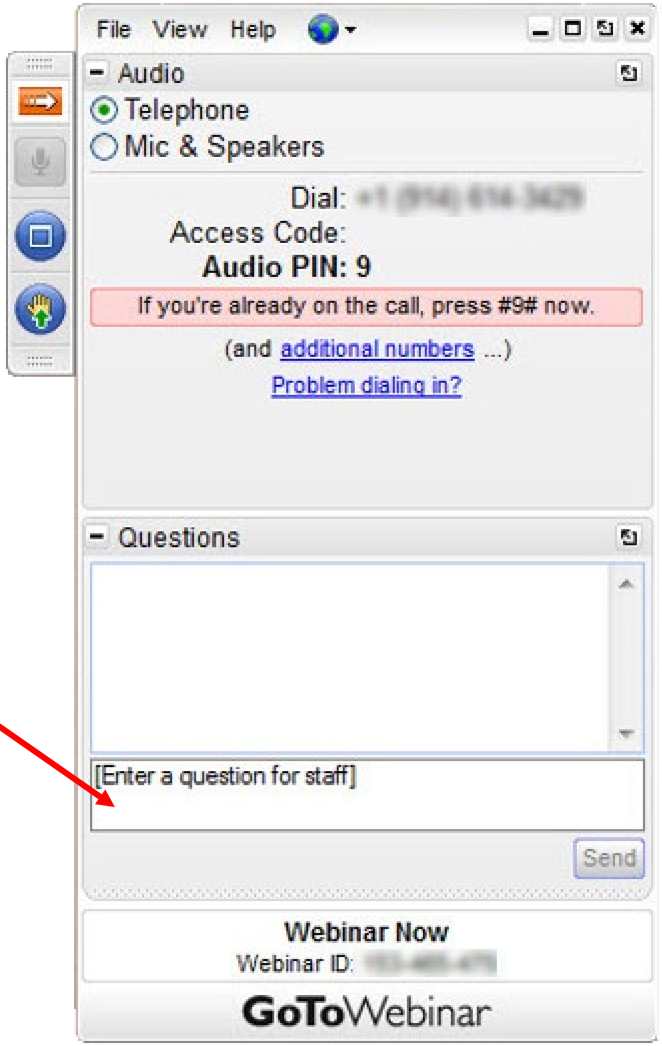
Itasca Constitutive Model for Advanced Strain Softening
IMASS

Background and Applied Examples

Ehsan Ghazvinian (Geomechanics Engineer)

Agenda

- Brief introduction to strain-softening constitutive models
- Theory of *IMASS*
- Examples
- Questions and answer session
    - Please type any questions in the question panel and we'll answer them at the end of the webinar



Introduction

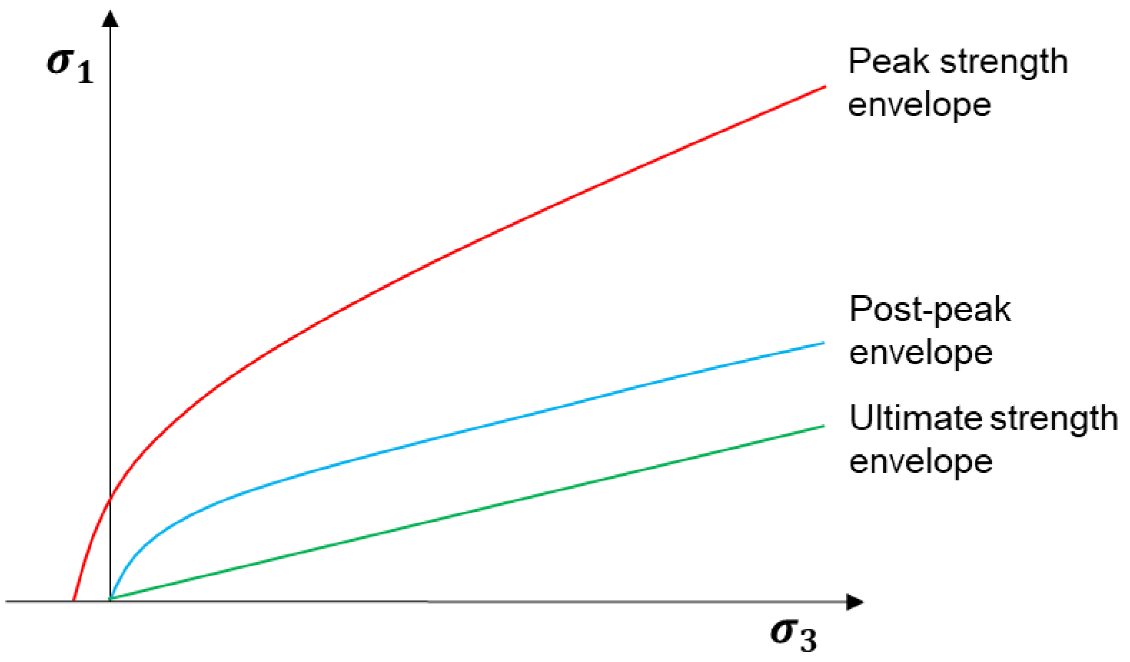
A numerical model that represents the damage around an excavation, slope or caving process must account for the progressive failure and disintegration of the rock mass from an intact/jointed condition to a bulked material. Four critical factors that control the overall behavior of the rock mass matrix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

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

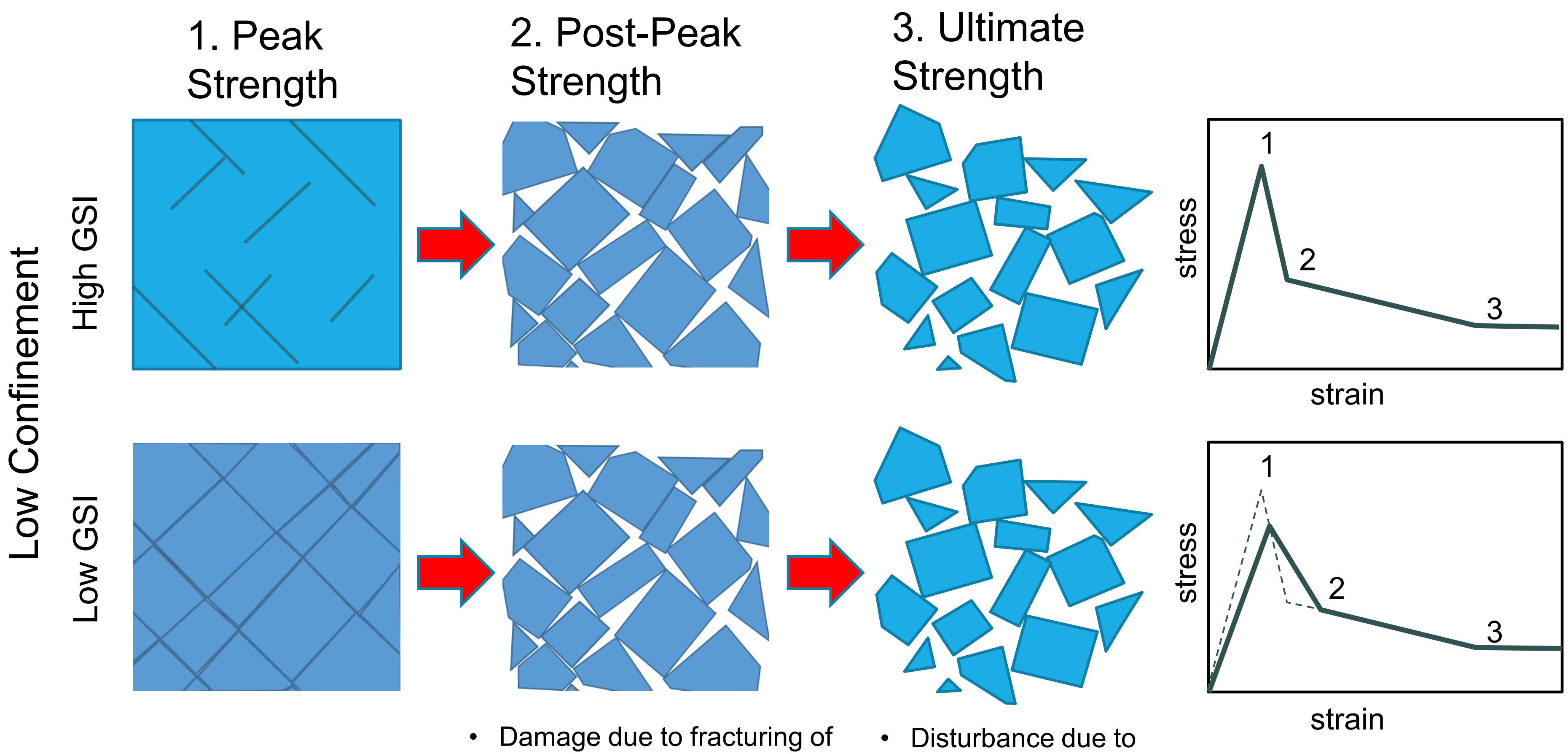
This overall process – loading the rock mass to its peak strength, followed by a post-peak reduction in strength to some residual level with increasing strain – often is termed a "strain-softening" process and is the result of strain-dependent material properties.

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*



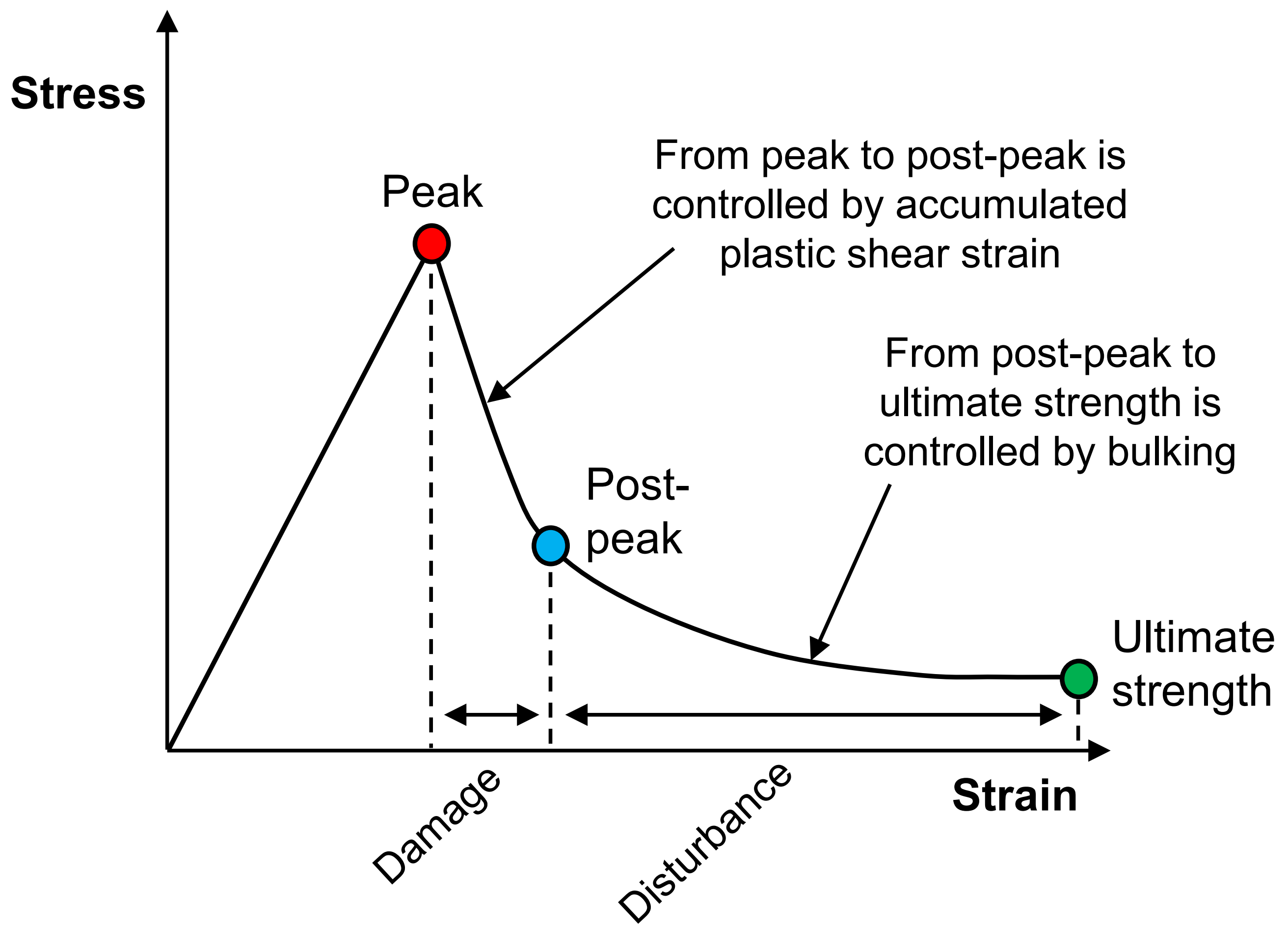
- Damage due to fracturing of intact rock
- Small (negligible) bulking
- Small strain processes
- Damage is dependent on the accumulation of plastic shear strain

Damaged rock

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

Disturbed rock

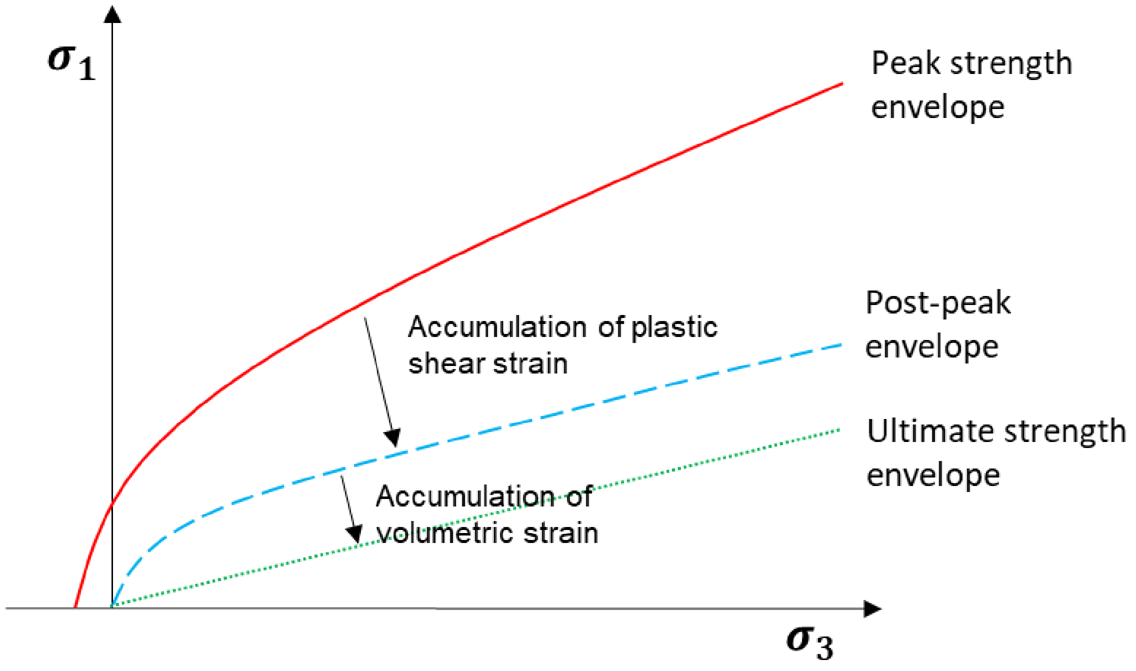
Conceptual stress-strain curve



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:

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



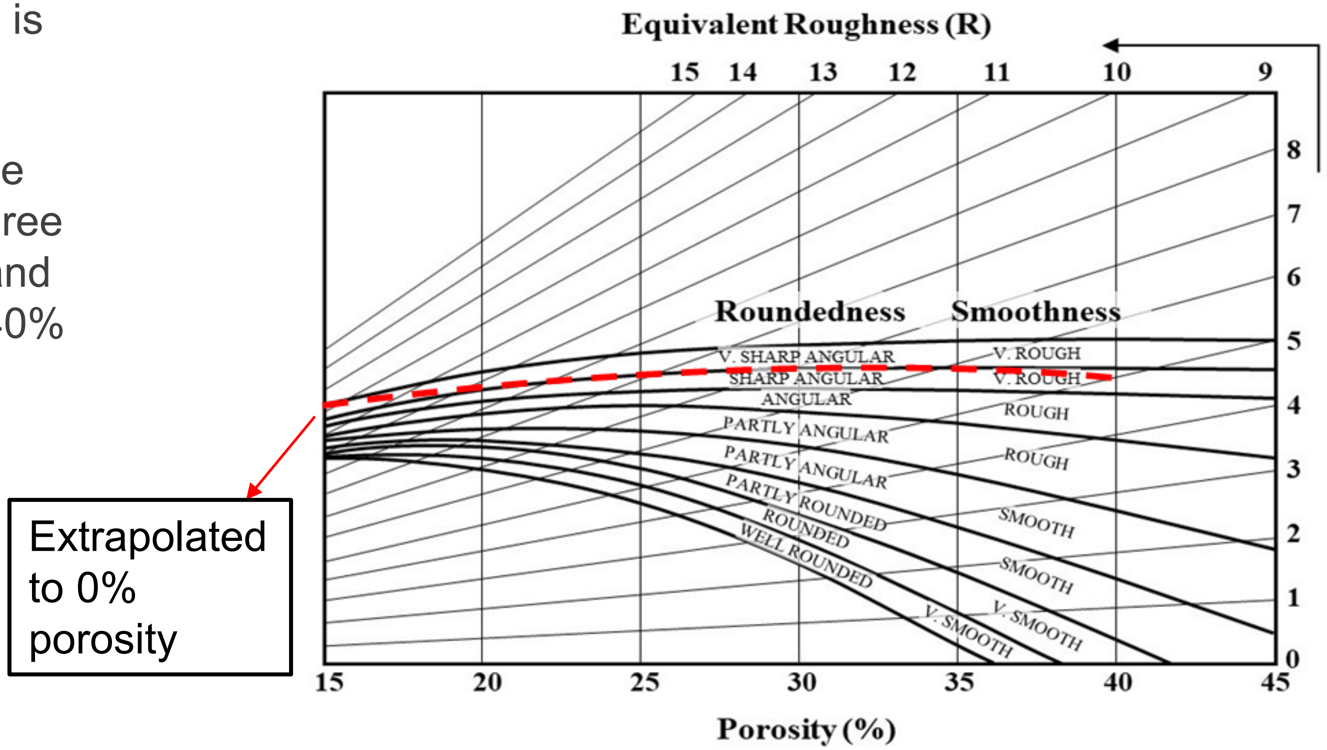
Residual strength envelopes in *IMASS*

- 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.

