rock

- Damage due to fracturing of intact rock
- Small (negligible) bulking
- **Small strain processes**
- **Damage is dependent on the accumulation of plastic shear strain**

Disturbed rock

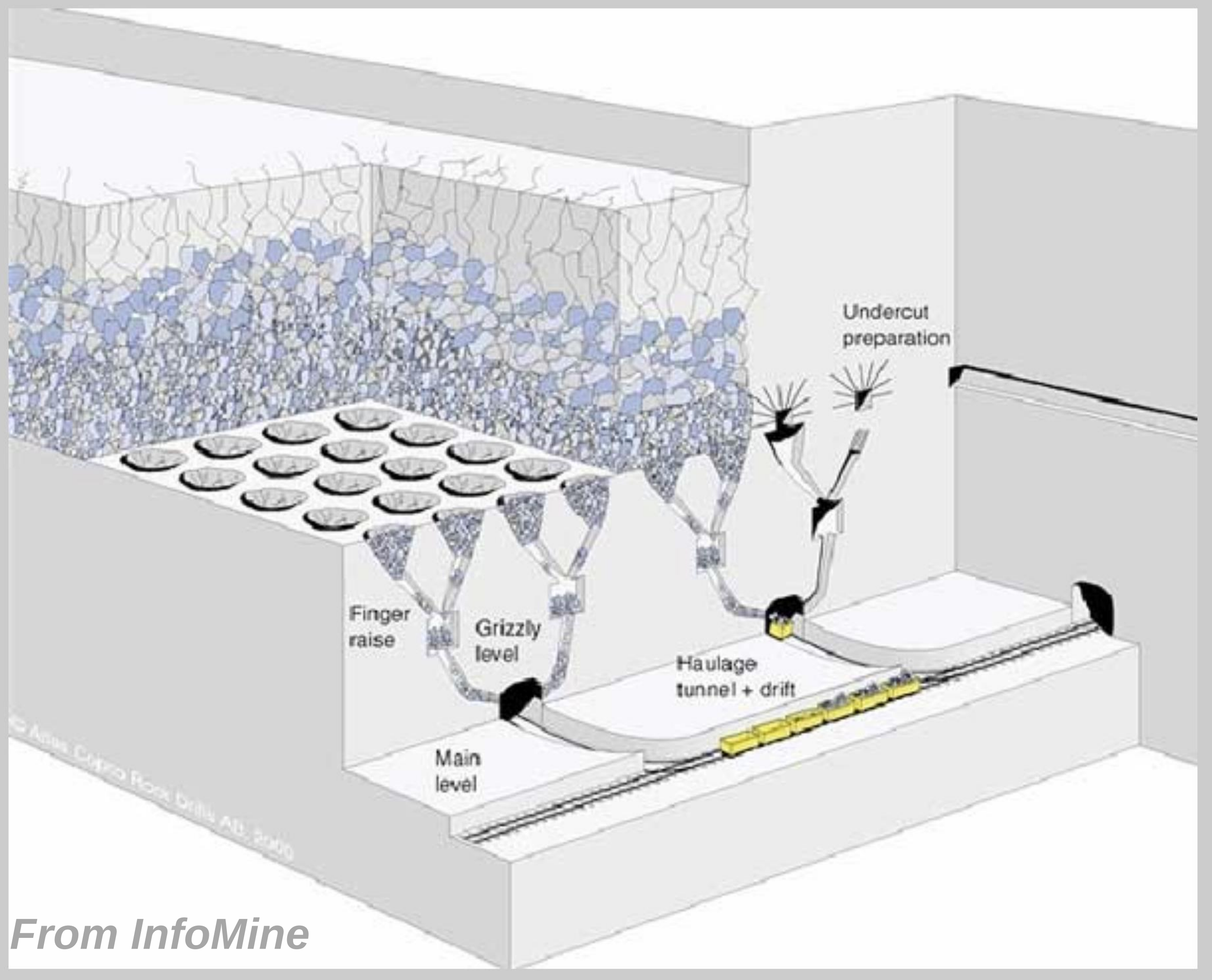
- Disturbance due to rearrangement of rock blocks
- Significant increase in bulking
- **Large strain processes**
- **Disturbance is dependent on the accumulation of volumetric strain**

Conceptual stress-strain curve

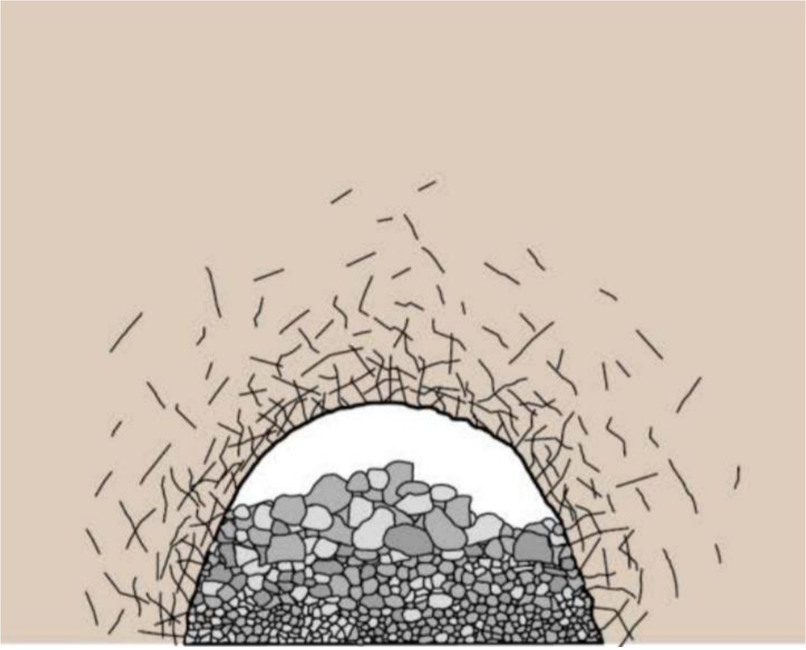


Conceptual stress-strain curve – **Caving Background**

Caving: *Exploitation minière souterraine dans laquelle des sections d'un grand gisement (à faible teneur en minerai) sont creusées (sous le gisement) puis autorisées à s'effondrer sous les contraintes naturelles, le minerai ainsi concassé étant récupéré par des galeries.*



From InfoMine



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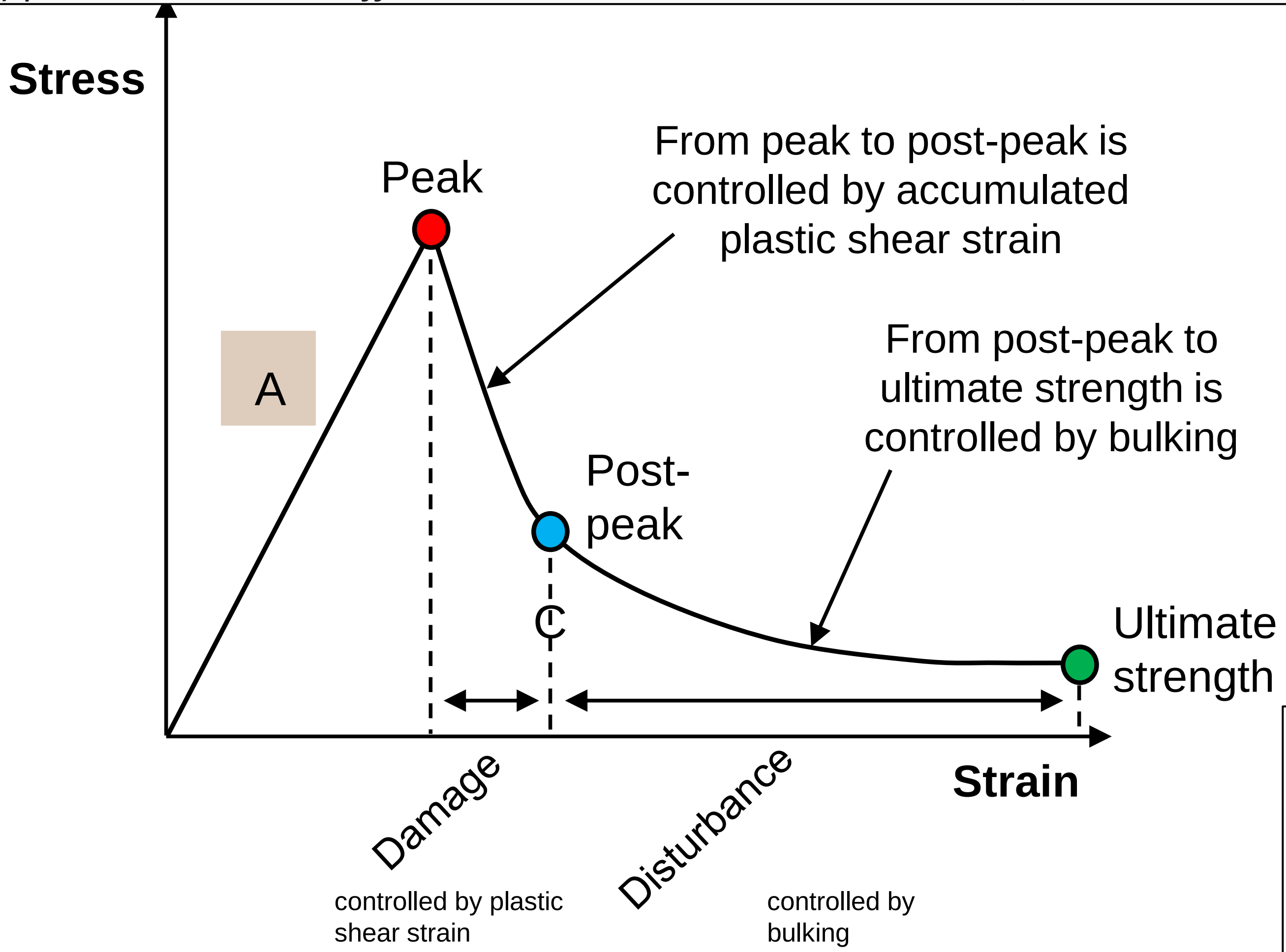

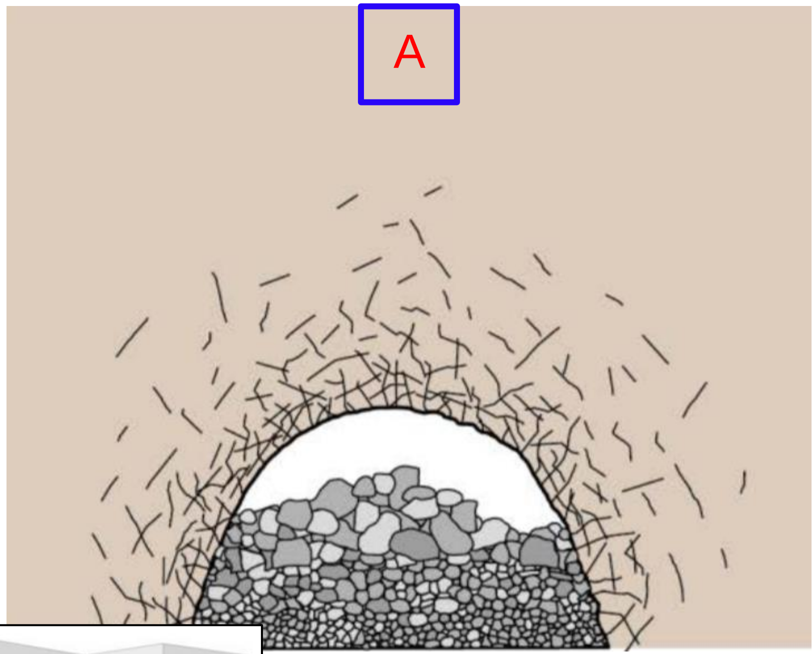

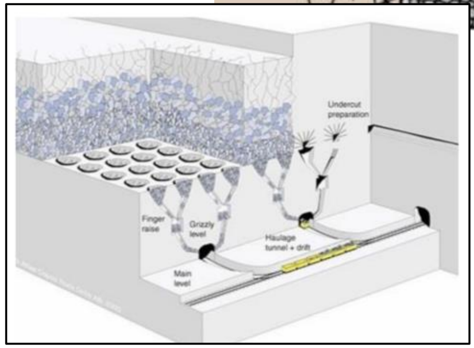

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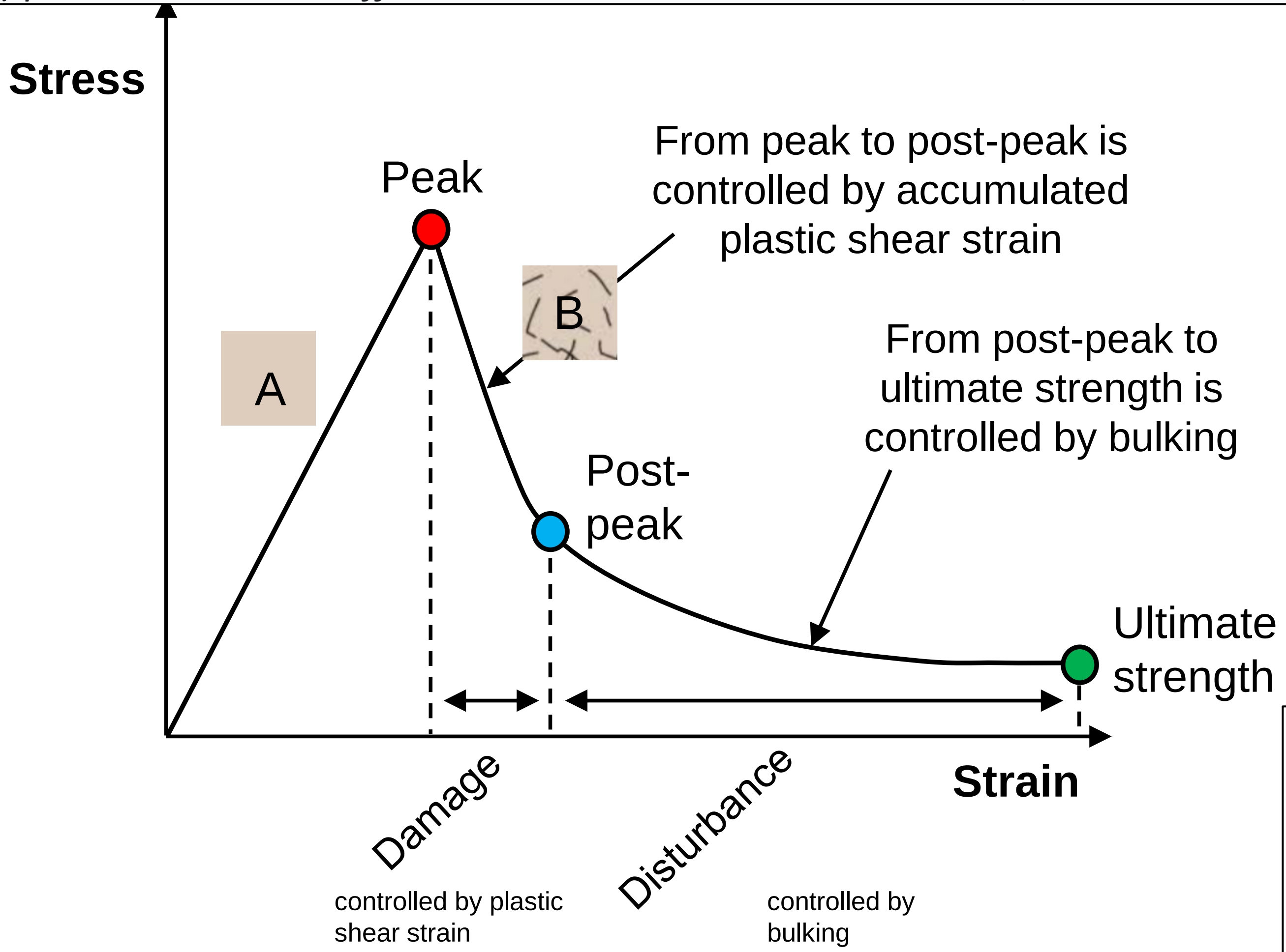

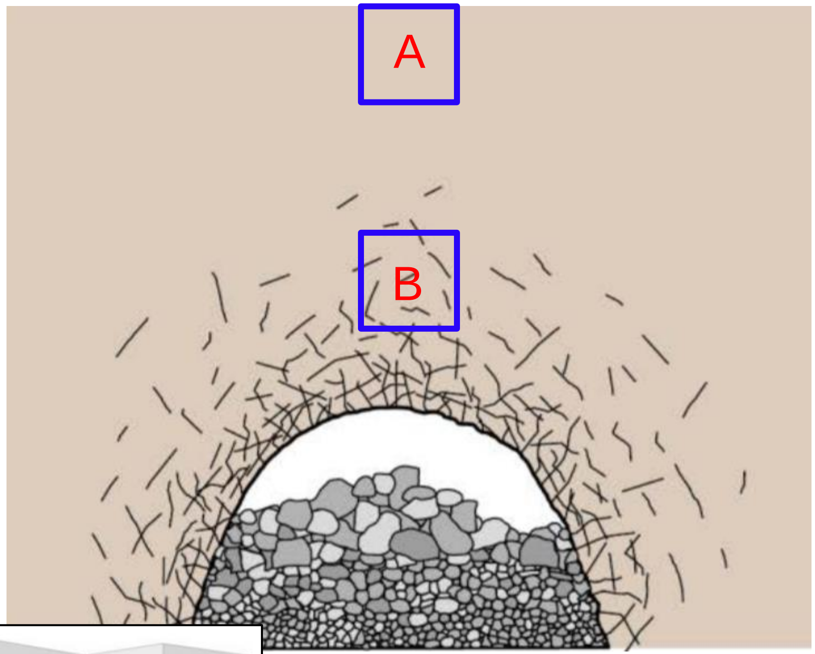

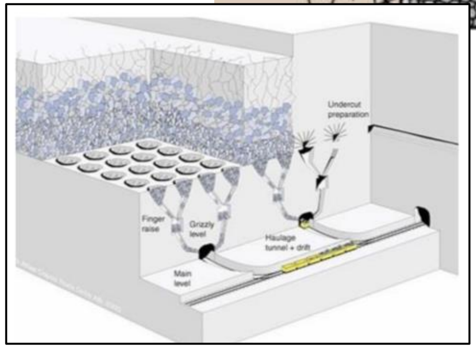

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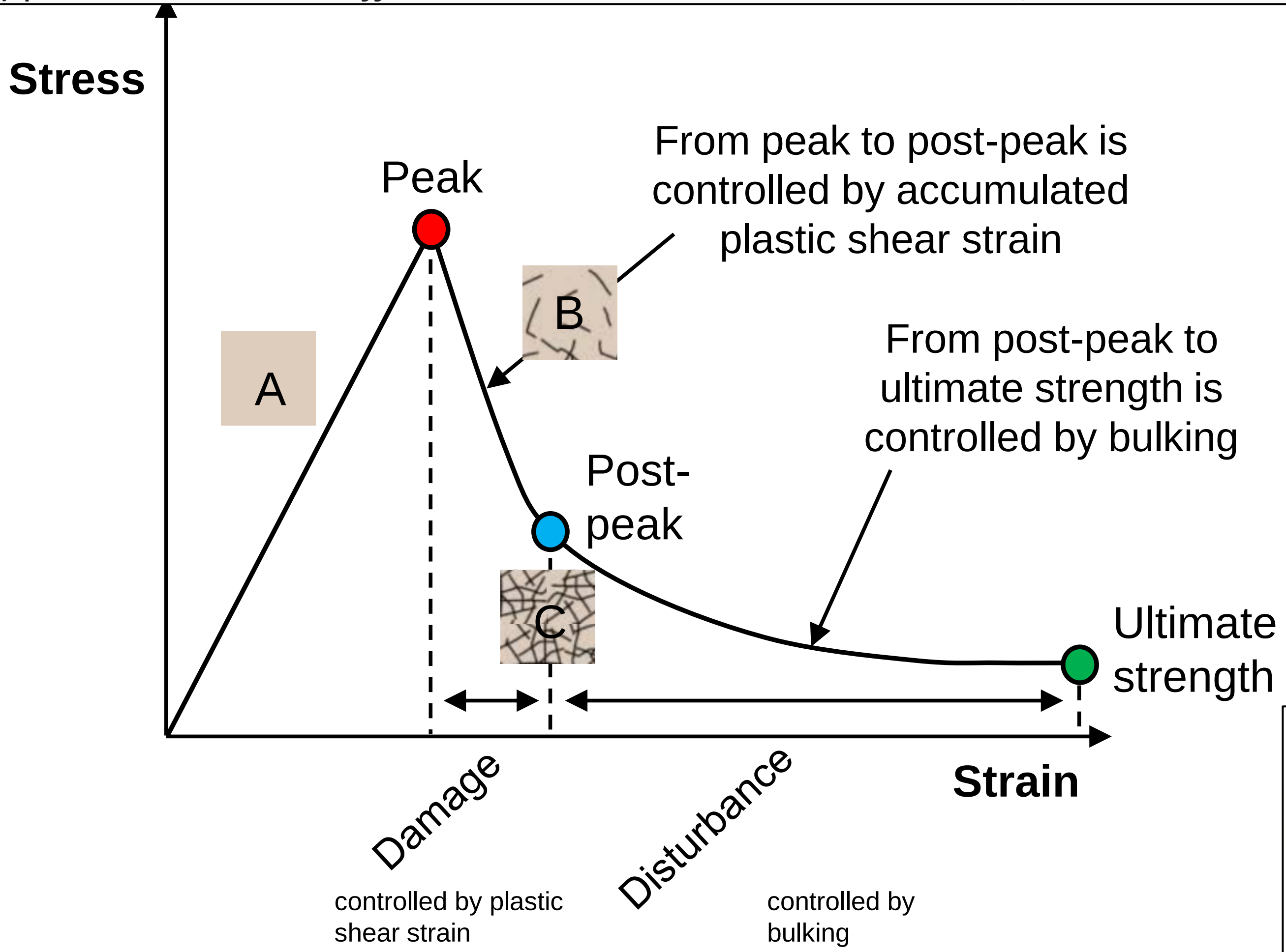