- 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).

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

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



Residual strength envelopes in *IMASS*

When the shear strength from the Barton & Kjaernsli (1981) equation is converted to a strength envelope in σ_1 - σ_3 space, it can be approximated by a Hoek-Brown envelope with the following parameters:

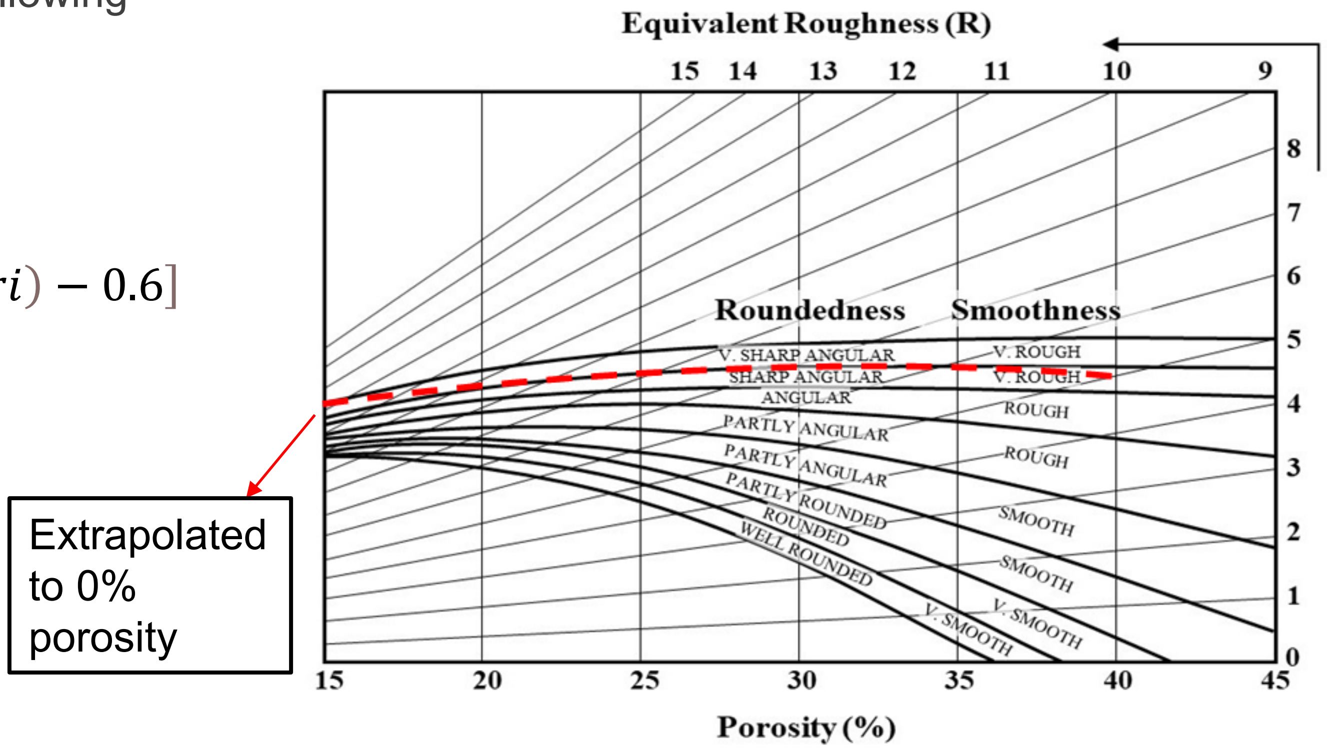
$$s = 0$$

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

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

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)



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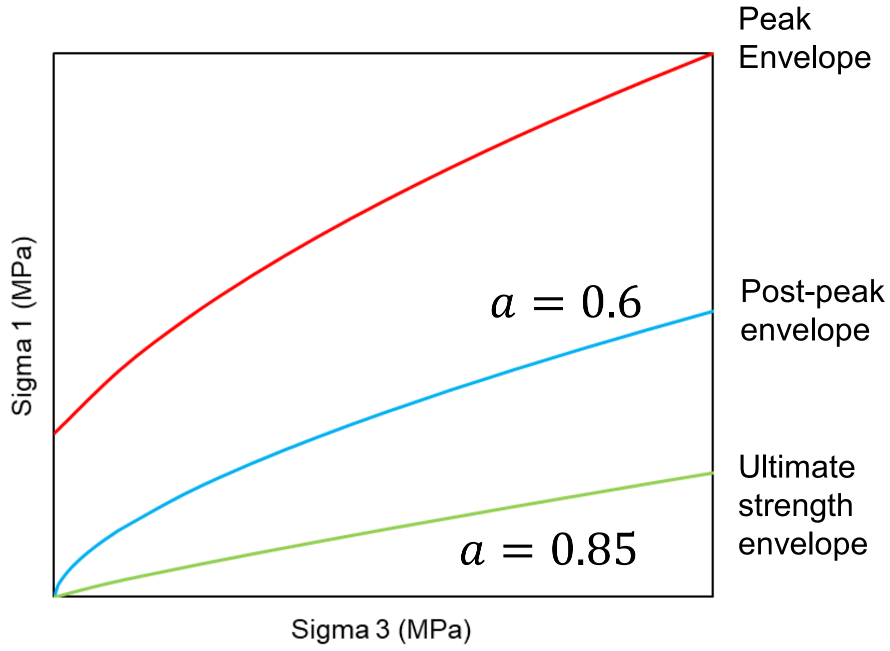
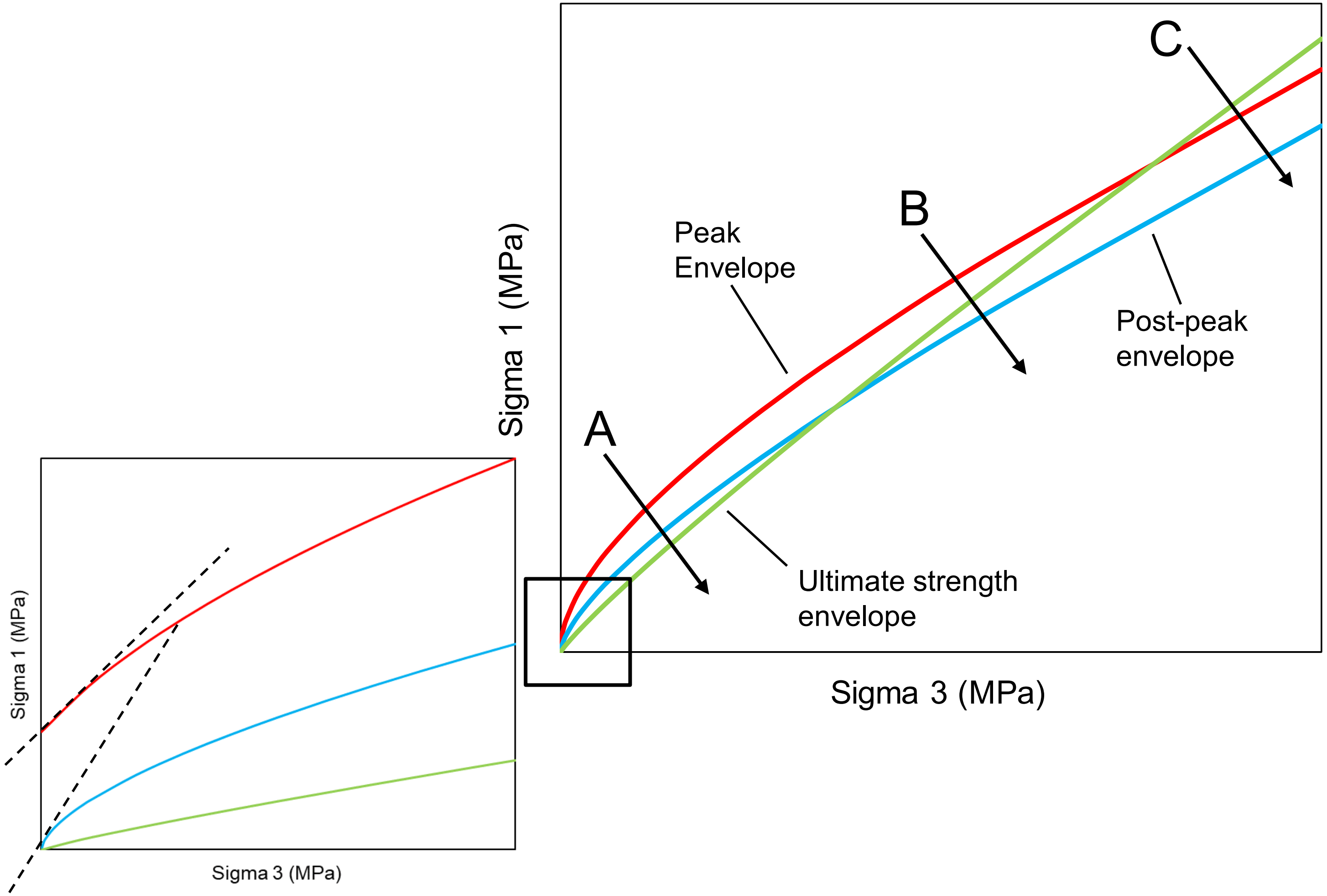
The Hoek-Brown approximation of Barton & Kjaernsli (1981) shear strength criteria for rockfill that is implemented in IMASS assumes formation and interaction of very sharp, angular and very rough fragments during the course of bulking, from porosity 0% to 40%.

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

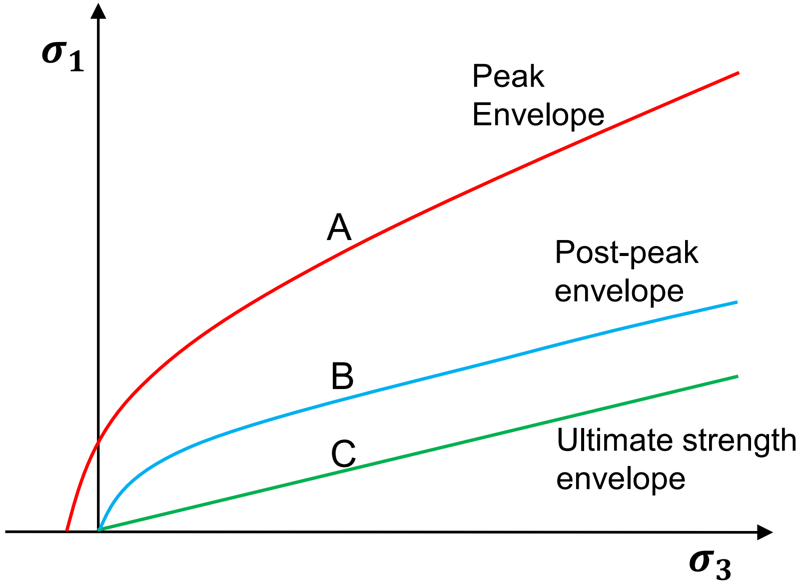


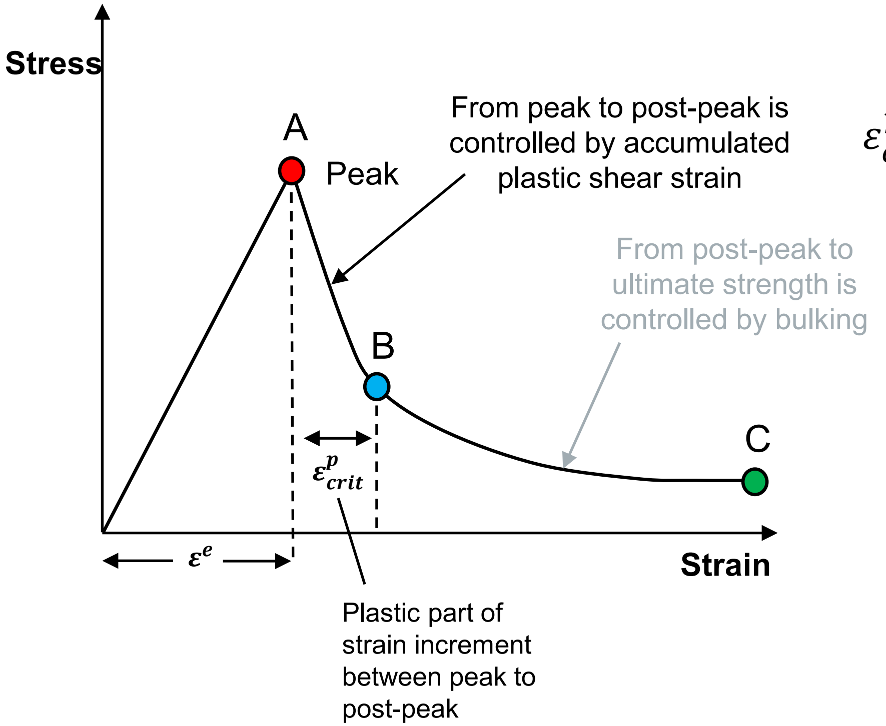
Characteristics of *IMASS* residual envelopes

- 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

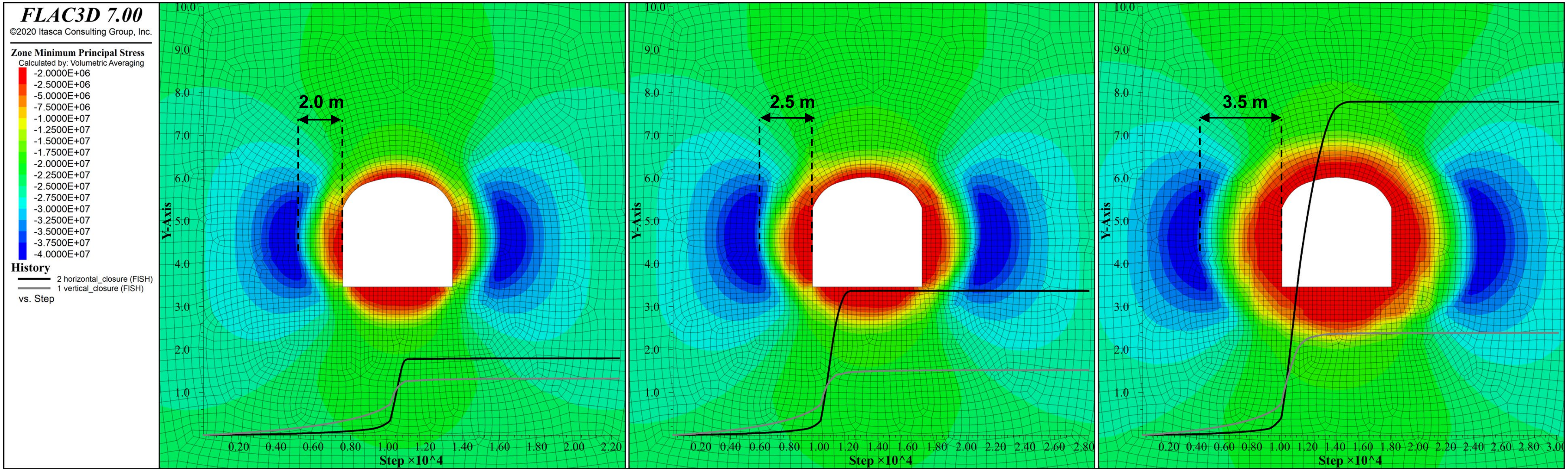




$$\varepsilon^{p}_{crit} = \frac{12.5 - 0.125 * GSI}{100 * d}$$

(Lorig & Pierce, 2000)

Critical Strain sensitivity

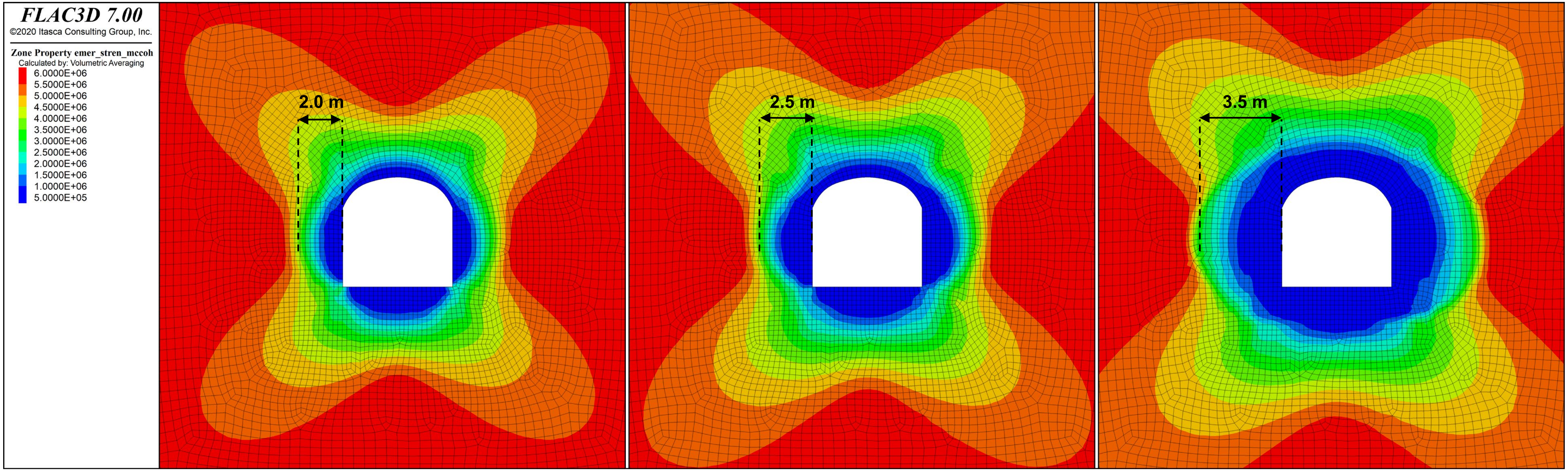


Multiplier ecrit = 1.0
ecrit ~ 30%
Vertical tunnel closure ~ 1%
Horizontal tunnel closure ~ 2%

Multiplier ecrit = 0.1
ecrit ~ 3%
Vertical tunnel closure ~ 1%
Horizontal tunnel closure ~ 3.5%

Multiplier ecrit = 0.01
ecrit ~ 0.3%
Vertical tunnel closure ~ 2%
Horizontal tunnel closure ~ 8%

Cohesion weakening



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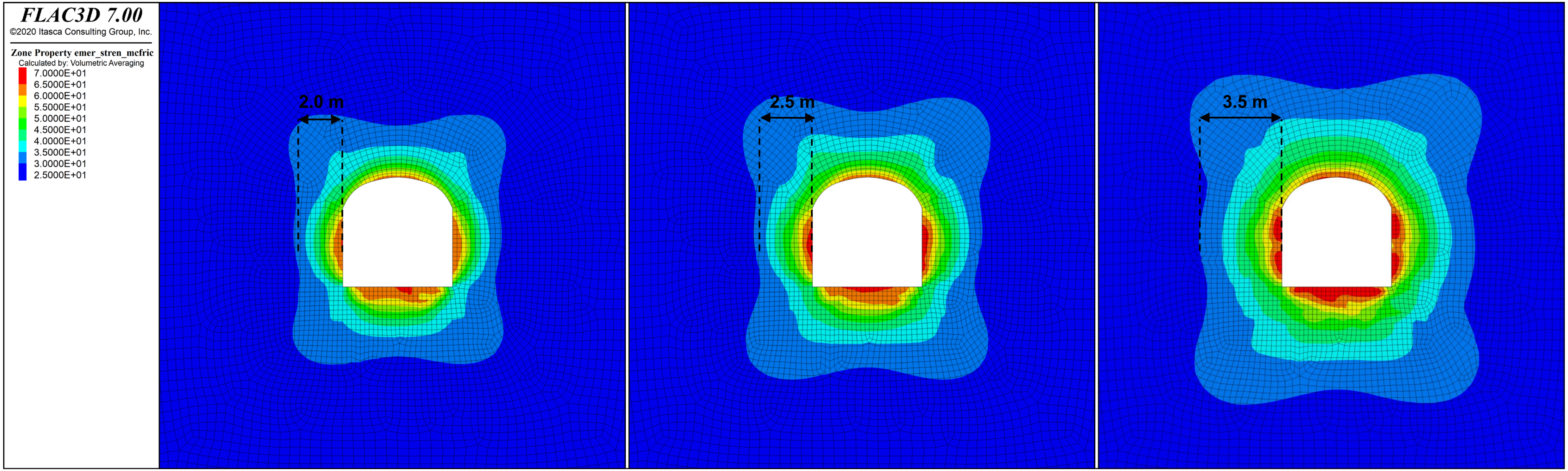
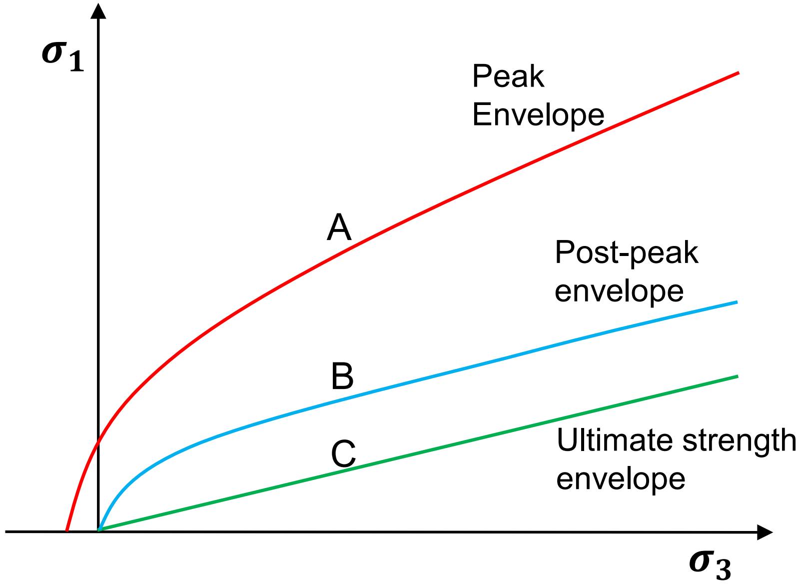
Multiplier ecrit = 0.01
ecrit ~ 0.3%
Vertical tunnel closure ~ 2%
Horizontal tunnel closure ~ 8%

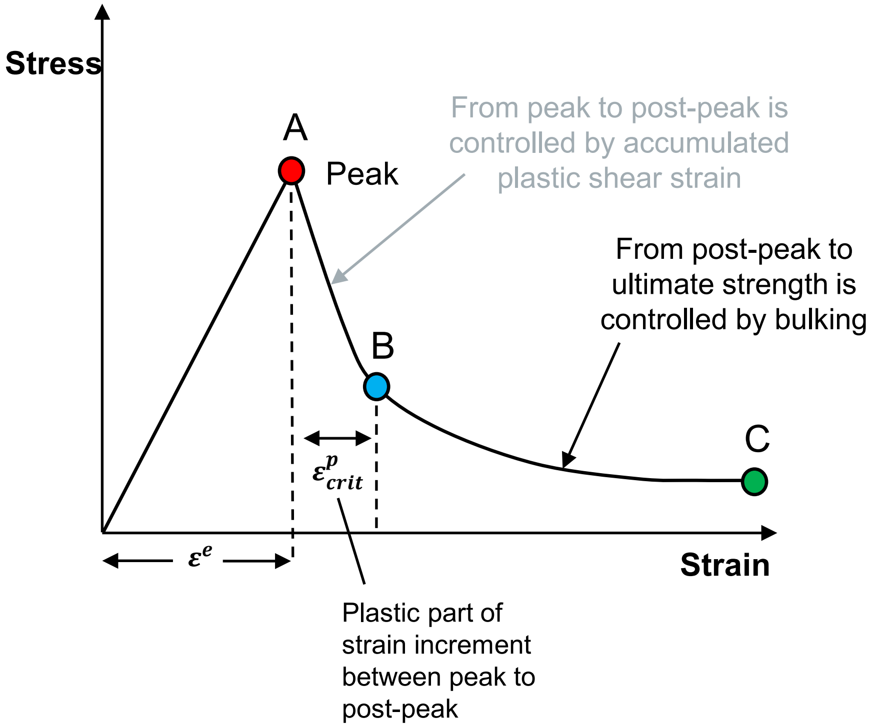
Frictional strengthening



Multiplier ecrit = 1.0	Multiplier ecrit = 0.1	Multiplier ecrit = 0.01
ecrit ~ 30%	ecrit ~ 3%	ecrit ~ 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%

Porosity-dependent softening/weakening

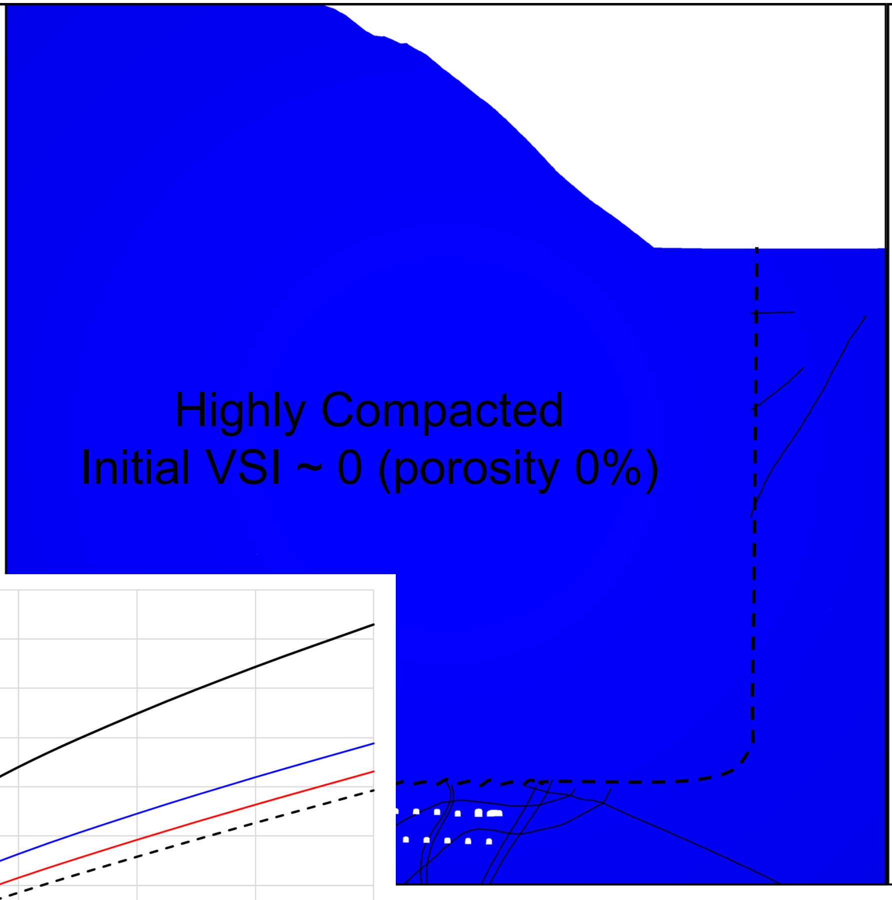


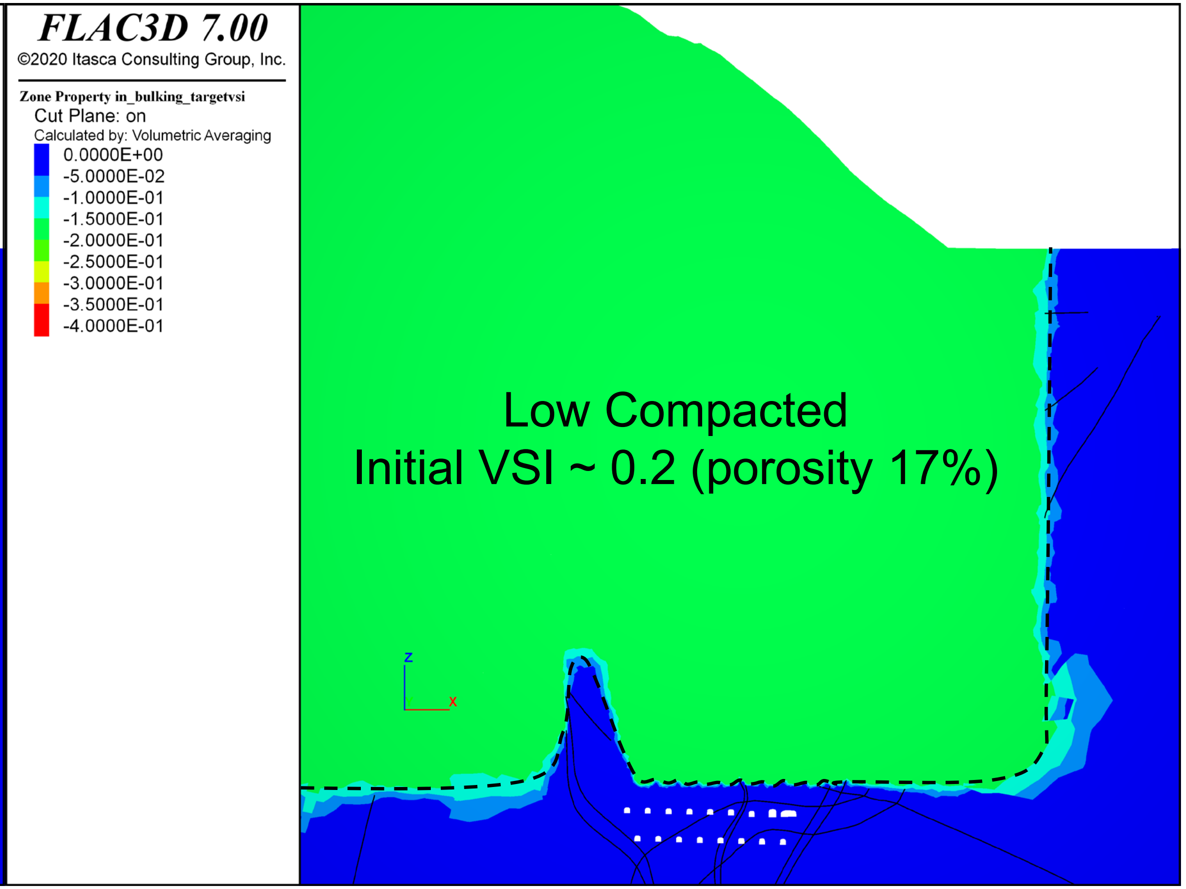


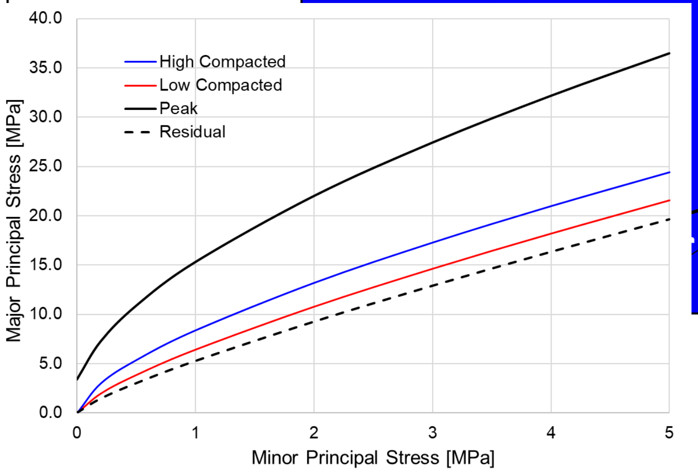
$$B = \frac{\Delta V}{V_i} = \frac{n}{1-n}$$