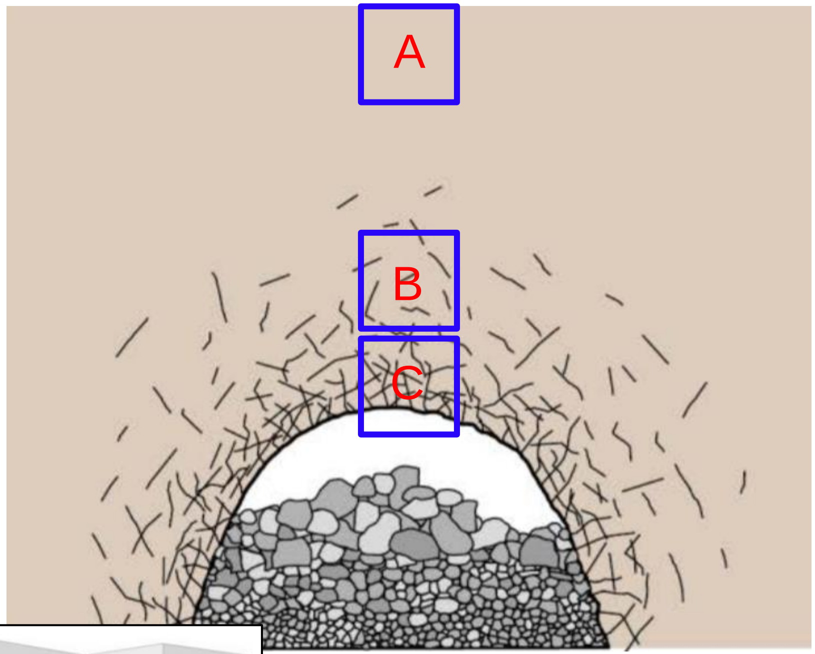

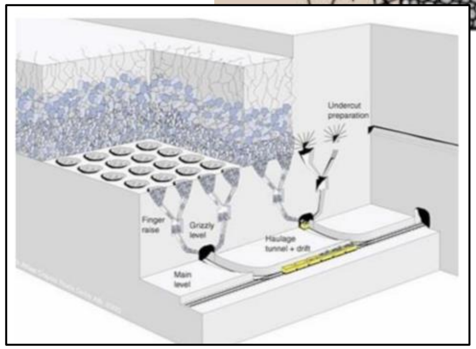

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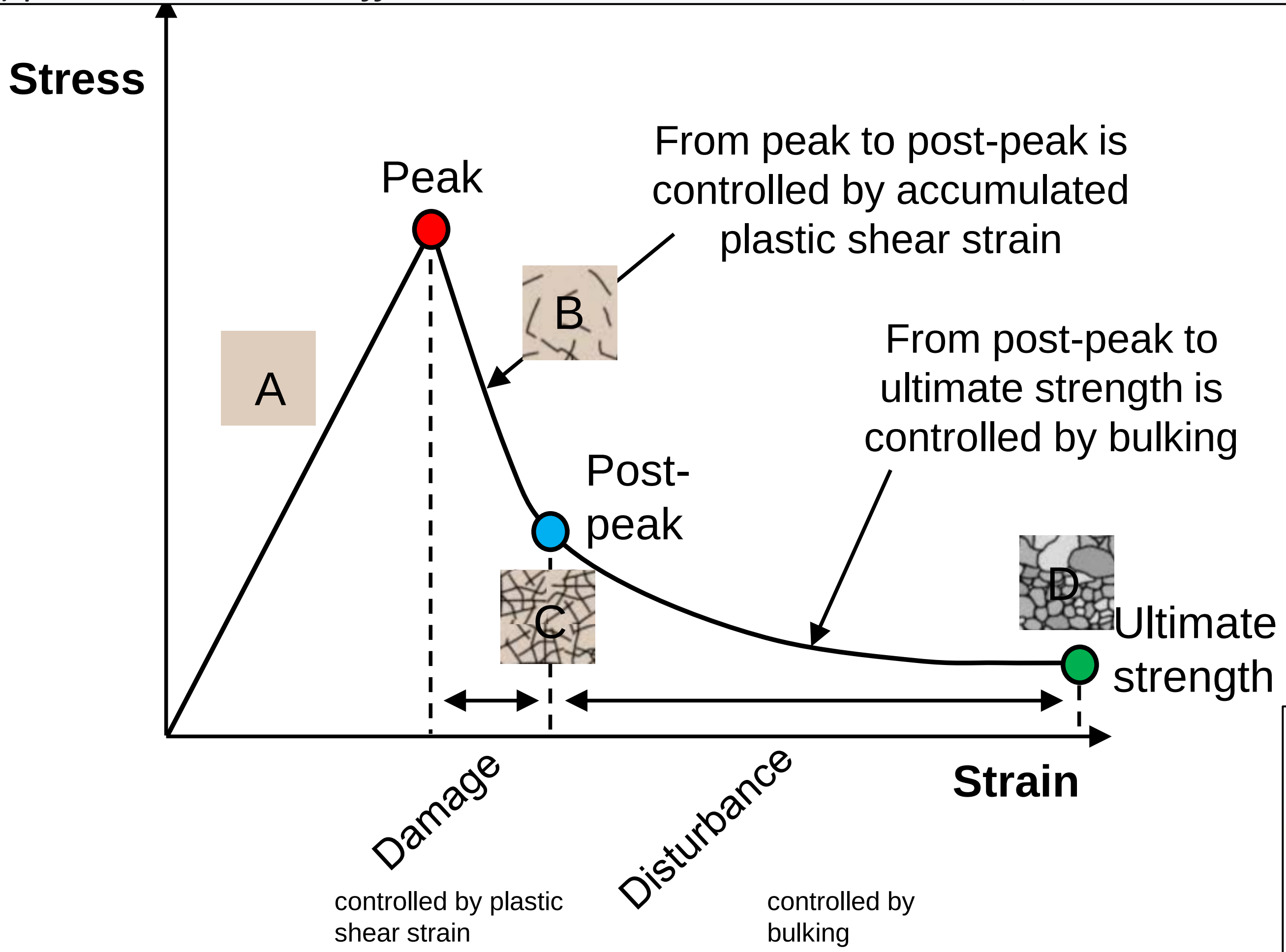
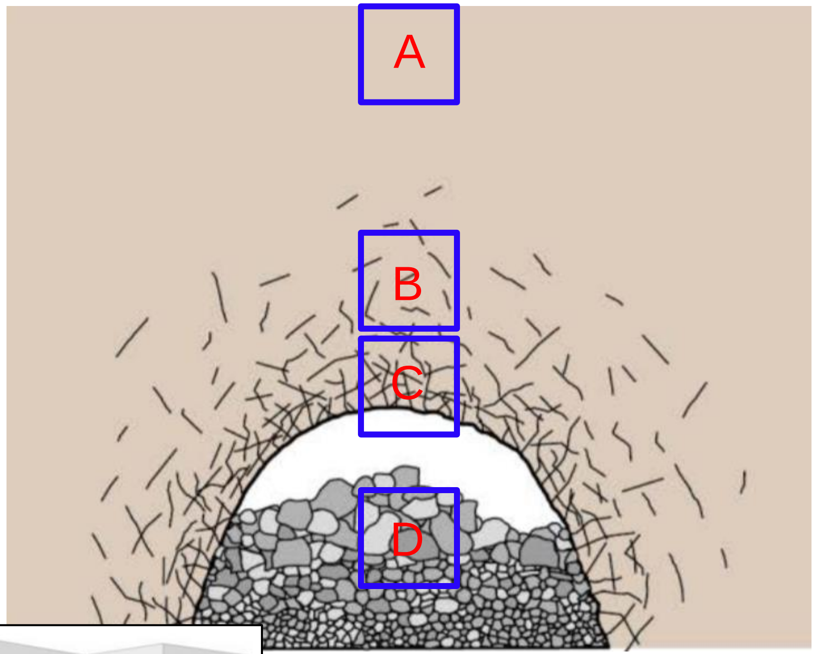
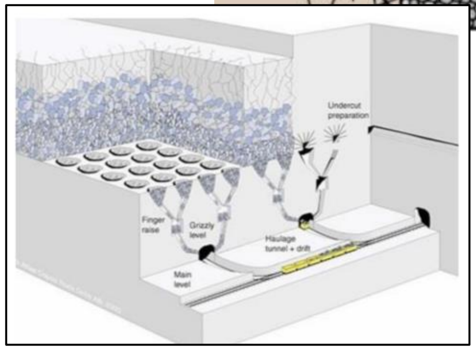