- 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

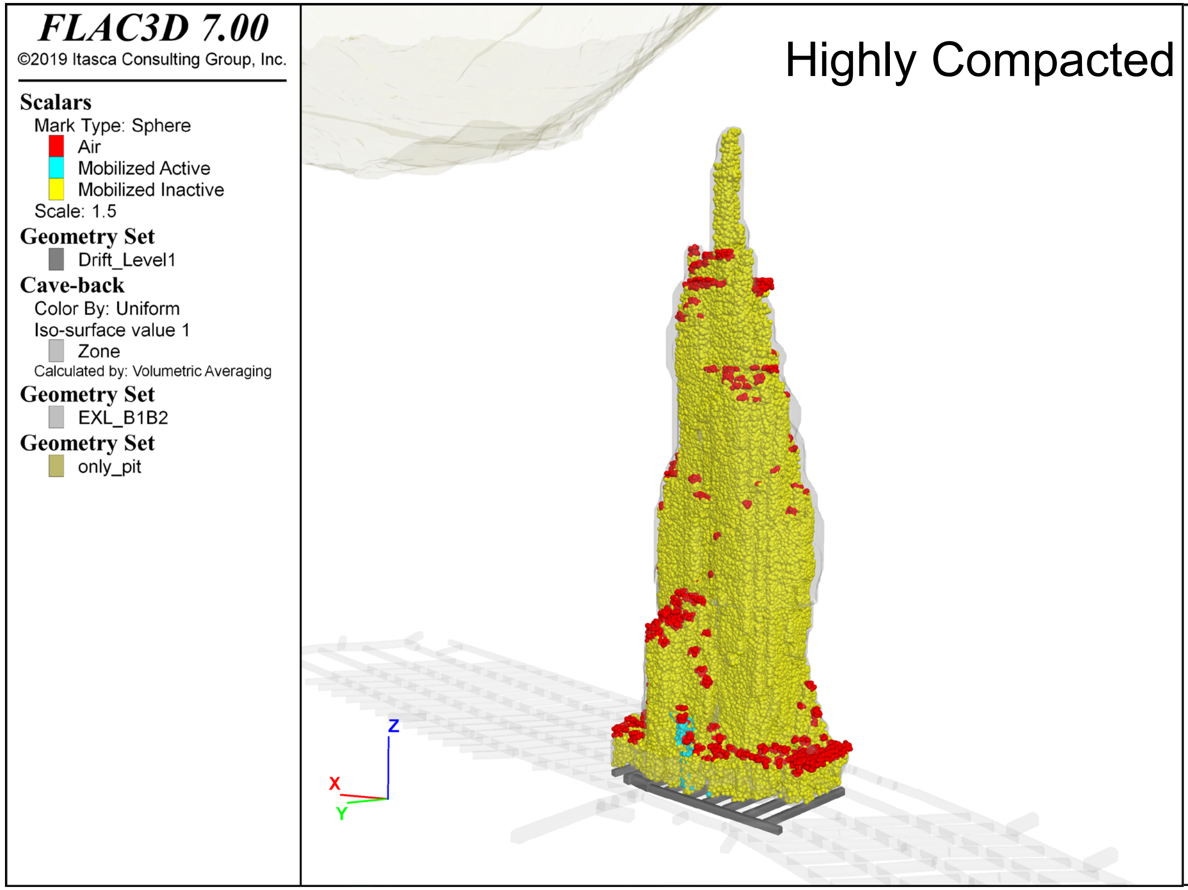
Two cases of initial compaction

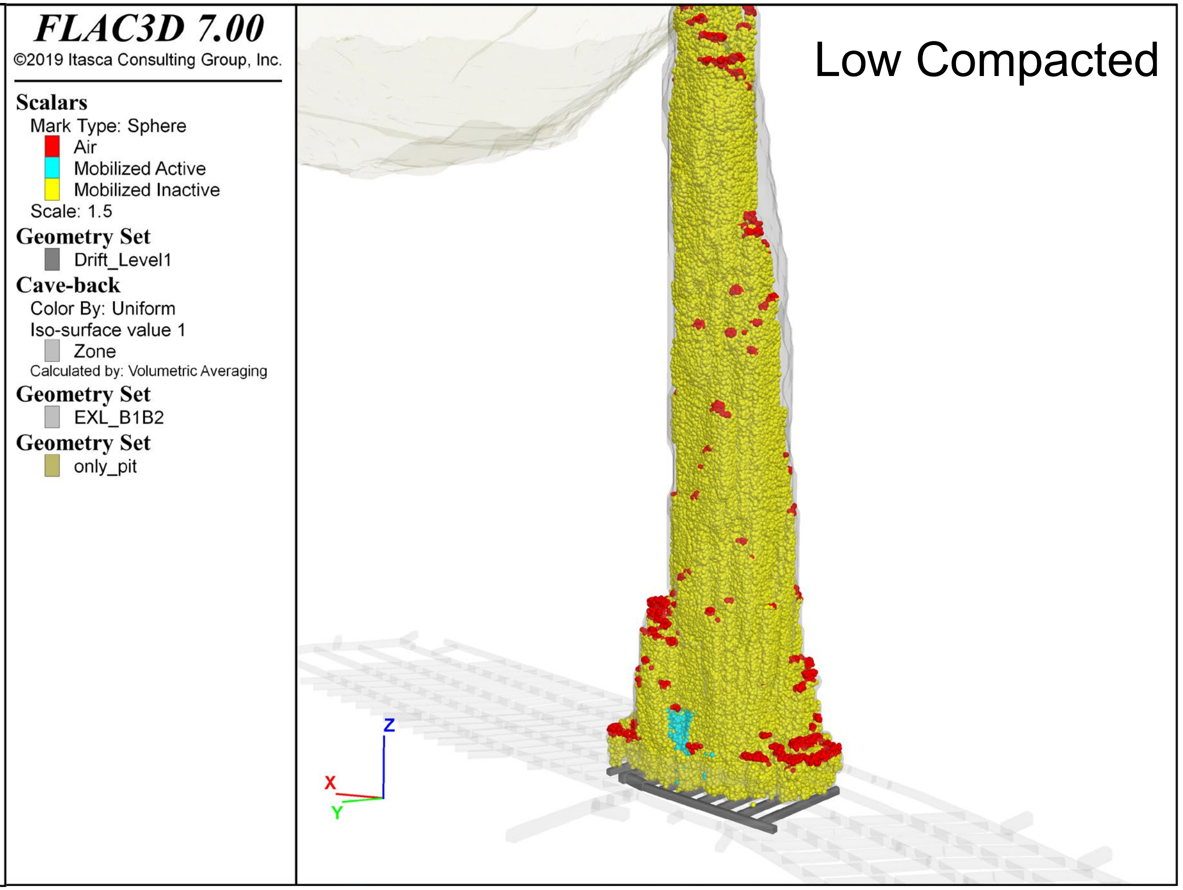






Cave propagation

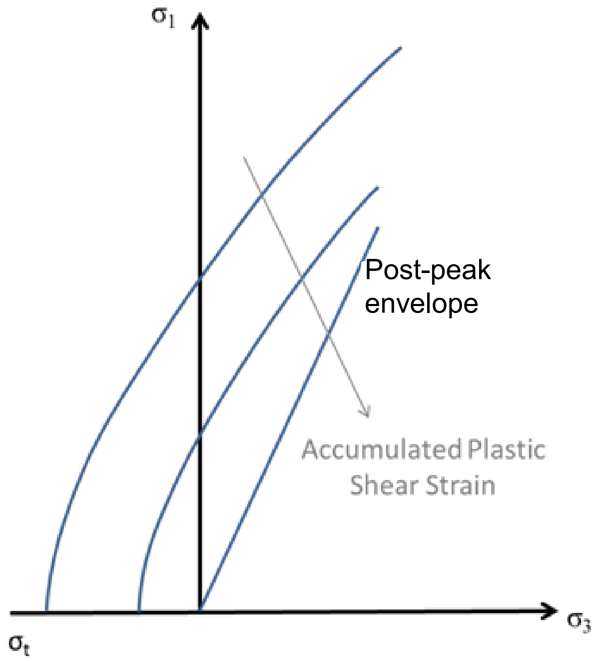




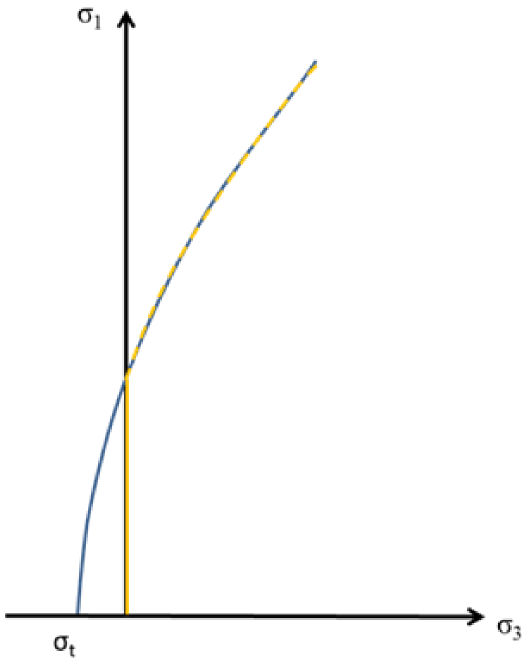
Tension weakening in *IMASS*

The mechanism of independent tensile softening is implemented in *IMASS*, i.e., in addition to softening tension and cohesion at the same rate based on plastic shear strain, tension is allowed to soften independently of the cohesion in the instance of a tensile yield state within a zone.

Alternatively, a table that correlates tension weakening to accumulated plastic tensile strain can be assigned to zones to control the tension weakening.



Tensile strength degradation occurring with accumulated plastic shear strain



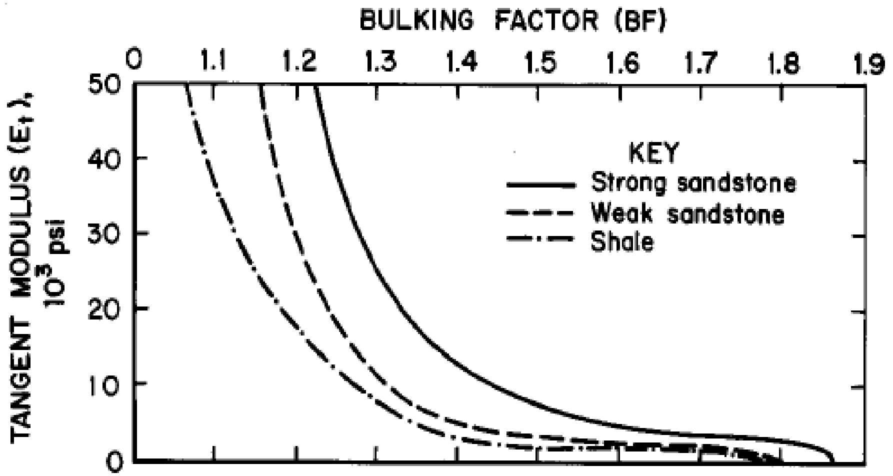
Sudden loss of tensile strength during tensile failure (perfectly brittle in tension)

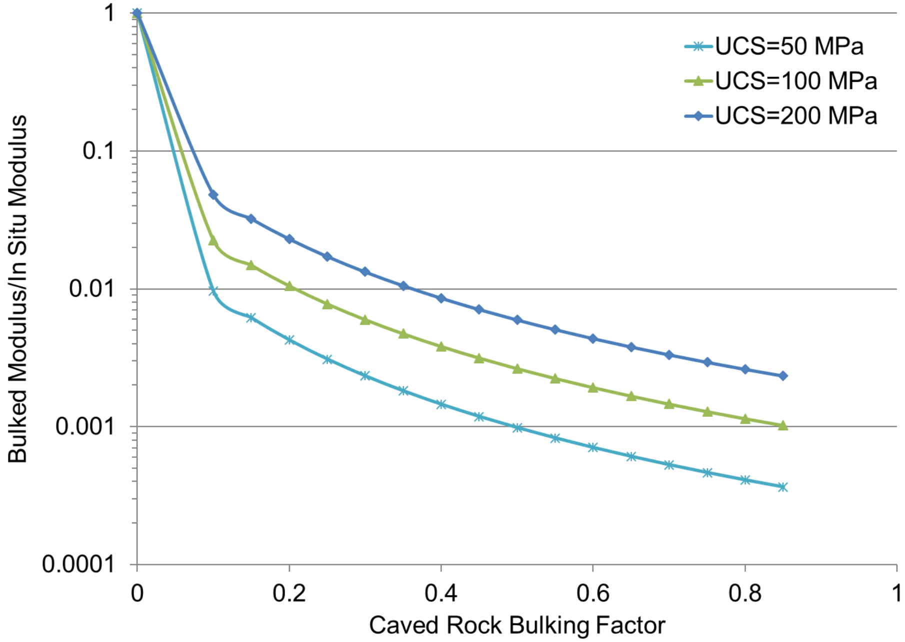
Modulus softening

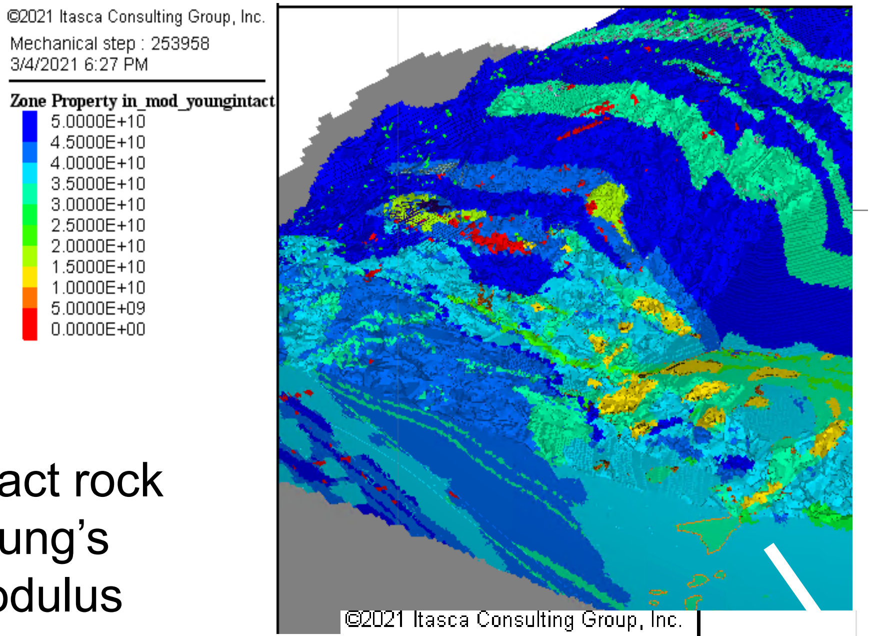
The rock mass Young's modulus (E_{rm}) can be estimated from the intact Young's modulus (E_i) and GSI using Hoek and Diederichs' (2006) equation:

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

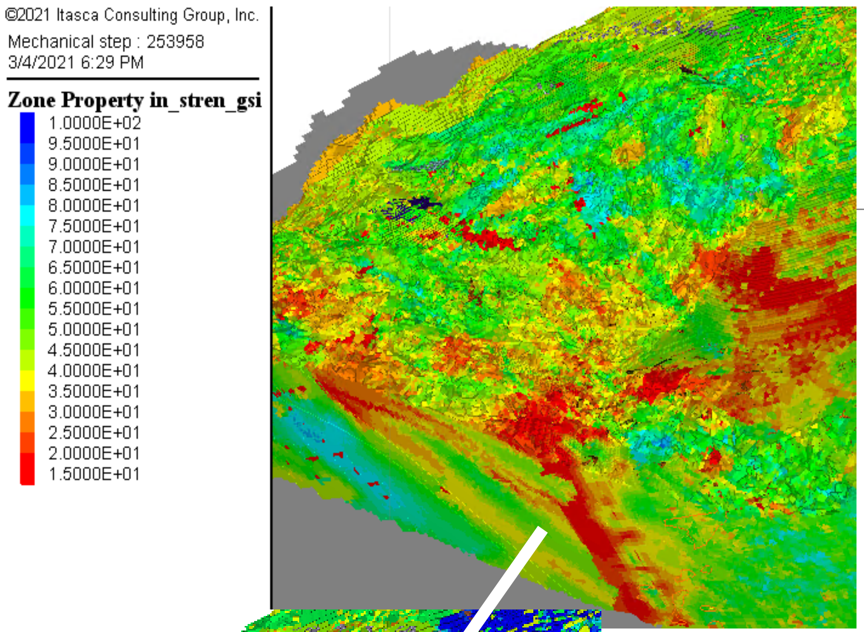
- Pappas and Mark (1993) show that the modulus of rock drops in a non-linear fashion with increased bulking, and that the rate of modulus change is a function of fragment shape and intact strength
- In *IMASS* the modulus is updated constantly via the zone-based volumetric strains. This allows for both modulus softening (during bulking) and modulus hardening (e.g., during recompaction)



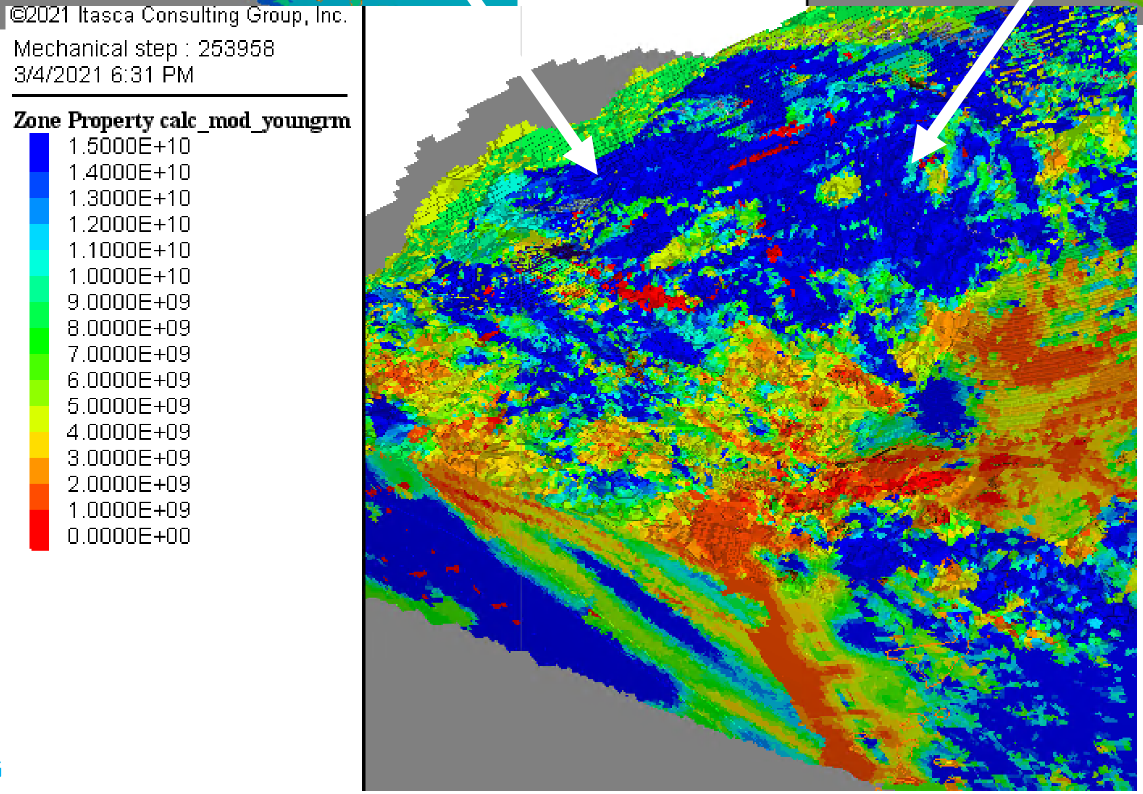




Intact rock Young's modulus

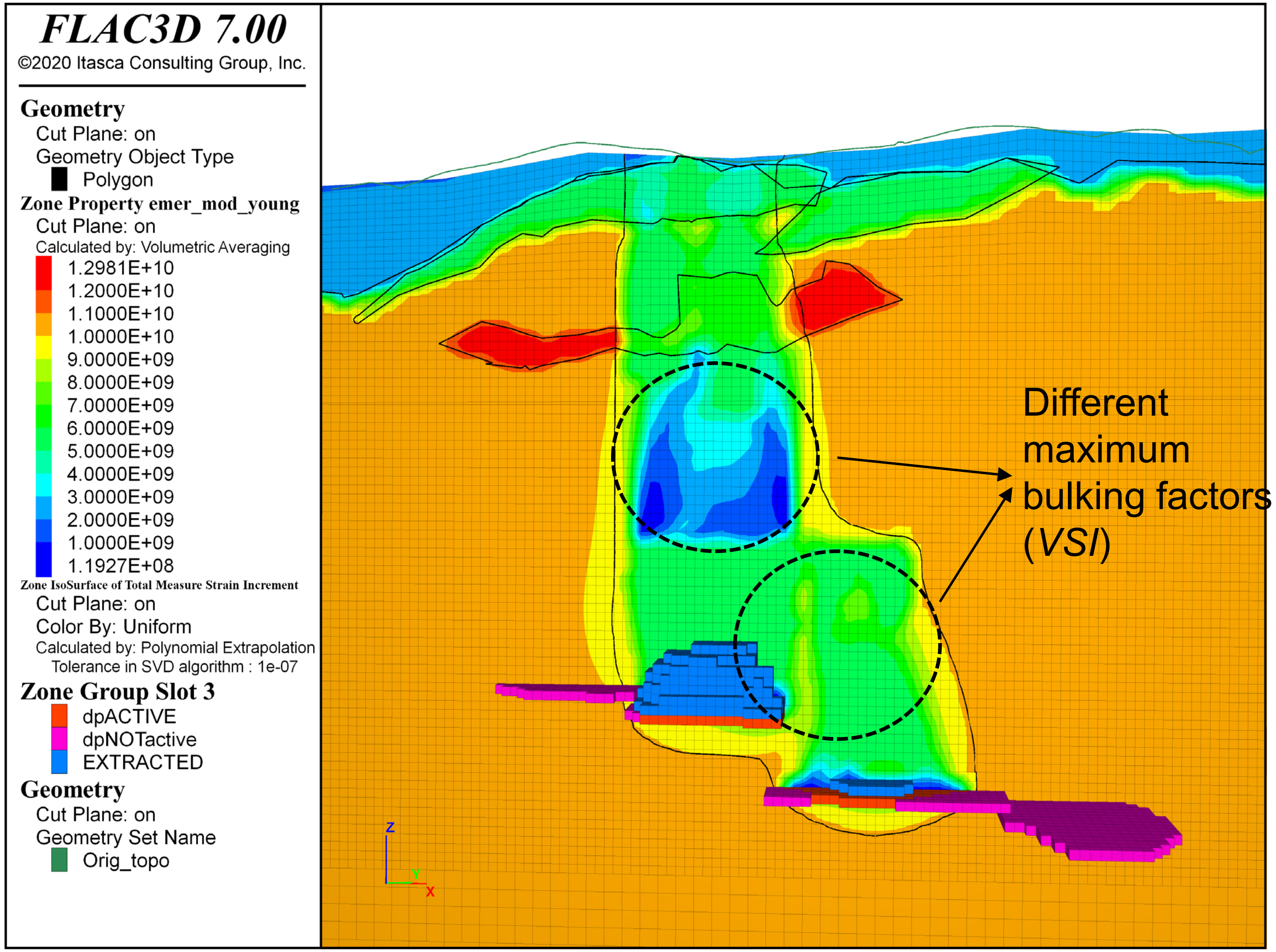


GSI



Rock mass modulus

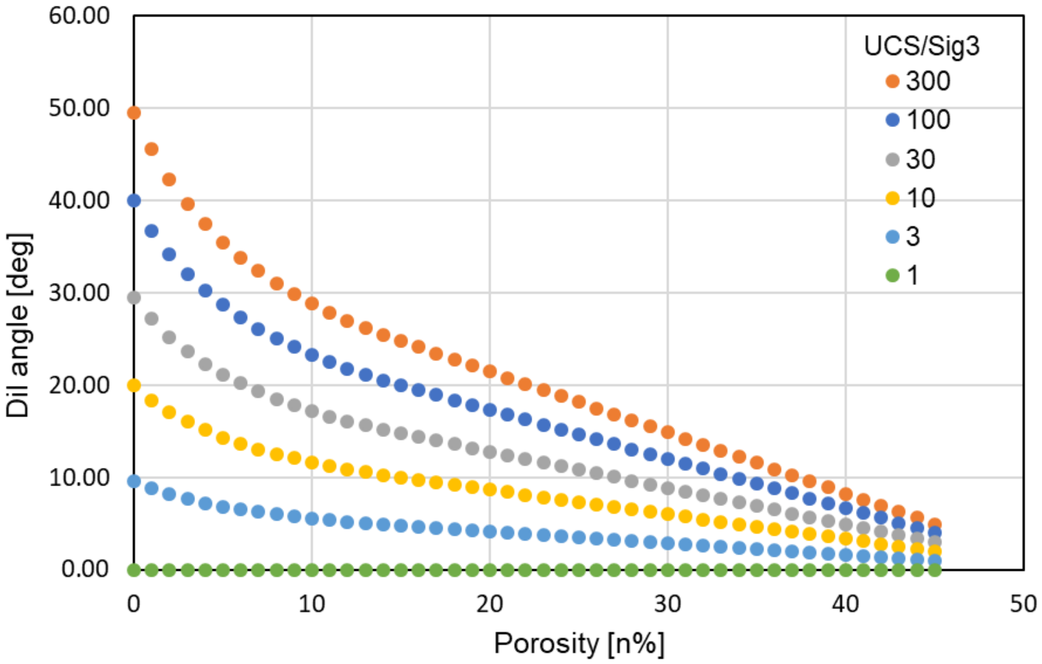
Modulus softening



Dilational behavior

- Within IMASS, the dilation angle is set as a standard material property and drops to zero once the user-defined maximum bulking factor is reached. This prevents zones from expanding to unrealistic levels during shear.
- A constant dilation angle can be assigned to the rock mass (i.e., equal everywhere) based on the available guidelines such as those provided by Hoek and Brown (1997).
- Alternatively, a more advanced dilation model is available that constantly updates the dilation angle for each zone as a function of confining stress and porosity (or VSI).

Currently being tested and validated by Itasca



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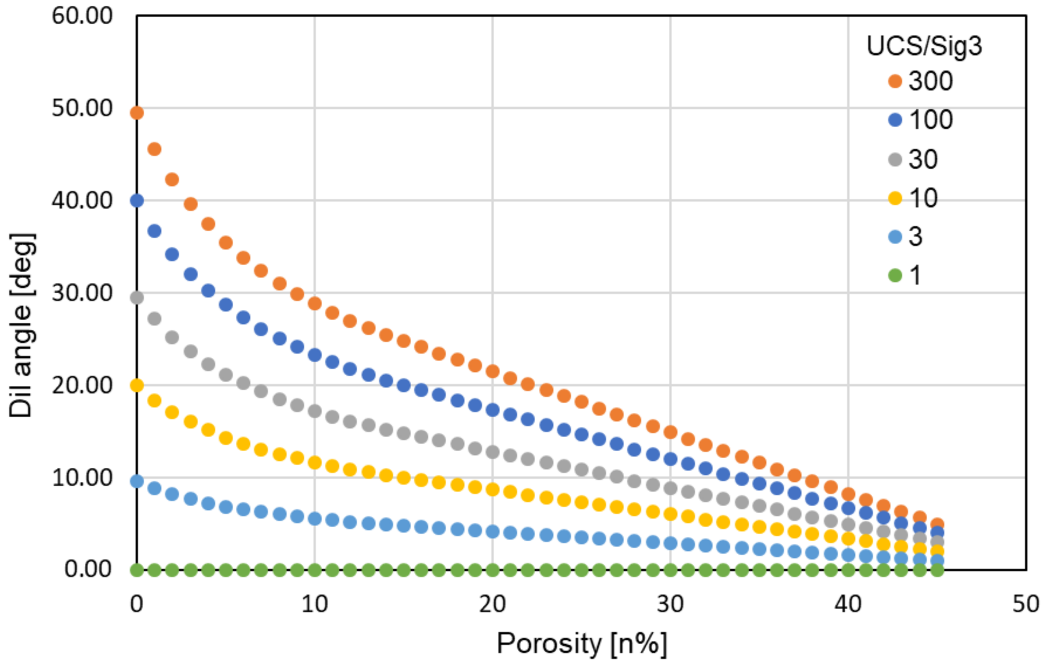
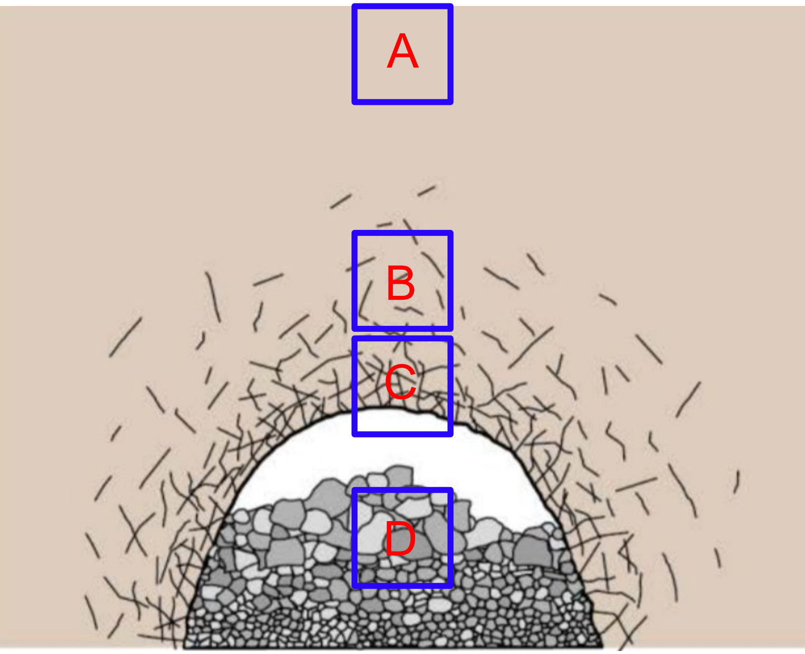
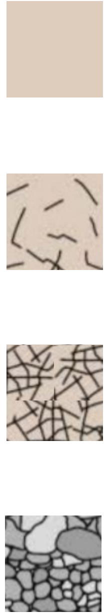


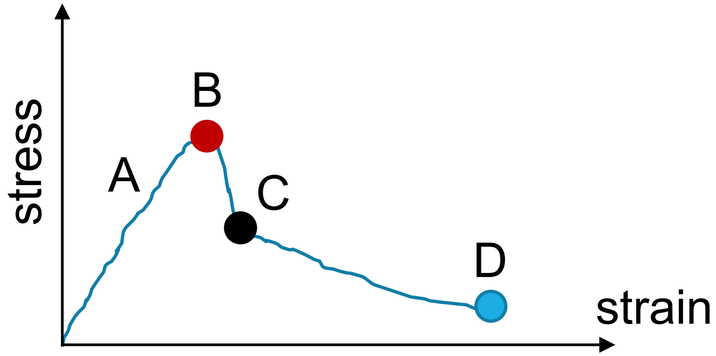
$$\tau = \sigma_n \tan\left(R.\log\left(\frac{S}{\sigma_n}\right) + \emptyset_b\right)$$

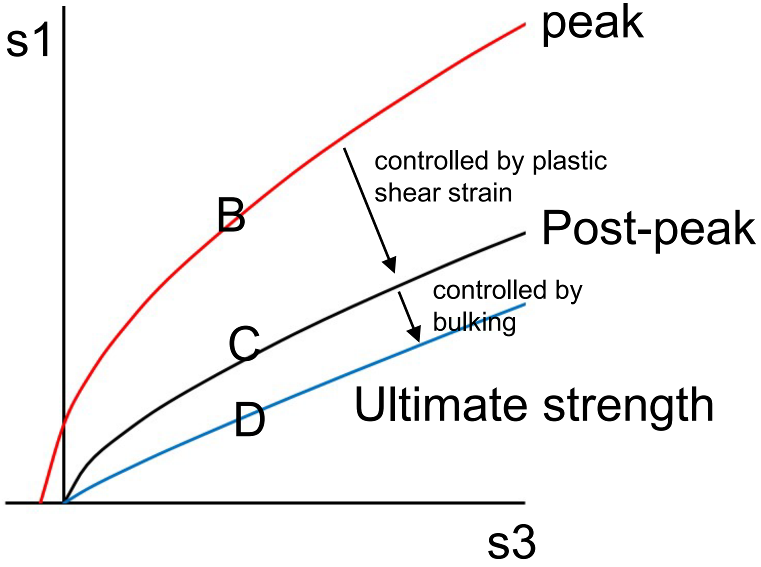
sloss – an indicator for damage in *IMASS*





	cohesion	sloss	bulking
A	max	1	0
B		1	0
C	0	0	0
D	0	-1	max

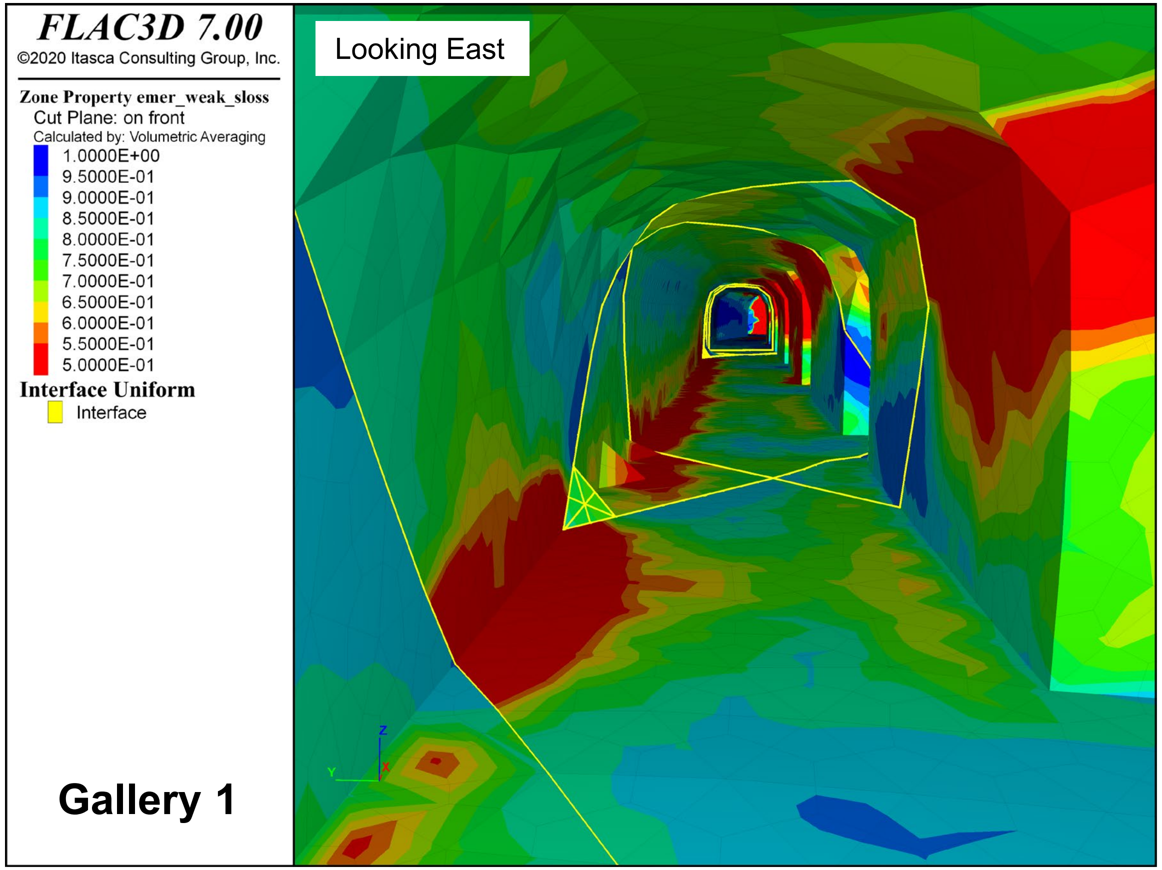


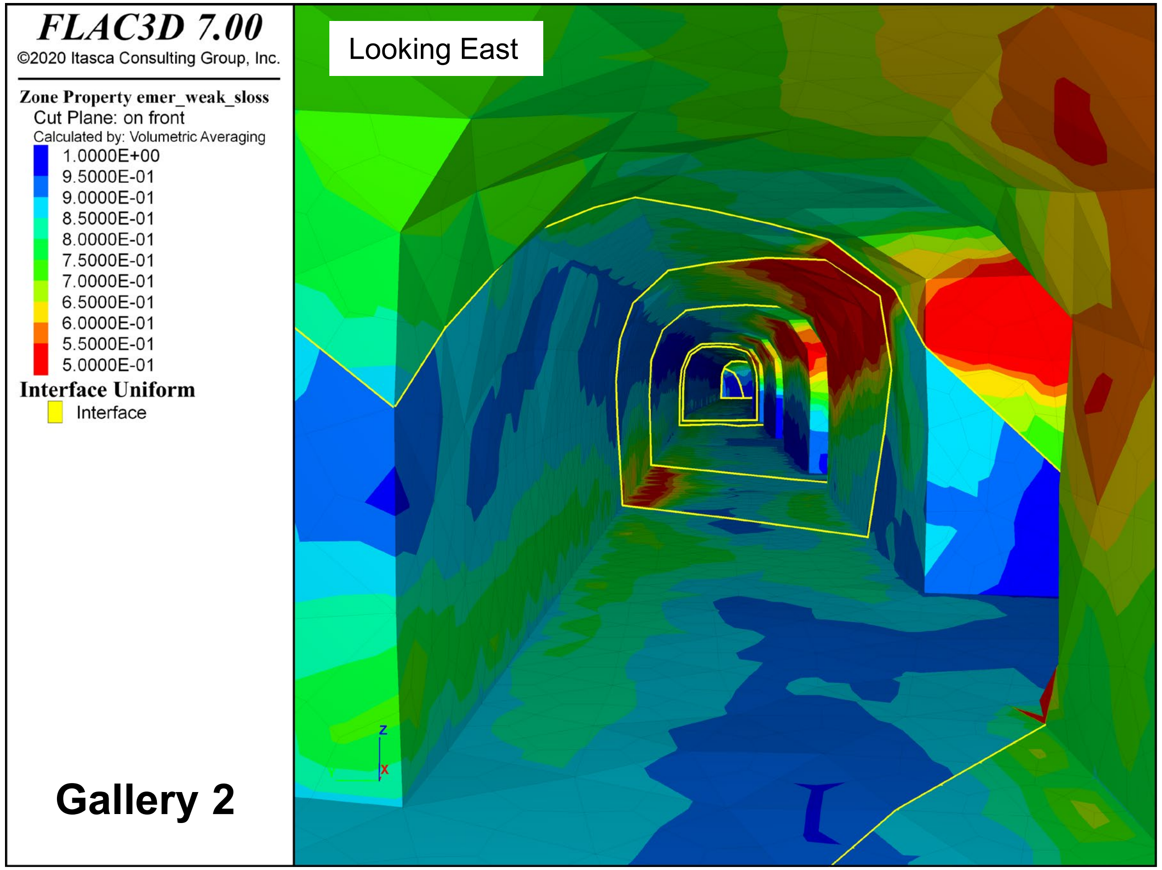


sloss changes between [1,-1]:

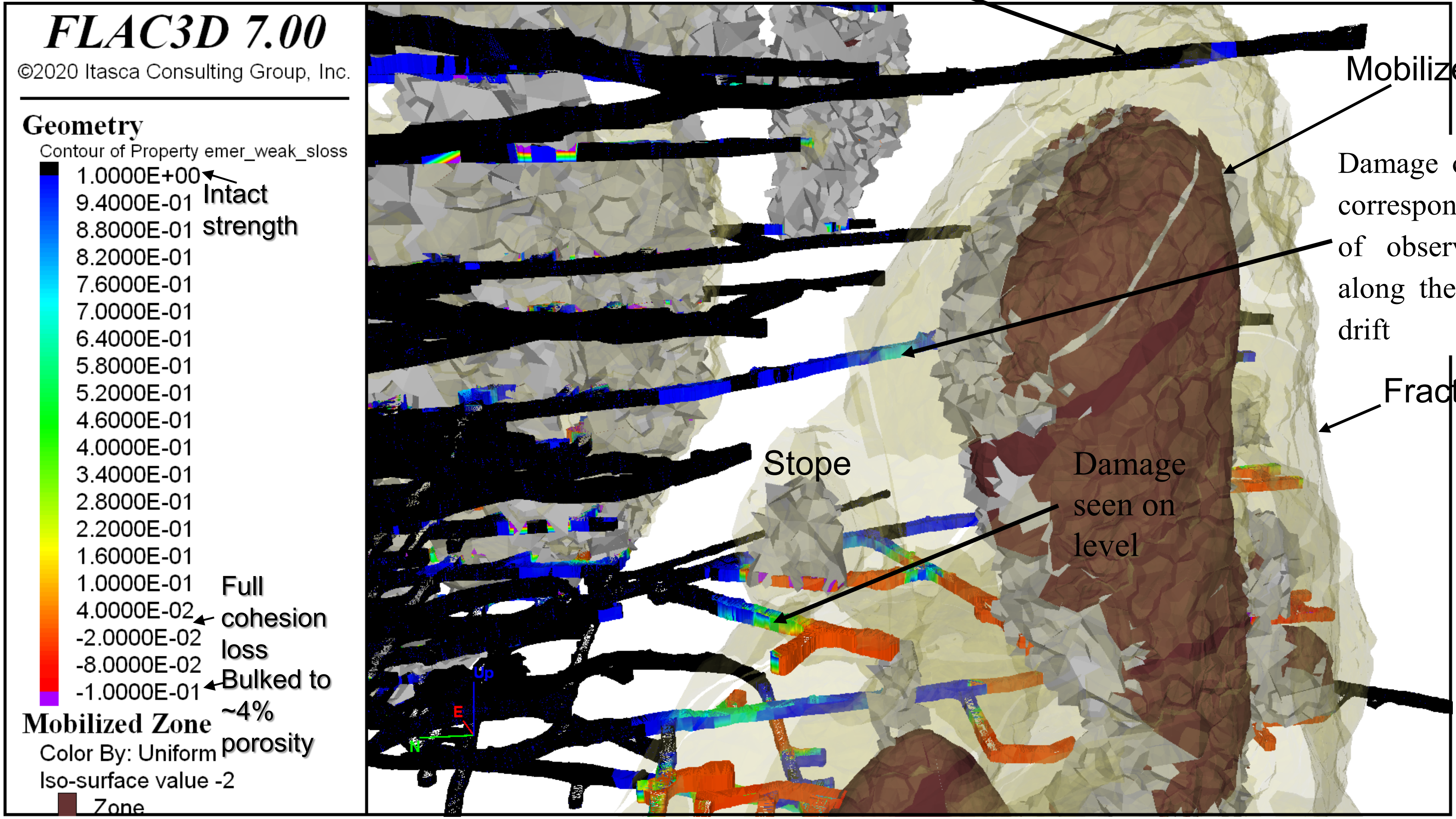
- Between Peak and post-peak envelope,
  sloss = 1 – (plastic shear strain/critical plastic shear strain)
- Between post-peak and ultimate strength envelope
  sloss = – (volumetric strain/max allowable volumetric strain)

sloss example

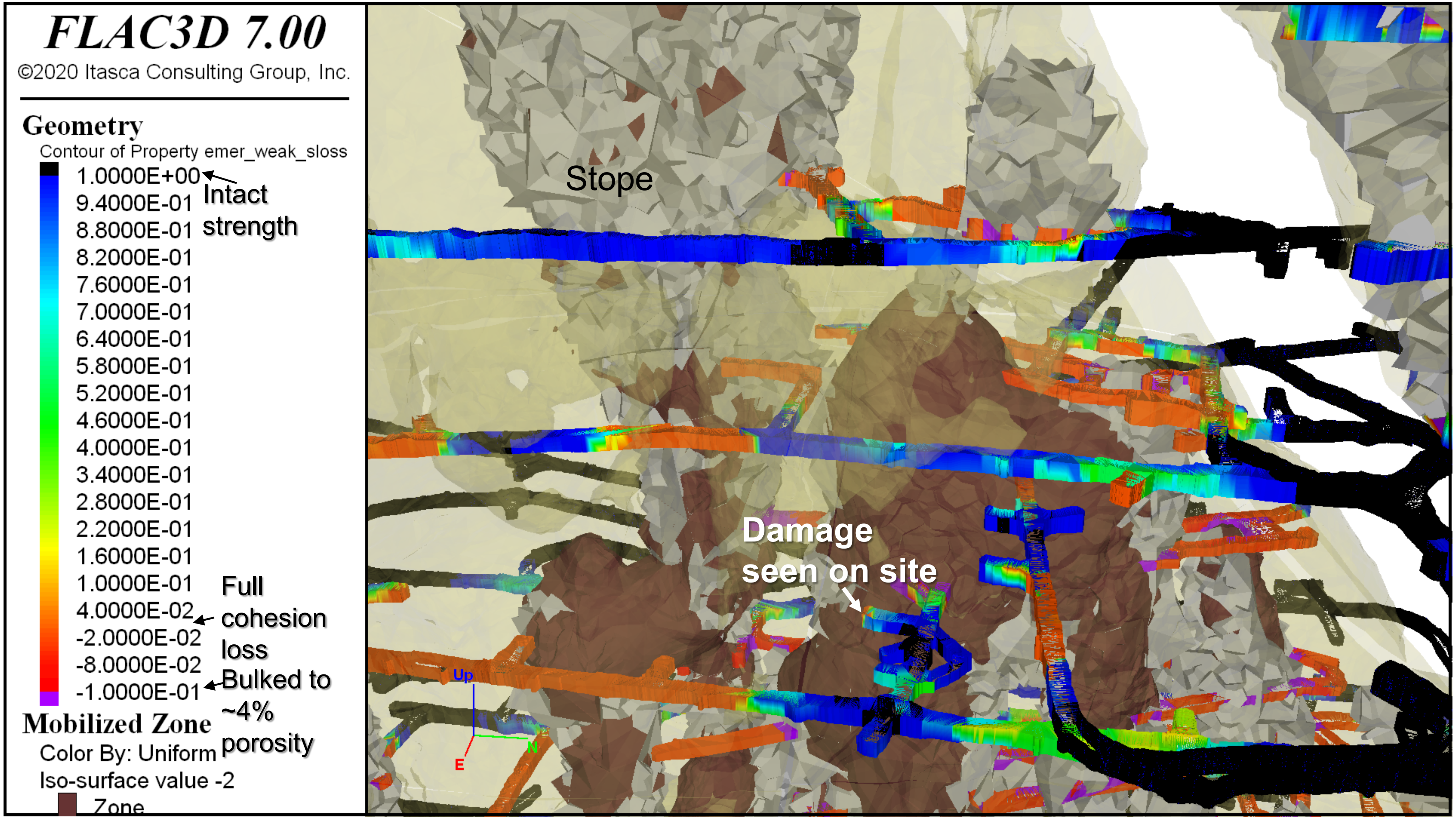




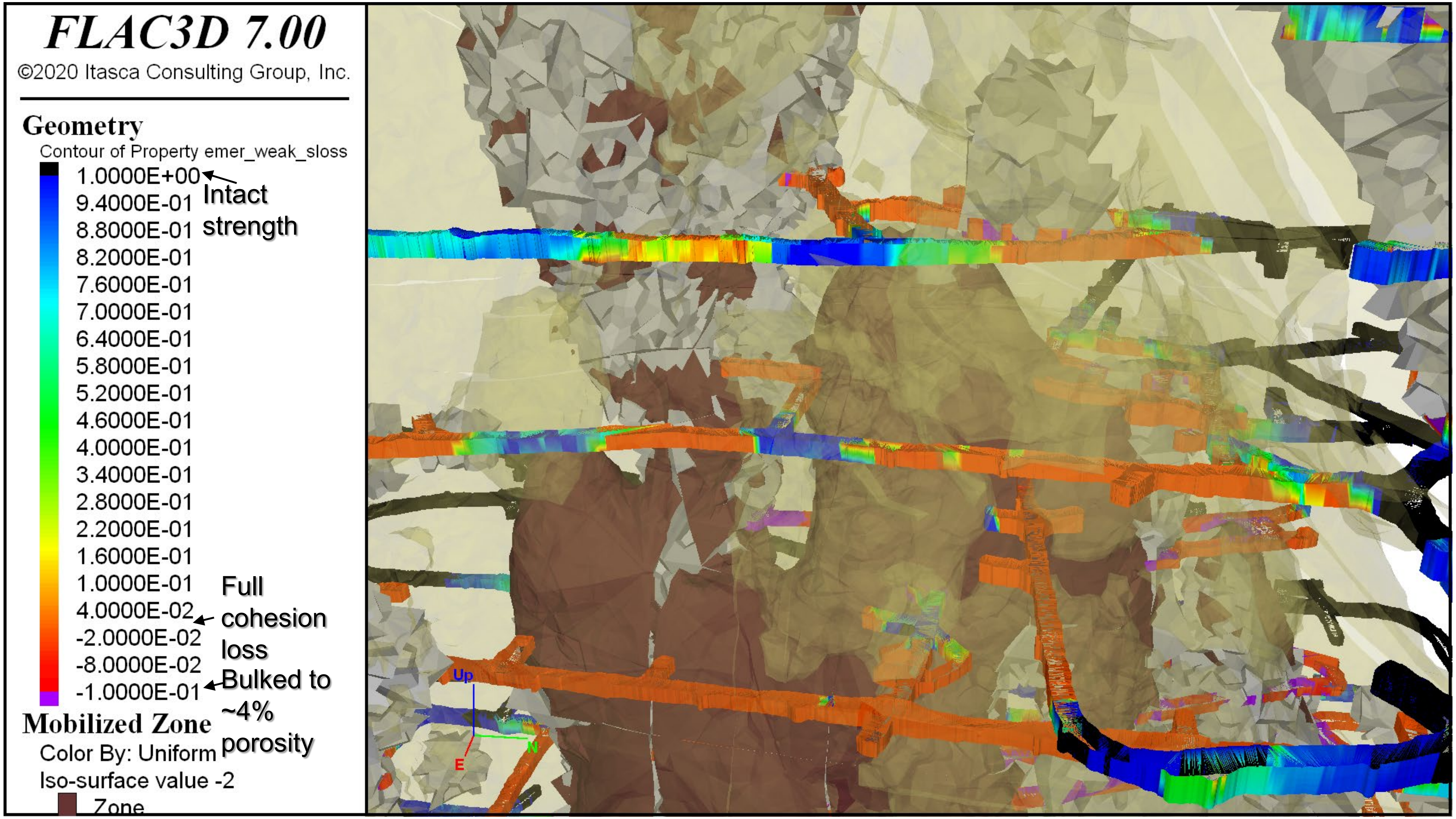
No signs of damage or fracturing in most of the level – in line with observations



Damage on this level corresponds to an area of observed damage along the wall of the drift



Current Conditions


FLAC3D 7.00
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Geometry
Contour of Property emer_weak_sloss
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9.4000E-01
8.8000E-01
8.2000E-01
7.6000E-01
7.0000E-01
6.4000E-01
5.8000E-01
5.2000E-01
4.6000E-01
4.0000E-01
3.4000E-01
2.8000E-01
2.2000E-01
1.6000E-01
1.0000E-01
4.0000E-02
-2.0000E-02
-8.0000E-02
-1.0000E-01
Intact strength
Full cohesion loss
Bulked to ~4% porosity
Mobilized Zone
Color By: Uniform
Iso-surface value -2
Zone
Up
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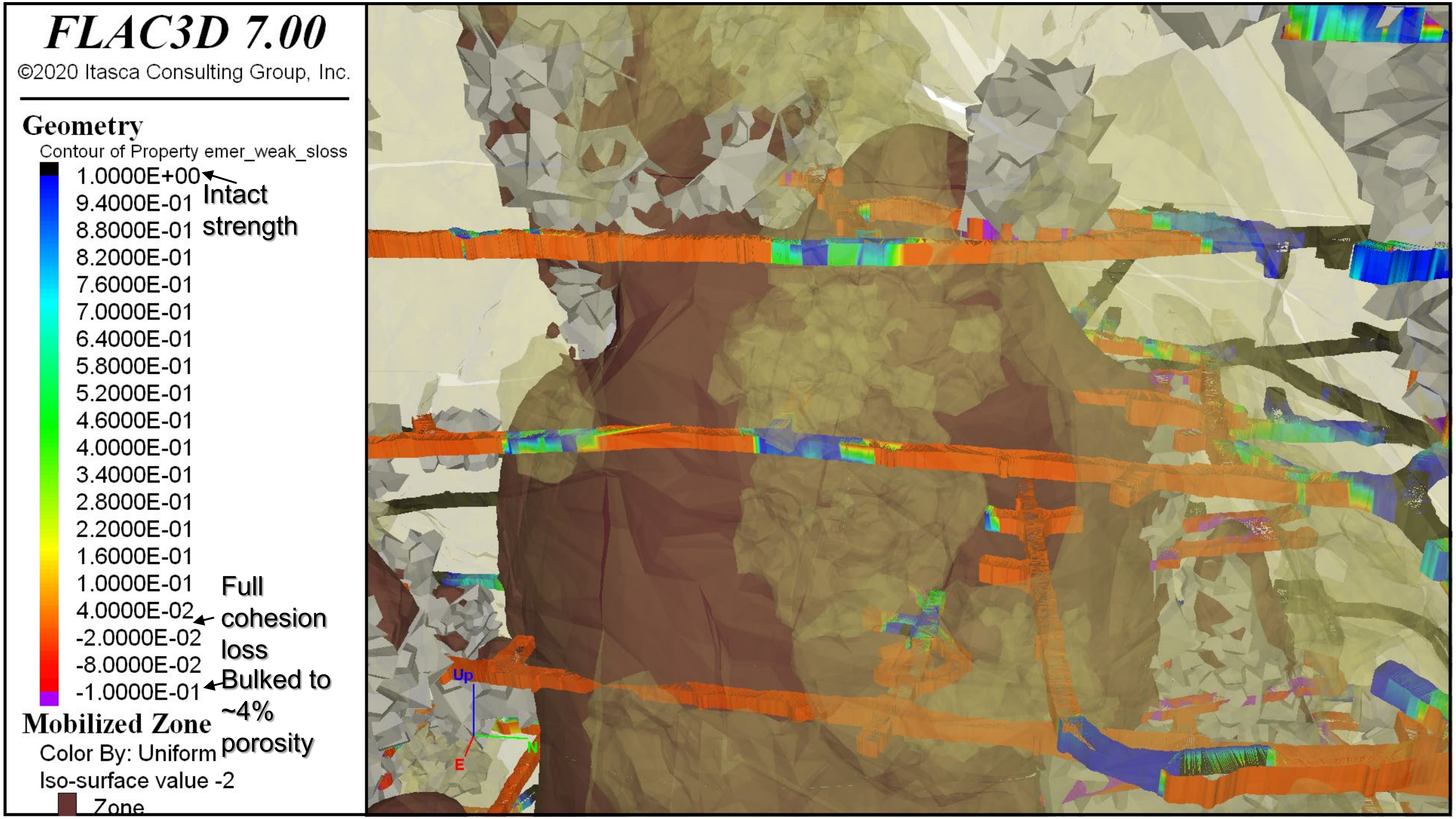
Year 3