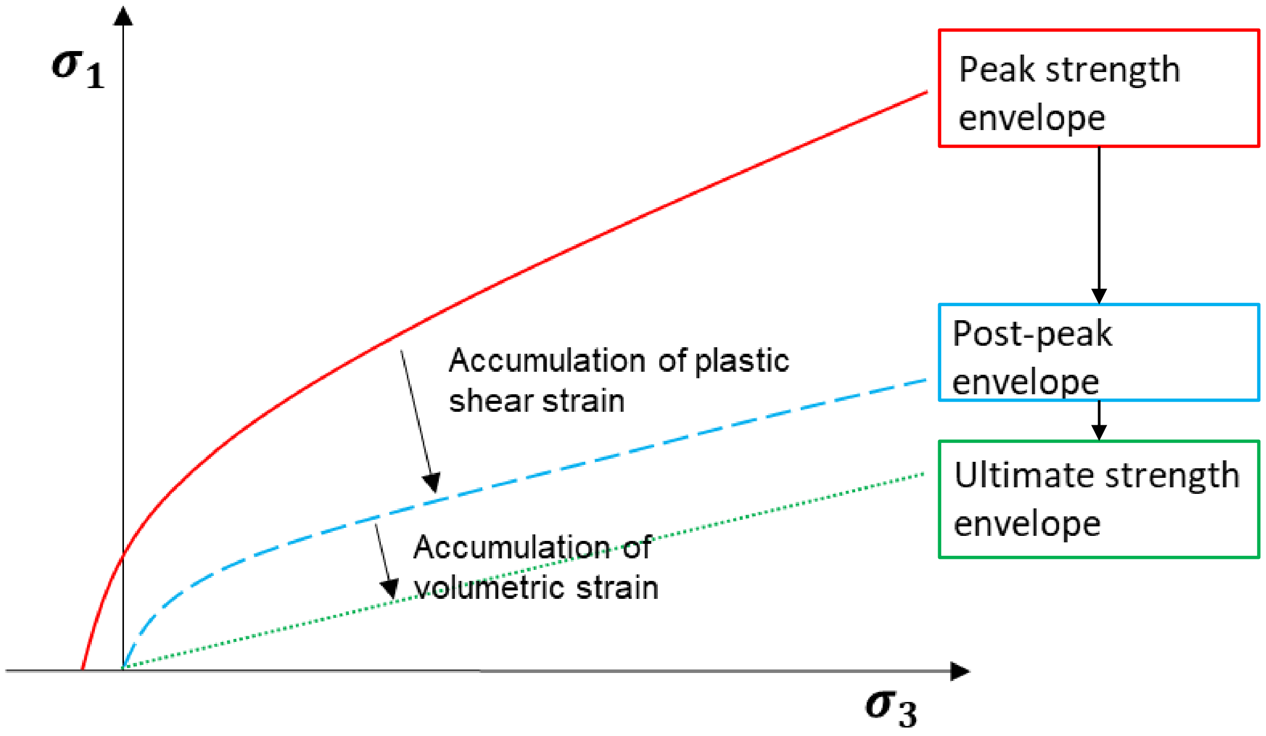




Strength weakening in *IMASS*

- *IMASS* constitutive model is defined by **three Hoek-Brown strength envelopes**
- The GSI, m_i, and UCS parameters control the shape of the **peak Hoek-Brown envelope** (Hoek et al., 2002)
- The Hoek-Brown parameters of the residual strength envelopes are calculated in order to approximate **Barton & Kjaernsli (1981) shear strength for rockfill material**:

$$\tau = \sigma_n \tan\left(R.\log\left(\frac{S}{\sigma_n}\right) + \emptyset_b\right)$$

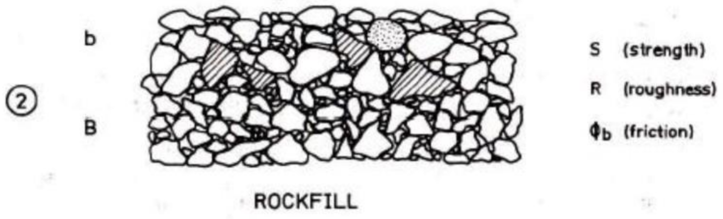


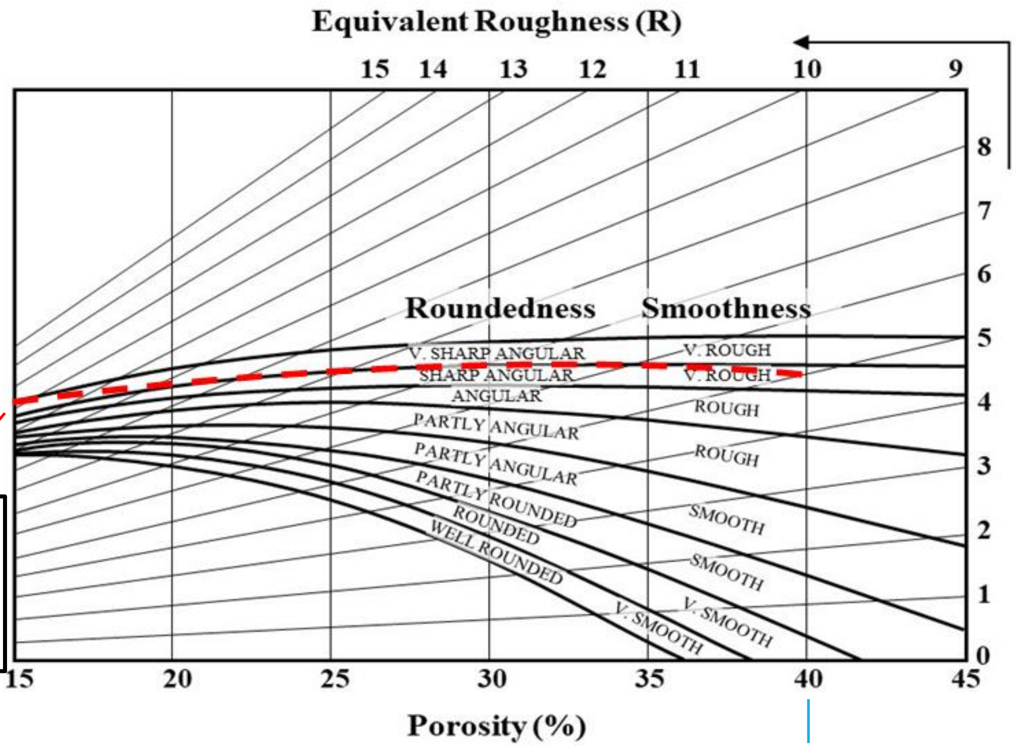
Residual strength envelopes in *IMASS*

Barton & Kjaernsli (1981)

$$\tau = \sigma_n \tan\left(R.\log\left(\frac{S}{\sigma_n}\right) + \emptyset_b\right)$$

τ *=Shear Strength*
$\emptyset_b$ *=Basic friction Angle*
S/σ_n *=Rock Block Strength/ Normal Stress*
R = *Equivalent Roughness* (See Nomogram)

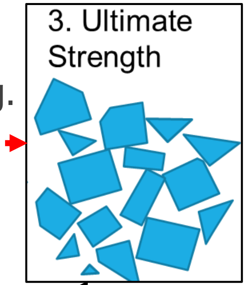




Extrapolated to 0% porosity

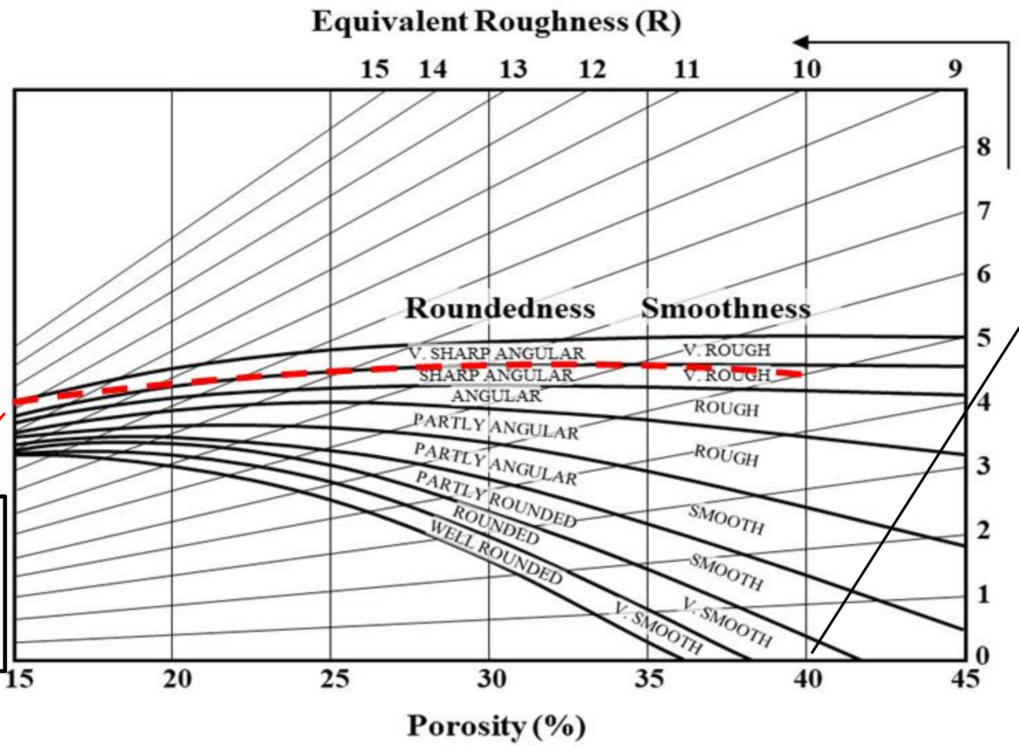
Residual strength envelopes in *IMASS*

Ideally, the first and second residual envelops describe the behavior of cohesionless perfectly frictional material with different degrees of interlocking.



At **post-peak strength** the rock mass is assumed to have undergone fracturing, but the resulting **rock fragments are still fully interlocked** hence porosity is considered to be zero.

Extrapolated to 0% porosity



The **ultimate strength envelope** represents the true rock mass residual strength. At this point, the degree of rock fragments interlocking is at its minimum, and the **porosity is maximized** (maximum porosity of 40% is assumed).

Residual strength envelopes in *IMASS*

Barton & Kjaernsli (1981)

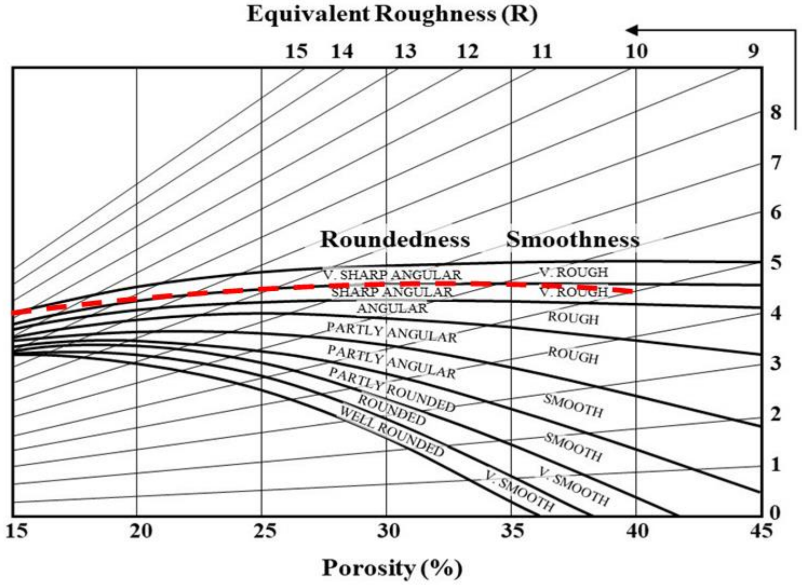
$$\tau = \sigma_n \tan\left(R.\log\left(\frac{S}{\sigma_n}\right) + \emptyset_b\right)$$

Equation converted to a strength envelope in σ_1 - σ_3 space, and approximated by a Hoek-Brown envelope with the following parameters:

$$\boldsymbol{s} = 0$$

$$\boldsymbol{a} = 0.6 + \frac{\boldsymbol{porosity}}{porosity_{max}} \times [(1 - 0.075 \times \boldsymbol{ri}) - 0.6]$$

$$\boldsymbol{m_b} = 0.1614 \times e^{0.0836 \times \boldsymbol{in\_weak\_phib}}$$



where,

- **ri is the roundedness index** (with ri = 0 for partly rounded/smooth blocks, ri = 1 for angular/rough blocks, and ri = 2 for very sharp, angular/very rough blocks.

- ***in_weak_phib*** is equivalent to $\emptyset_b$ (in degrees and default = 30 deg)

Residual strength envelopes in *IMASS*

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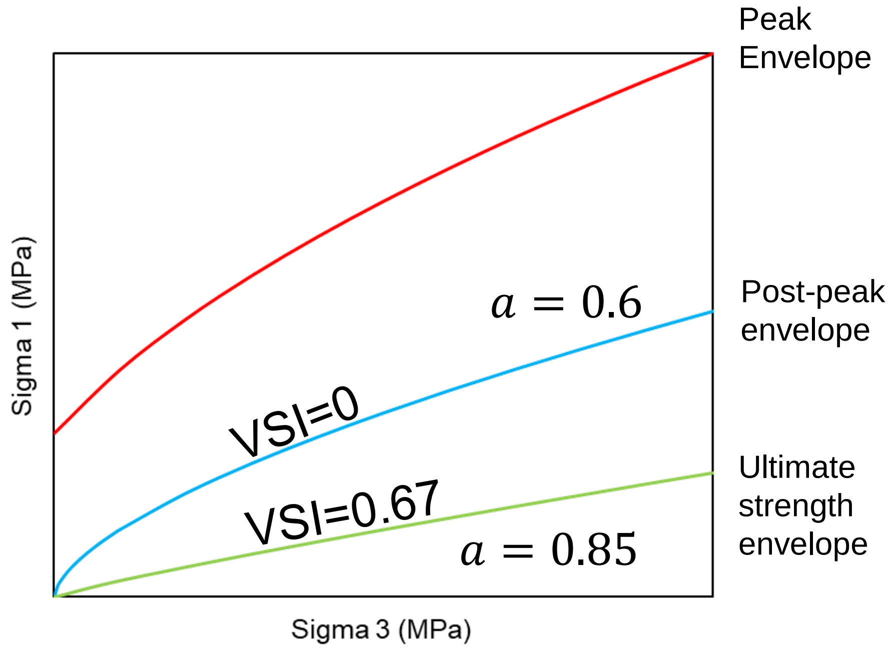
$$ri = 2$$

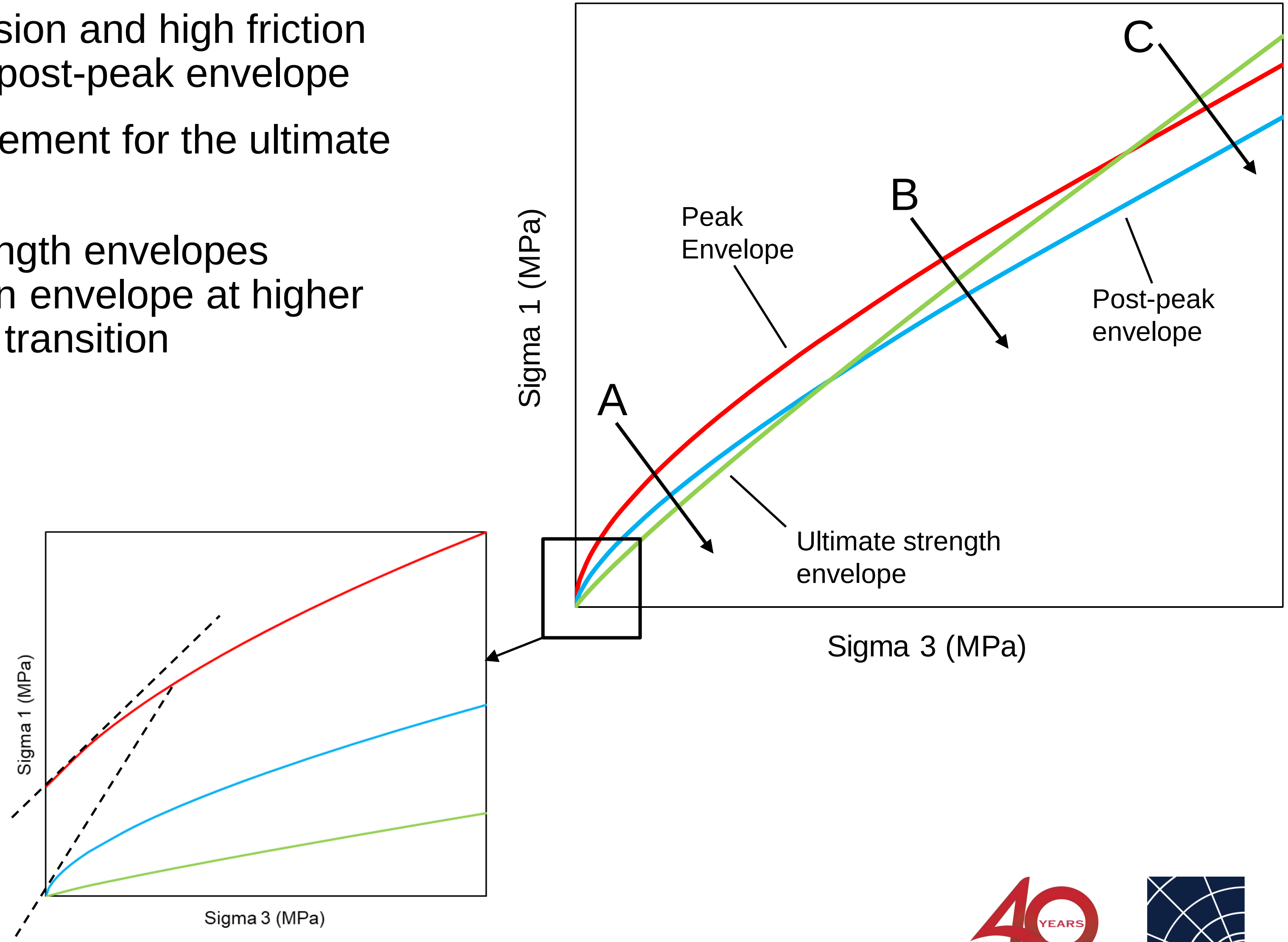
$$a = 0.6 + (\frac{VSI}{0.67} \times 0.25)$$

assumes formation and interaction of very sharp, angular and very rough fragments during the course of bulking, from porosity 0% to 40%.

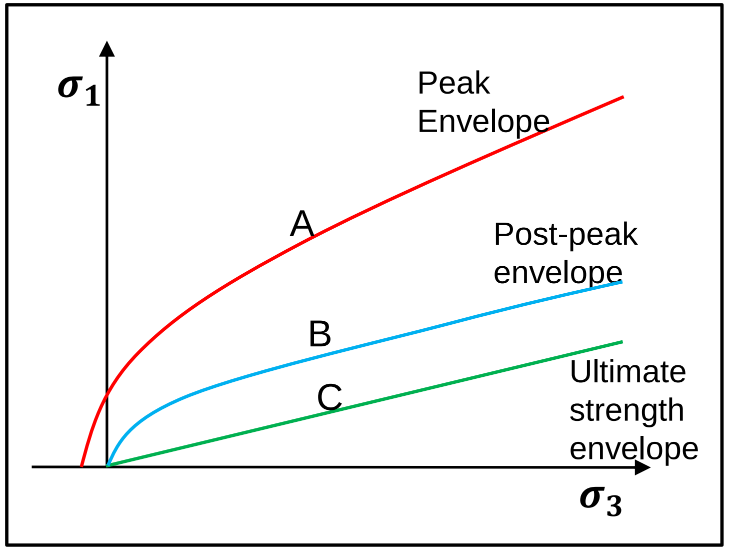


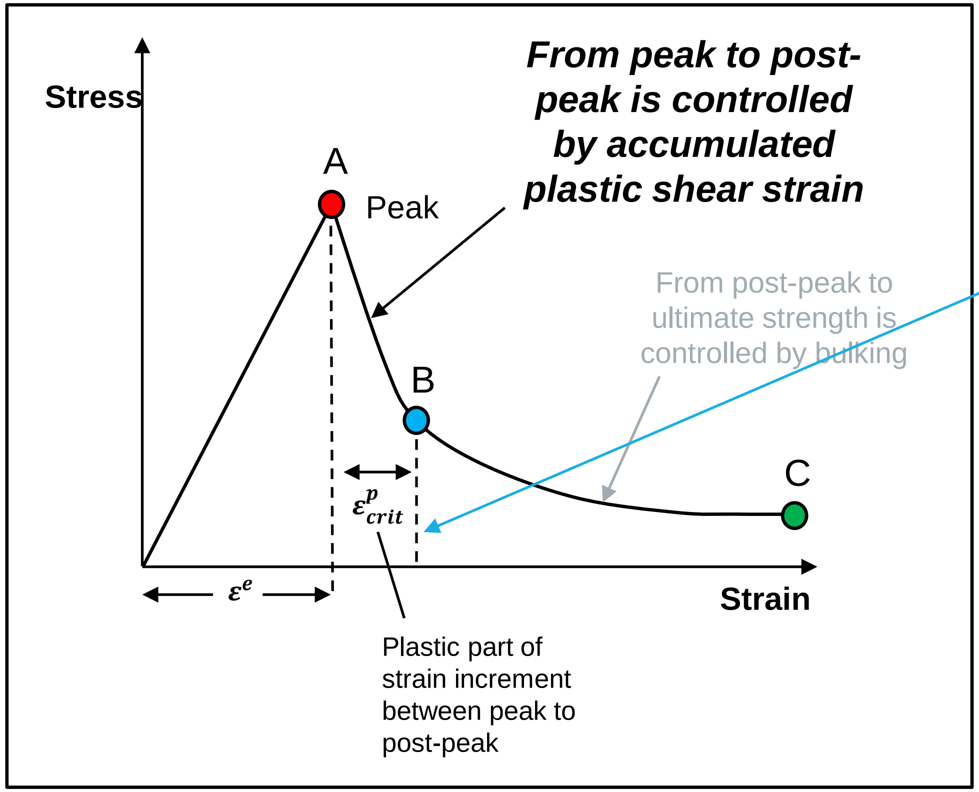
Characteristics of *IMASS* residual envelopes