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Intact strength
Full cohesion loss
Bulked to ~4% porosity
Mobilized Zone
Color By: Uniform
Iso-surface value -2
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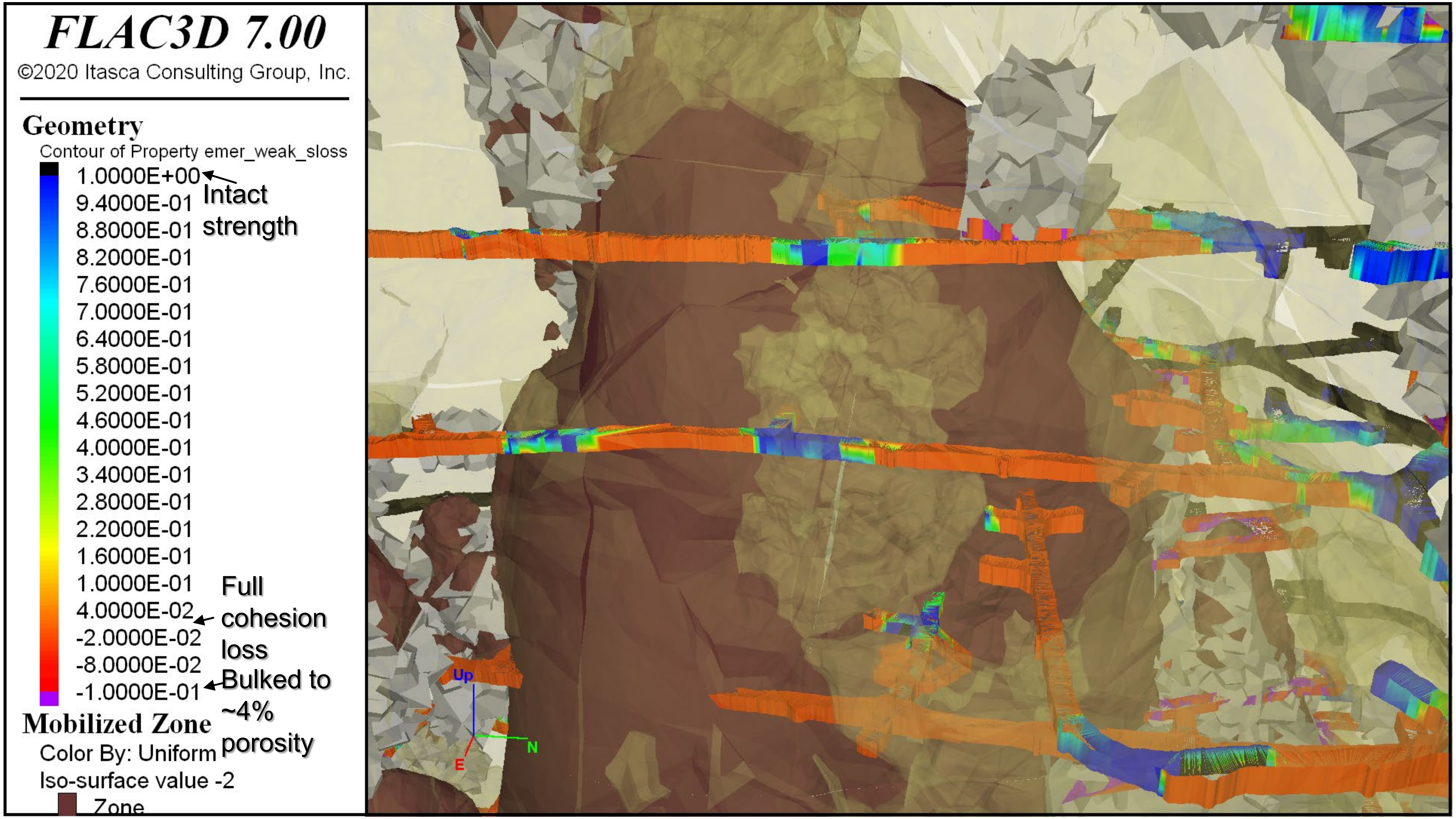
Year 6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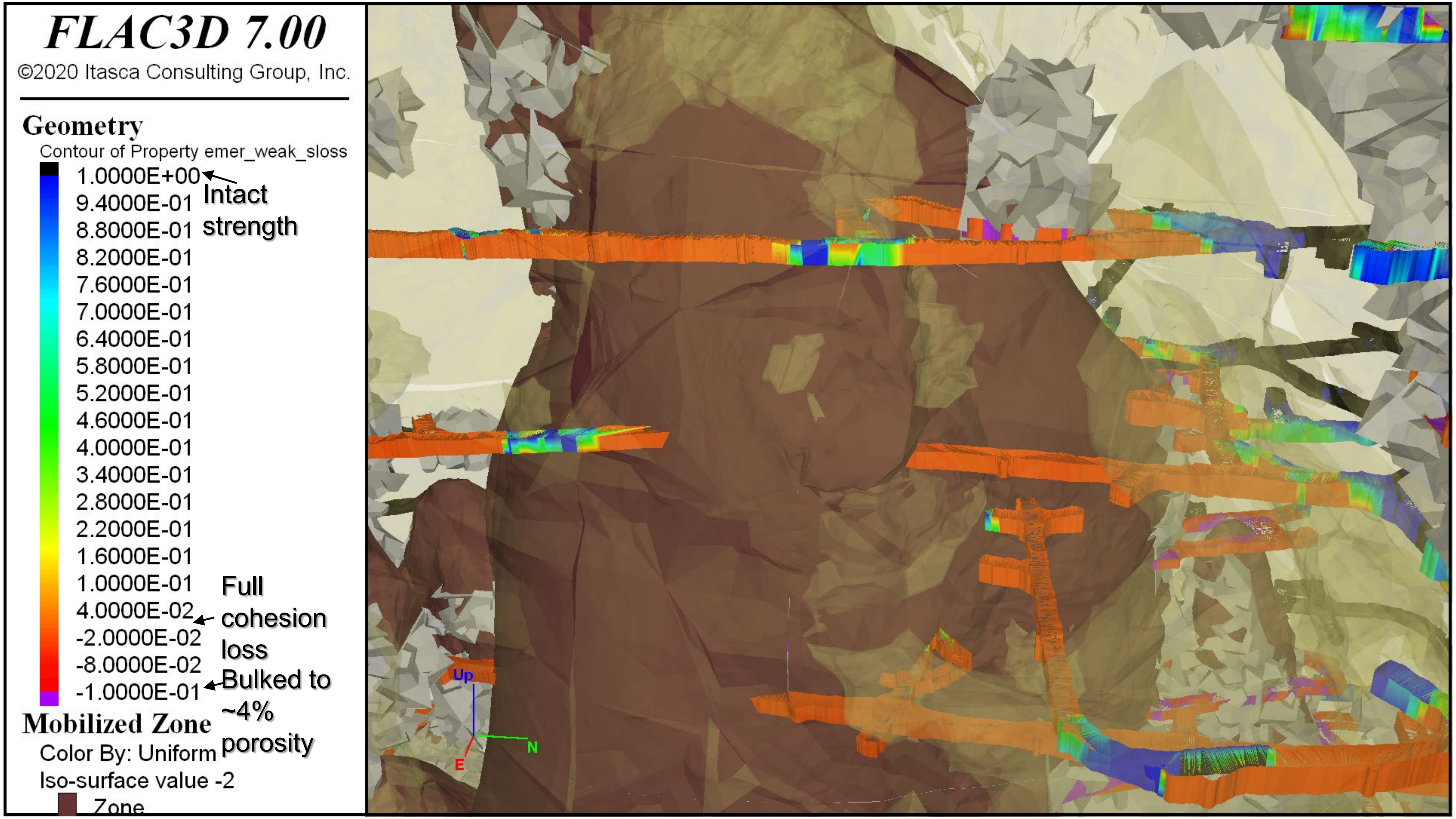
Year 7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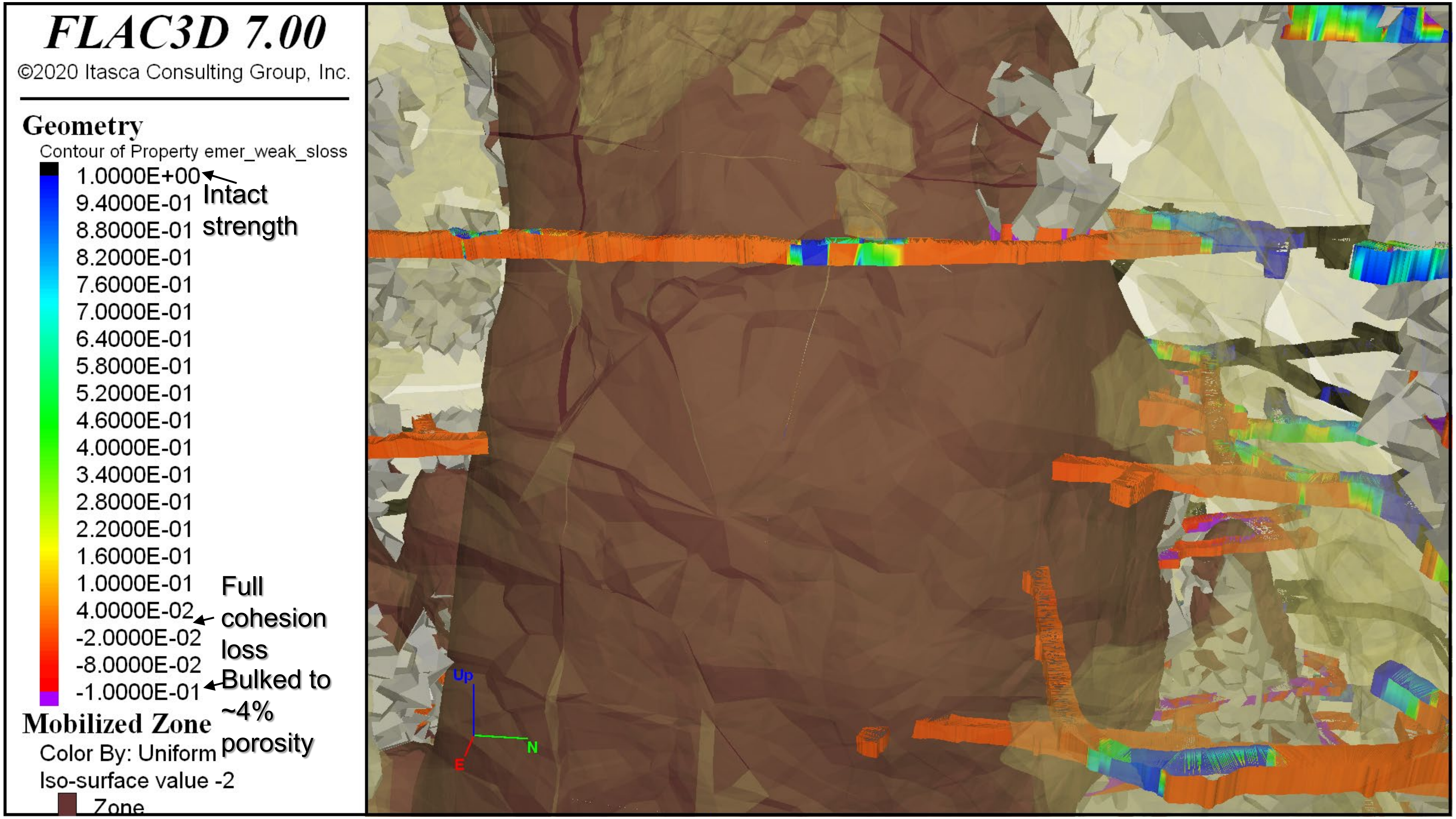
E

Year 8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©2020 Itasca Consulting Group, Inc.
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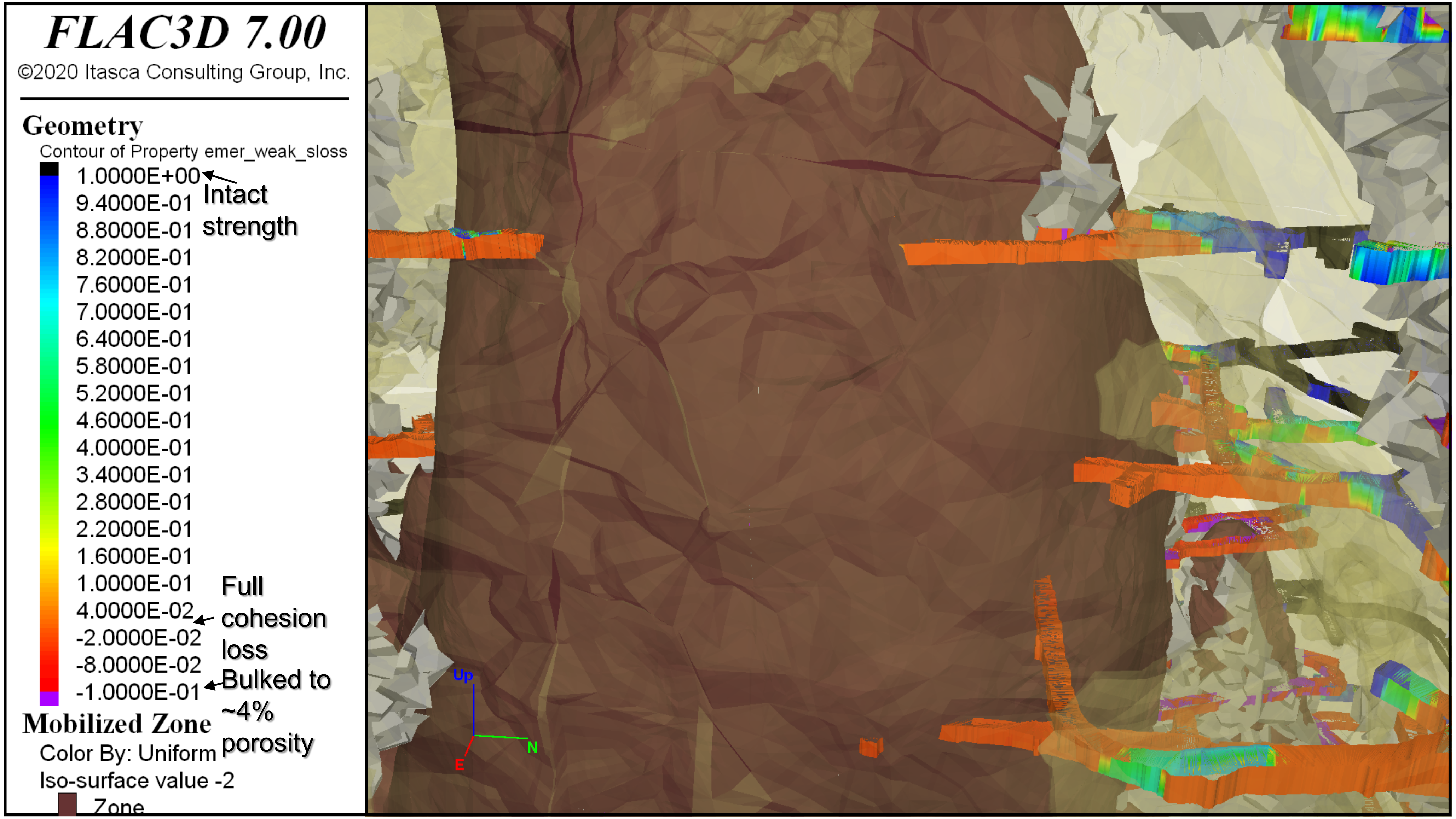
Full cohesion loss
Bulked to ~4% porosity
Mobilized Zone
Color By: Uniform
Iso-surface value -2
Zone
Up
N
E

Year 9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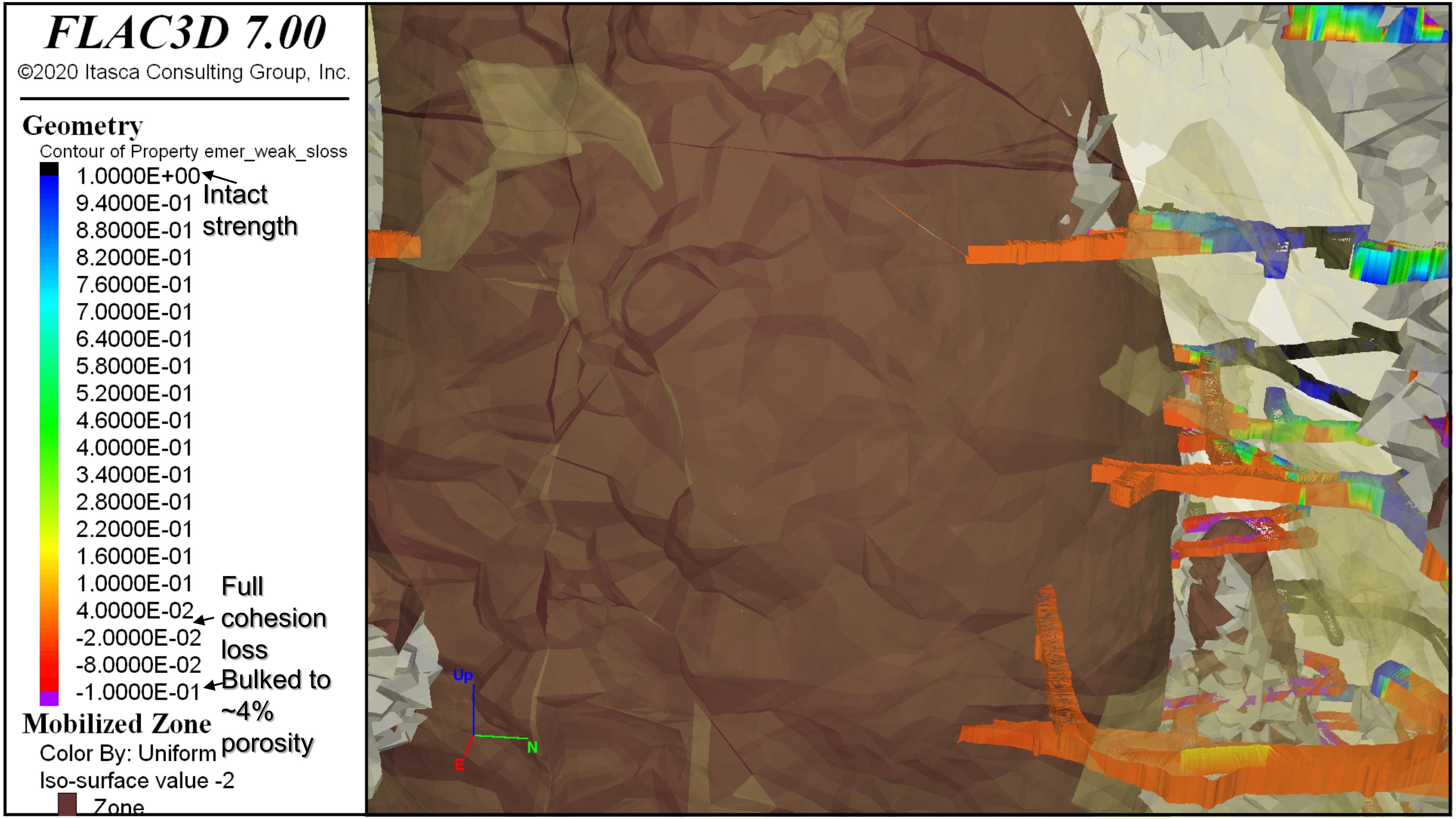
Intact strength
Full cohesion loss
Bulked to ~4% porosity
Mobilized Zone
Color By: Uniform
Iso-surface value -2
Zone
Up
N
E