- Zero or near zero apparent cohesion and high friction angle at low confinement for the post-peak envelope
- Lower friction angle at low confinement for the ultimate strength envelope
- Both post-peak and ultimate strength envelopes continue to use peak Hoek-Brown envelope at higher confinement above brittle-ductile transition



Post-peak brittleness



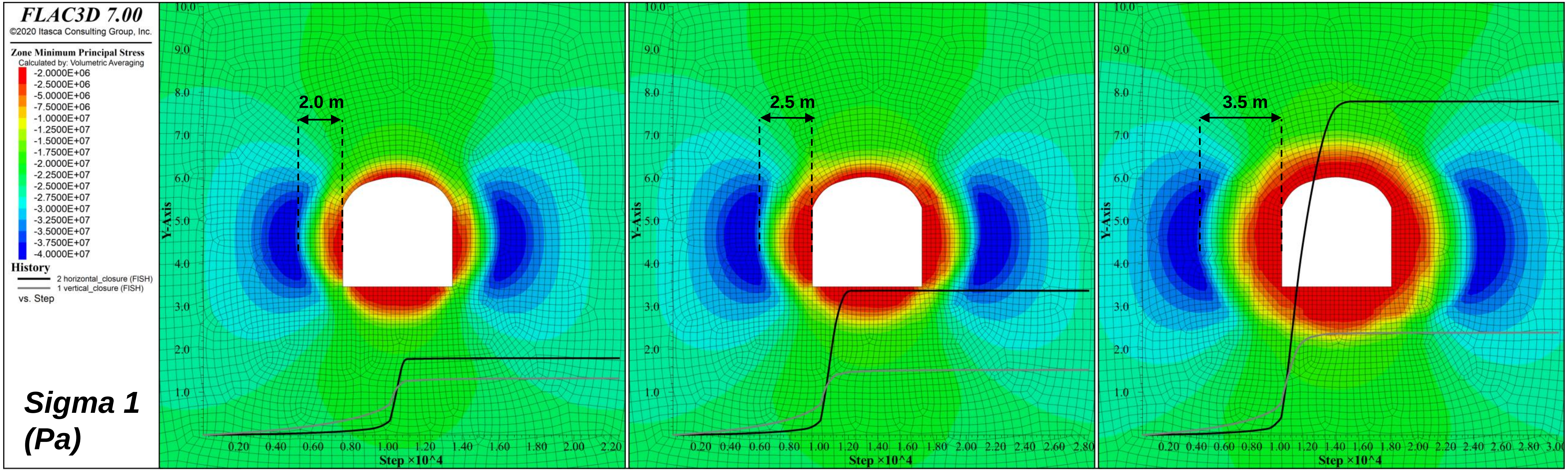


Critical Plastic Shear Strain:

$$\varepsilon^p_{crit} = \frac{12.5 - 0.125 * GSI}{100 * d}$$

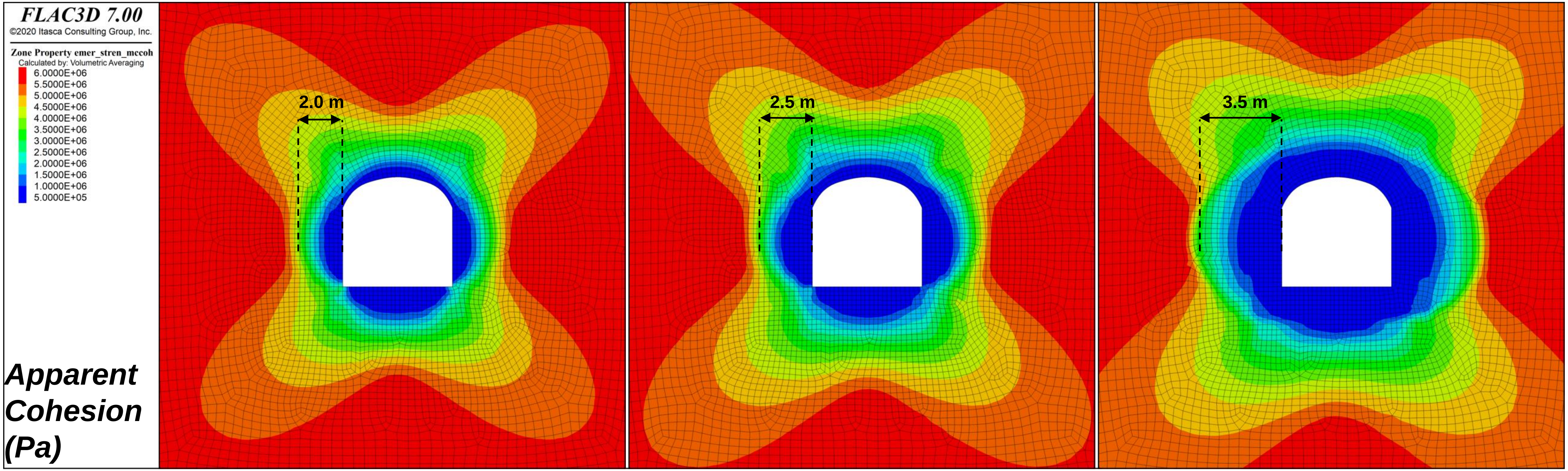
(Lorig & Pierce, 2000)

Critical Strain sensitivity



Multiplier ecrit = 1.0	Multiplier ecrit = 0.1	Multiplier ecrit = 0.01
ε^{p}_{crit} ~ 30%	ε^{p}_{crit} ~ 3%	ε^{p}_{crit} ~ 0.3%
Vertical tunnel closure ~ 1%	Vertical tunnel closure ~ 1%	Vertical tunnel closure ~ 2%
Horizontal tunnel closure ~ 2%	**Horizontal tunnel closure ~ 3.5%**	**Horizontal tunnel closure ~ 8%**

Cohesion weakening



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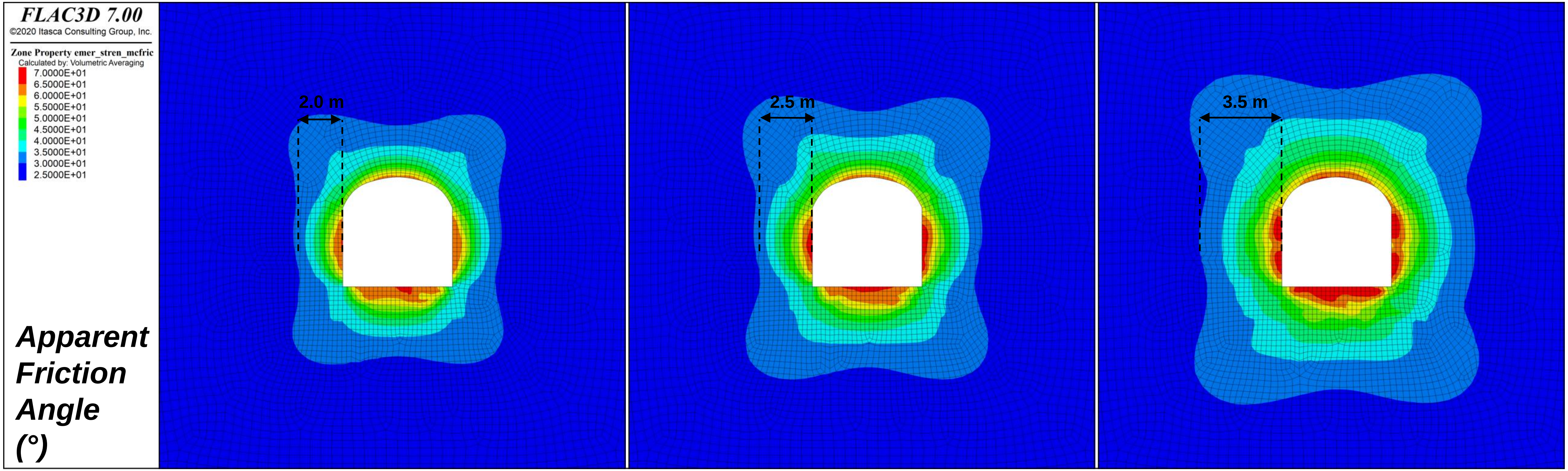
Frictional strengthening



Multiplier ecrit = 1.0	Multiplier ecrit = 0.1	Multiplier ecrit = 0.01
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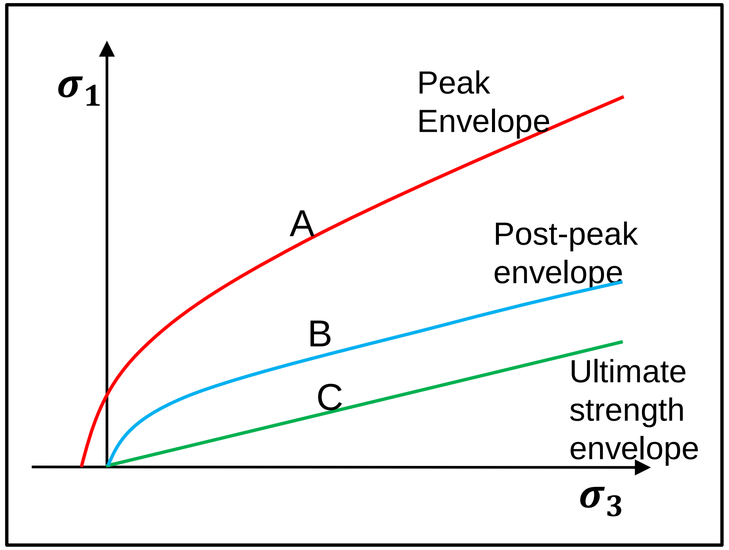
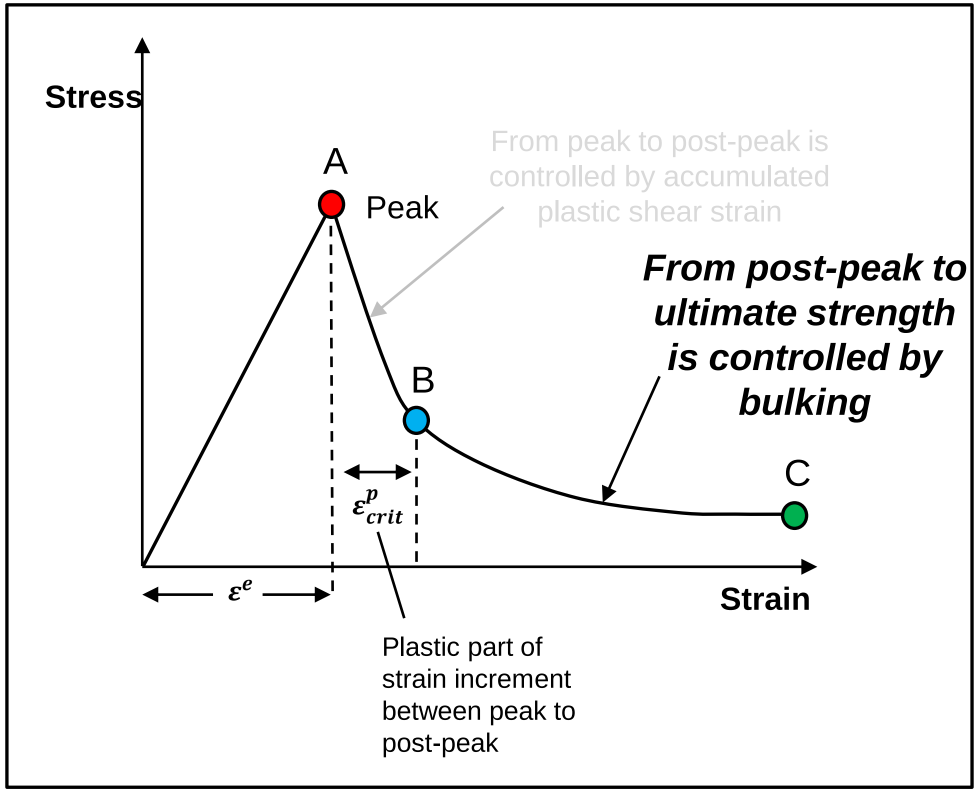
Vertical tunnel closure ~ 1%	Vertical tunnel closure ~ 1%	Vertical tunnel closure ~ 2%
Horizontal tunnel closure ~ 2%	**Horizontal tunnel closure ~ 3.5%**	**Horizontal tunnel closure ~ 8%**

Porosity-dependent softening/weakening





$$a = 0.6 + \left(\frac{VSI}{0.67} \times 0.25\right)$$

$$B = \frac{\Delta V}{V_i} = \frac{n}{1-n}$$

- Residual strength can weaken and strengthen between post-peak and ultimate strength envelopes as a function of porosity
- This would allow for capturing strength gain in material due to recompaction

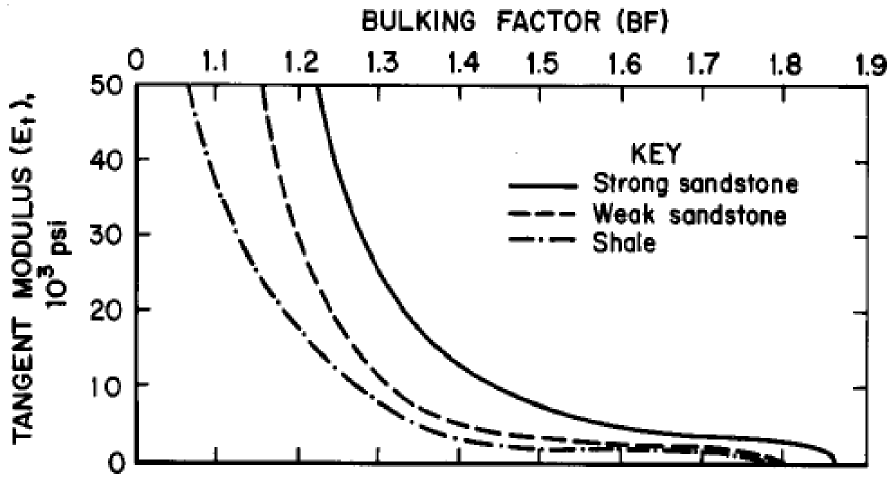
Modulus softening

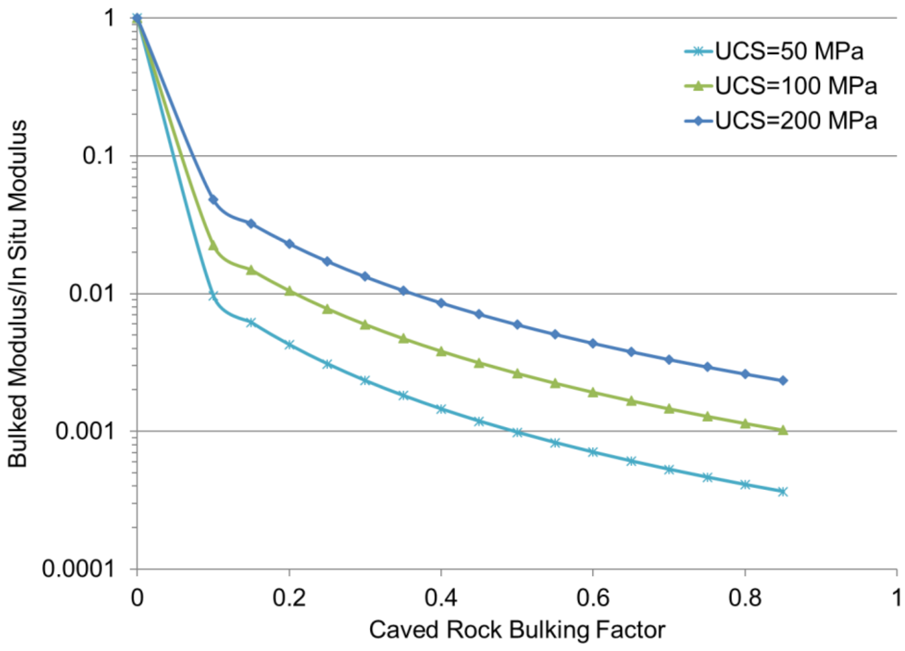
The rock mass Young's modulus (E_{rm}) can be estimated from the intact Young's modulus (E_i) and GSI using **Hoek and Diederichs' (2006)** equation:

$$E_{rm} = E_i \left(0.02 + \frac{1}{1+e^{\frac{60-GSI}{11}}}\right)$$

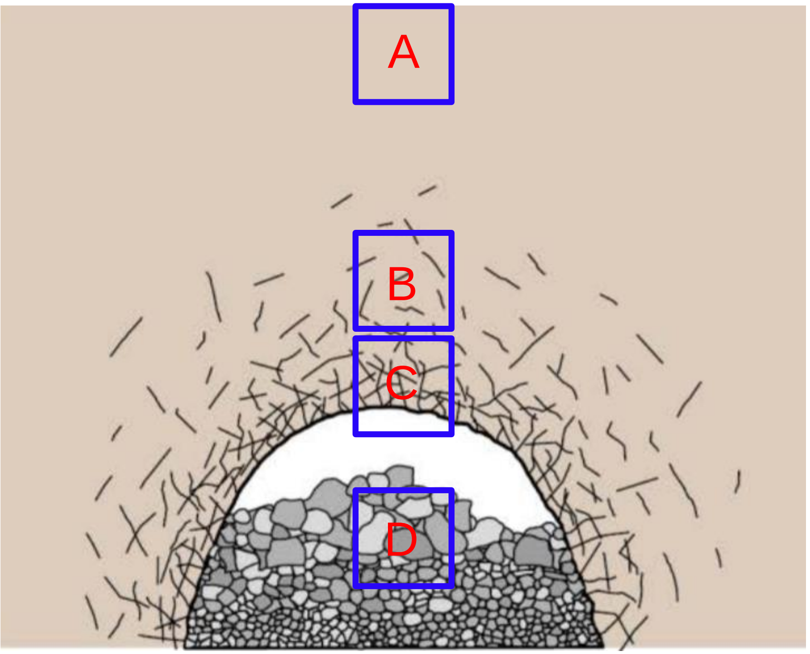
Pappas and Mark (1993) show that the modulus of rock drops in a non-linear fashion with increased bulking, and that the rate of modulus change is a function of fragment shape and intact strength

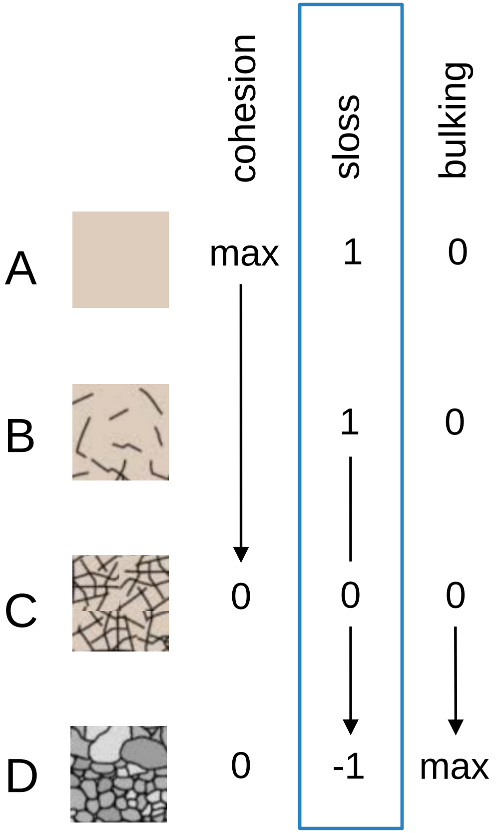
In *IMASS* the modulus is updated constantly via the zone-based volumetric strains. This allows for both modulus softening (during bulking) and modulus hardening (e.g., during recompaction)

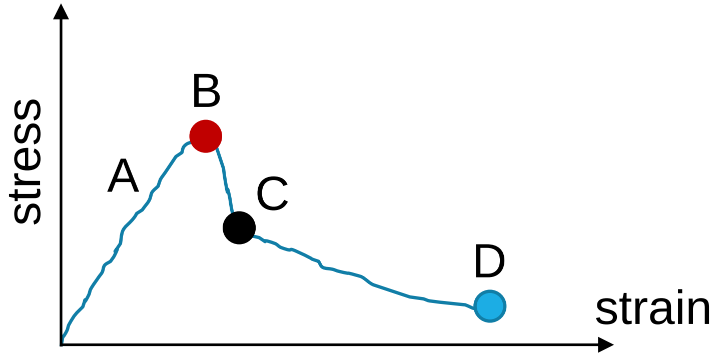


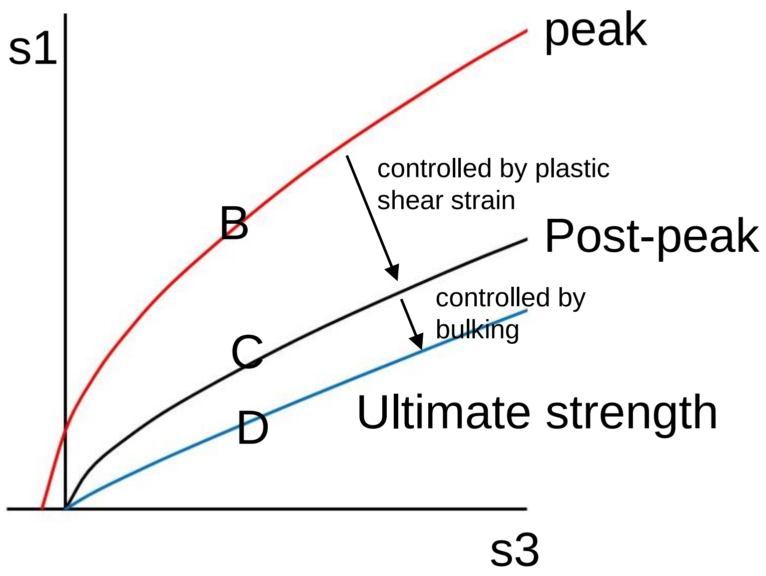


sloss – an indicator for damage in *IMASS*









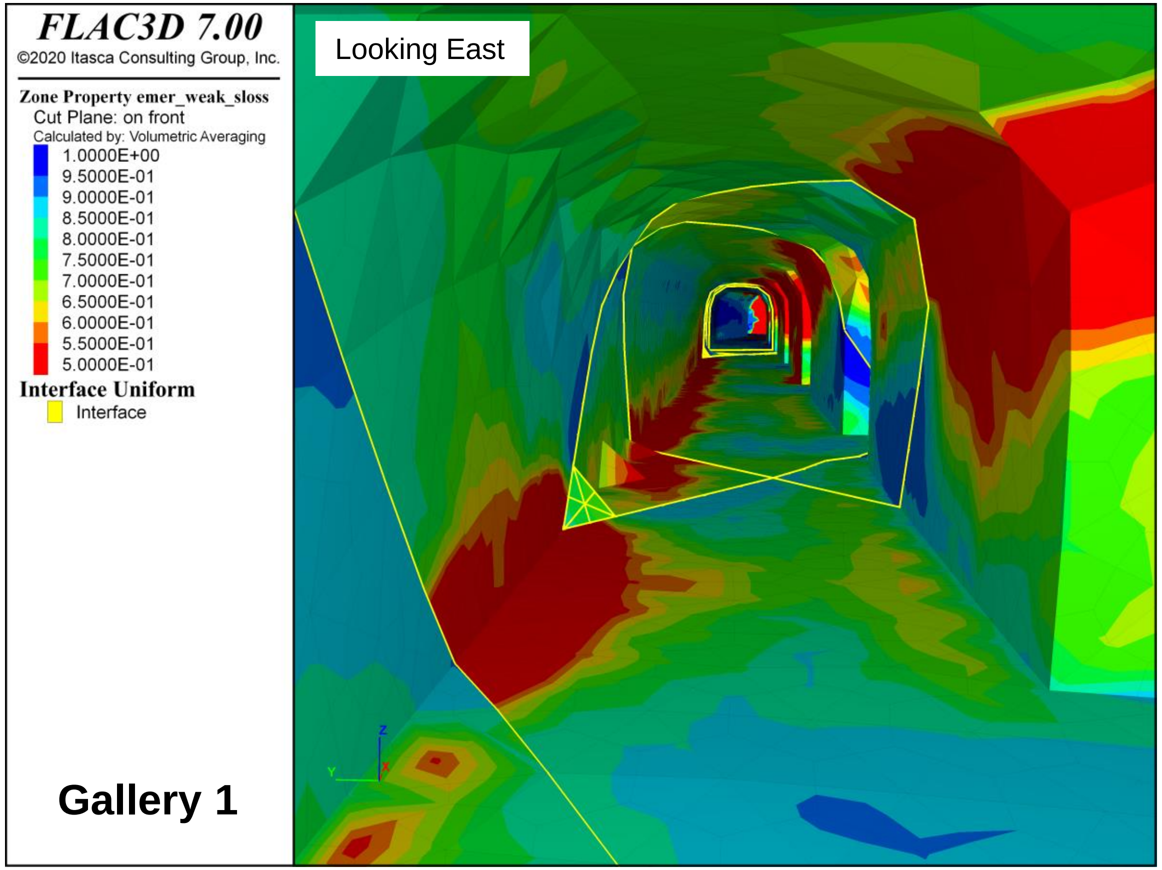
***sloss* changes between [1,-1]:**

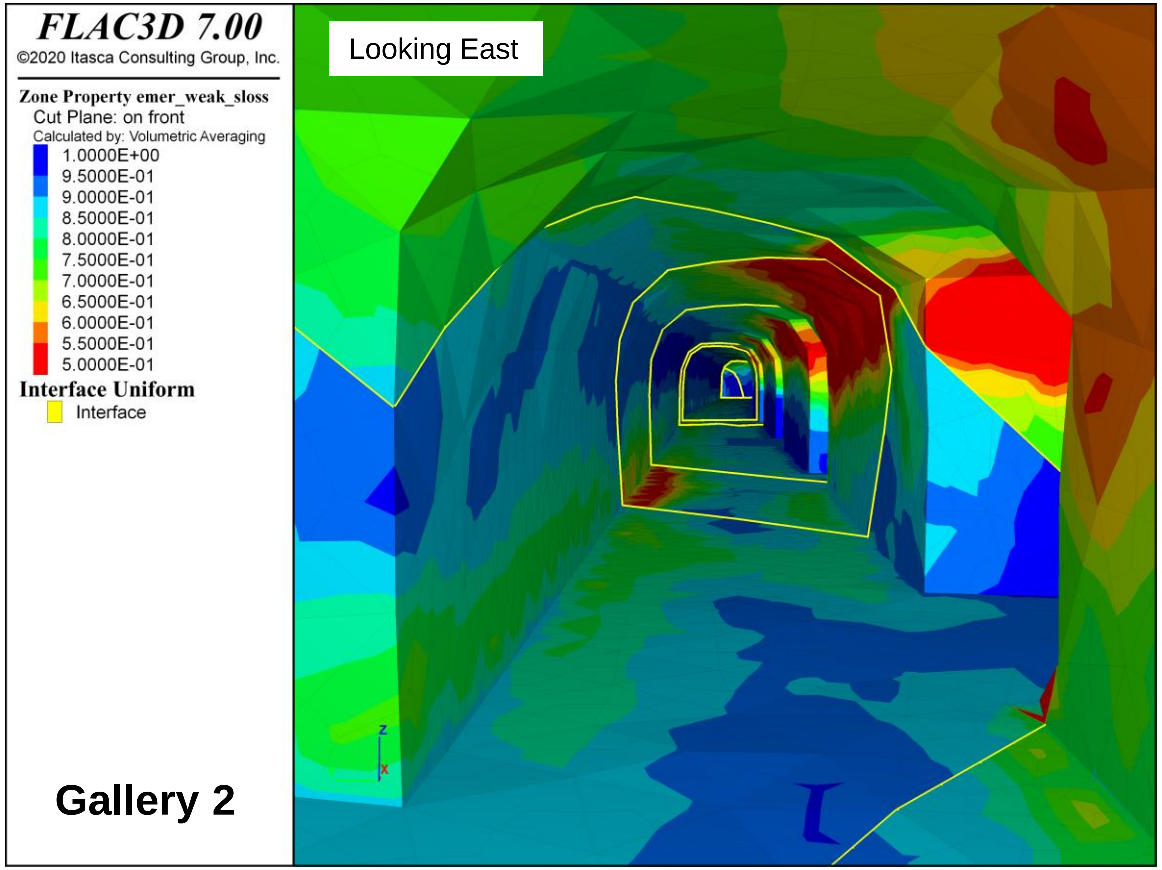
- Between Peak and post-peak envelope,

  sloss = 1 – (plastic shear strain/critical plastic shear strain)
- Between post-peak and ultimate strength envelope

  sloss = – (volumetric strain/max allowable volumetric strain)

sloss example





Research and improvements

- **IMASS is a constitutive model based on empirical relationships**, its formulation is **ever-evolving with the state-of-the-art knowledge of strength and post-peak behavior of brittle rock masses**. The current focus on refinement of the IMASS behavior include:
  - A more robust criteria for estimation of critical plastic shear strain (post-peak brittleness)
  - Refinement of the dilation model

Final remarks

- *IMASS* has been developed to represent the rock-mass response to stress changes using **strain-dependent properties that are adjusted to reflect the impacts of dilation and bulking** as a rock mass undergoes plastic deformation.
- The two-mode softening in *IMASS* allows for mobilization of a high apparent friction angle at low confinement when the fragments are formed in the rock mass. This followed by reduction in friction angle as the rock mass bulks allow for a **realistic simulation of the rock mass post-peak behavior**.
- *IMASS* and its predecessor, *CaveHoek*, have been **developed and refined over the past decade with mining applications being their core purpose**. They have been used successfully by Itasca on numerous operations and projects.

Merci pour votre attention.

Questions ?

Learn more about *IMASS* at www.itascainternational.com/software/imass