Year 10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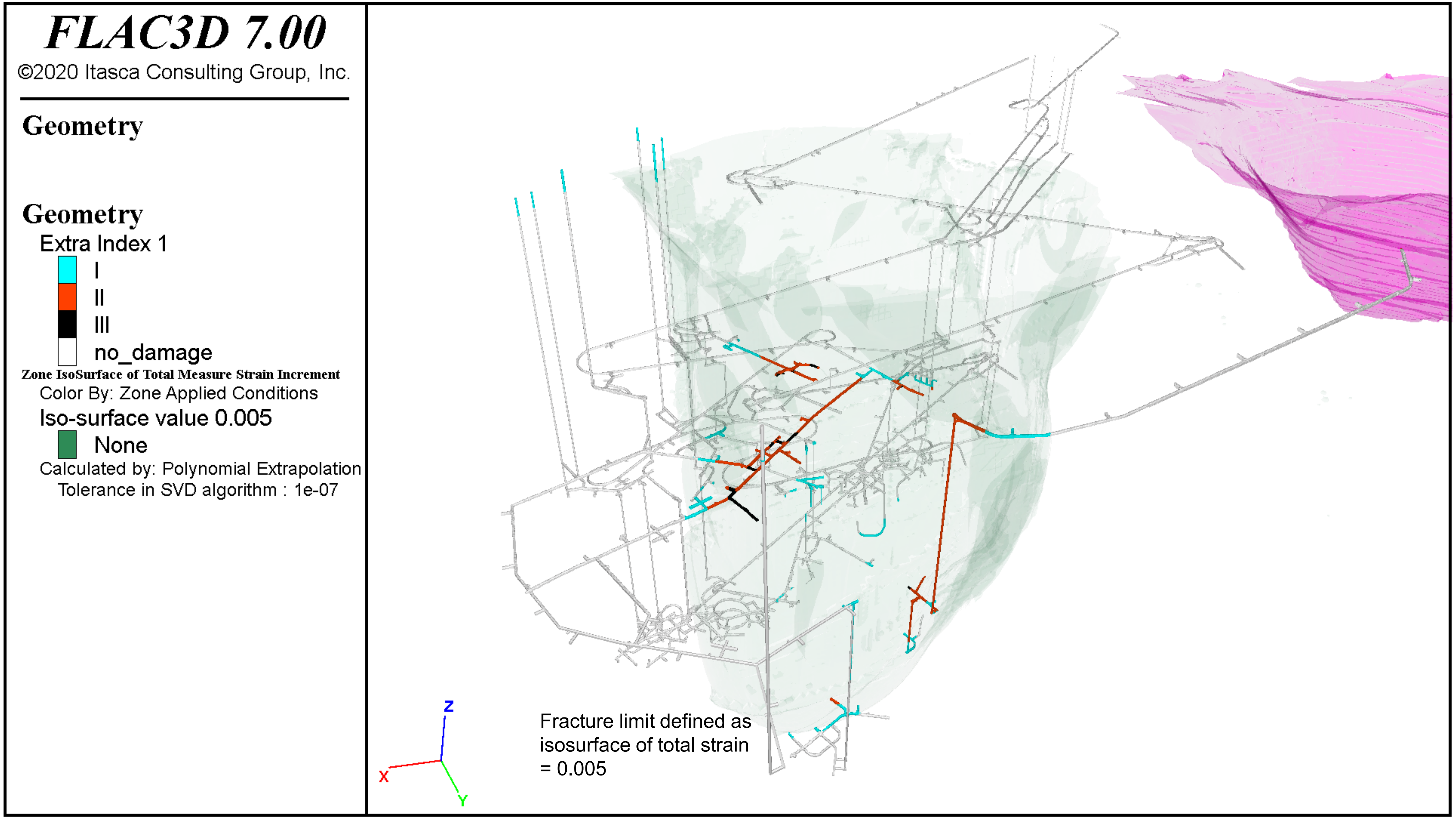
Intact strength
Full cohesion loss
Bulked to ~4% porosity
Mobilized Zone
Color By: Uniform
Iso-surface value -2
Zone
Up
N
E

Year 11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II
III
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Color By: Zone Applied Conditions
Iso-surface value 0.005
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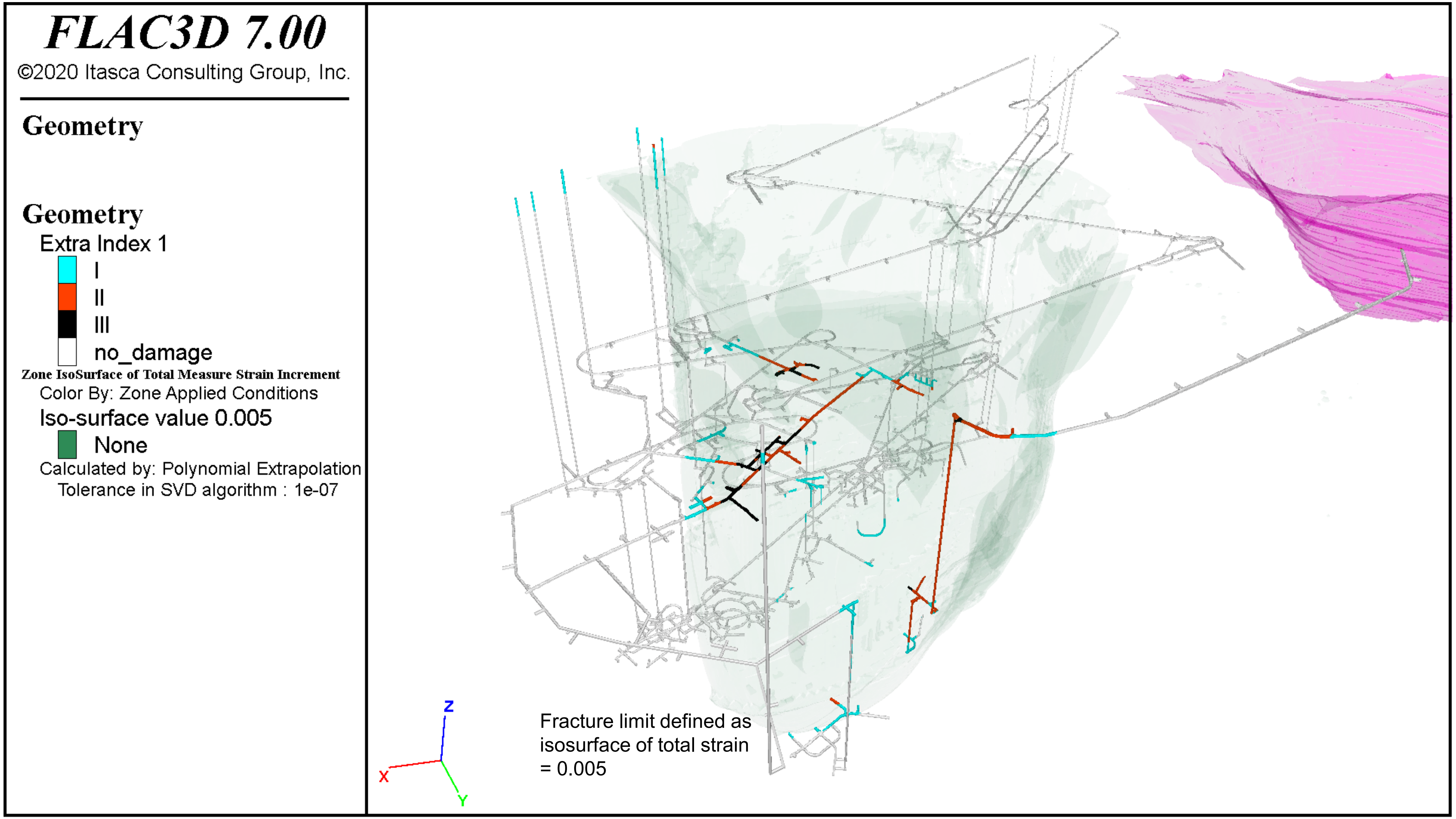
Calculated by: Polynomial Extrapolation
Tolerance in SVD algorithm : 1e-07
Z
X
Y
Fracture limit defined as isosurface of total strain = 0.005

UG_infra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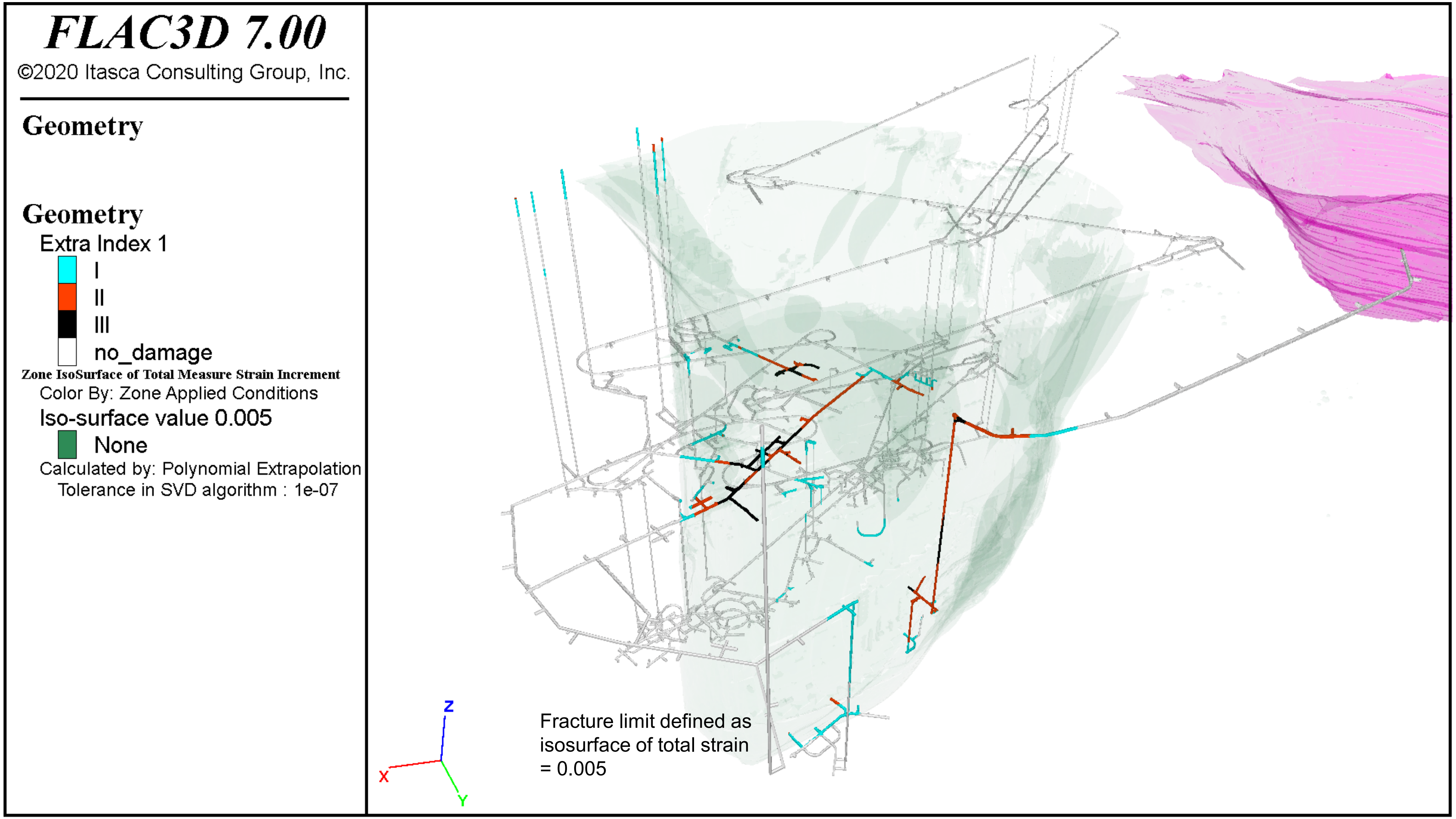
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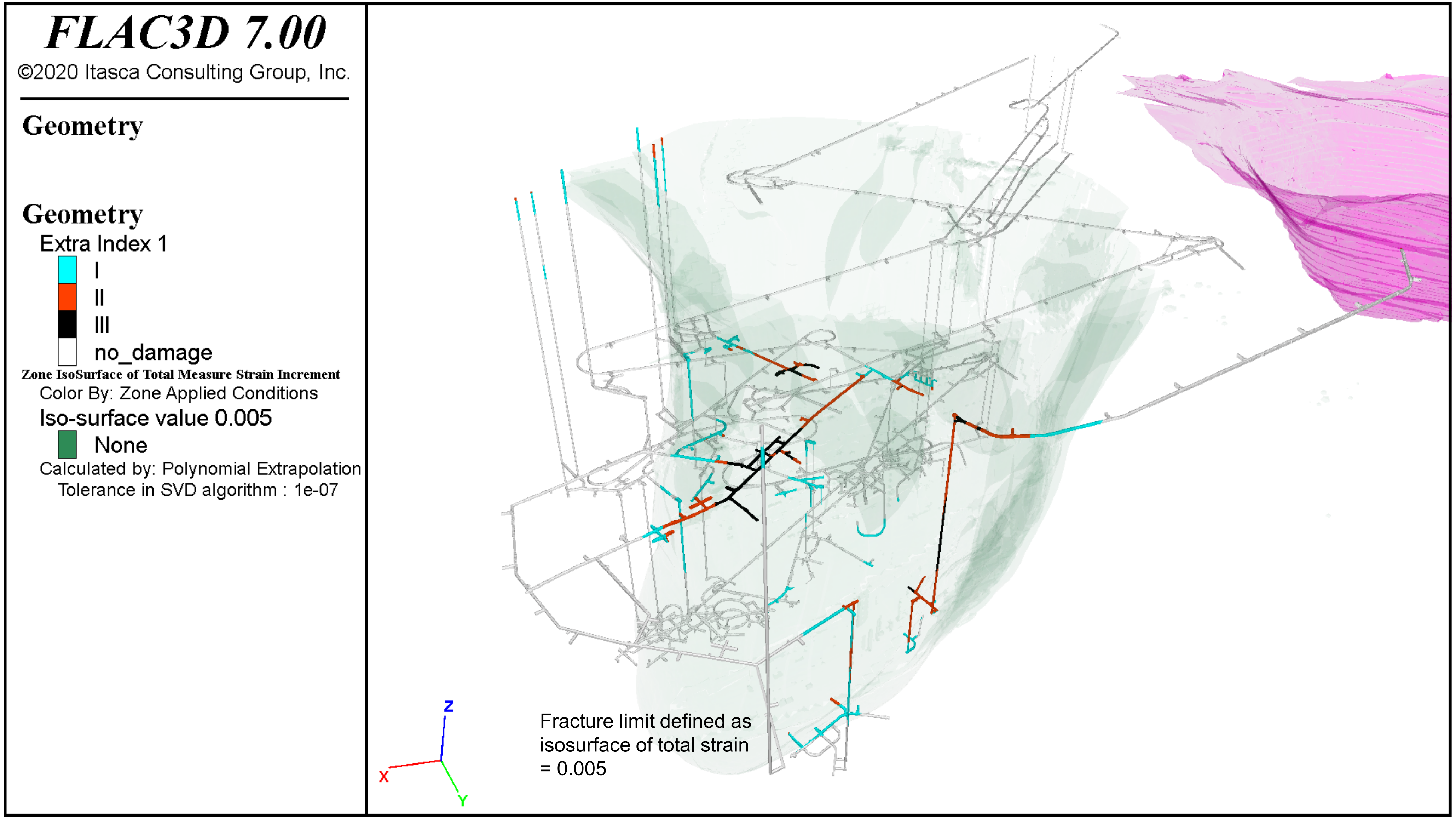
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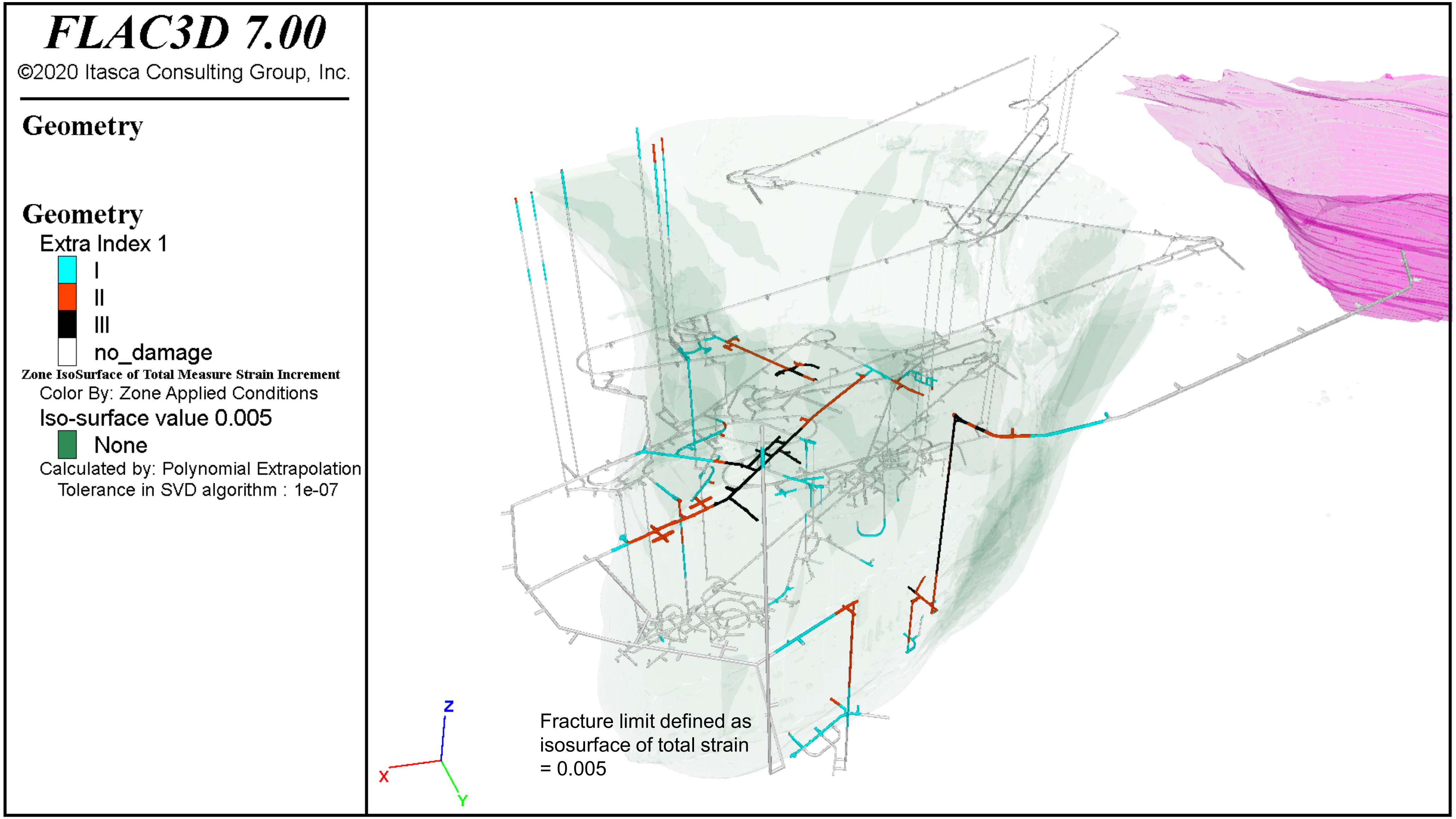

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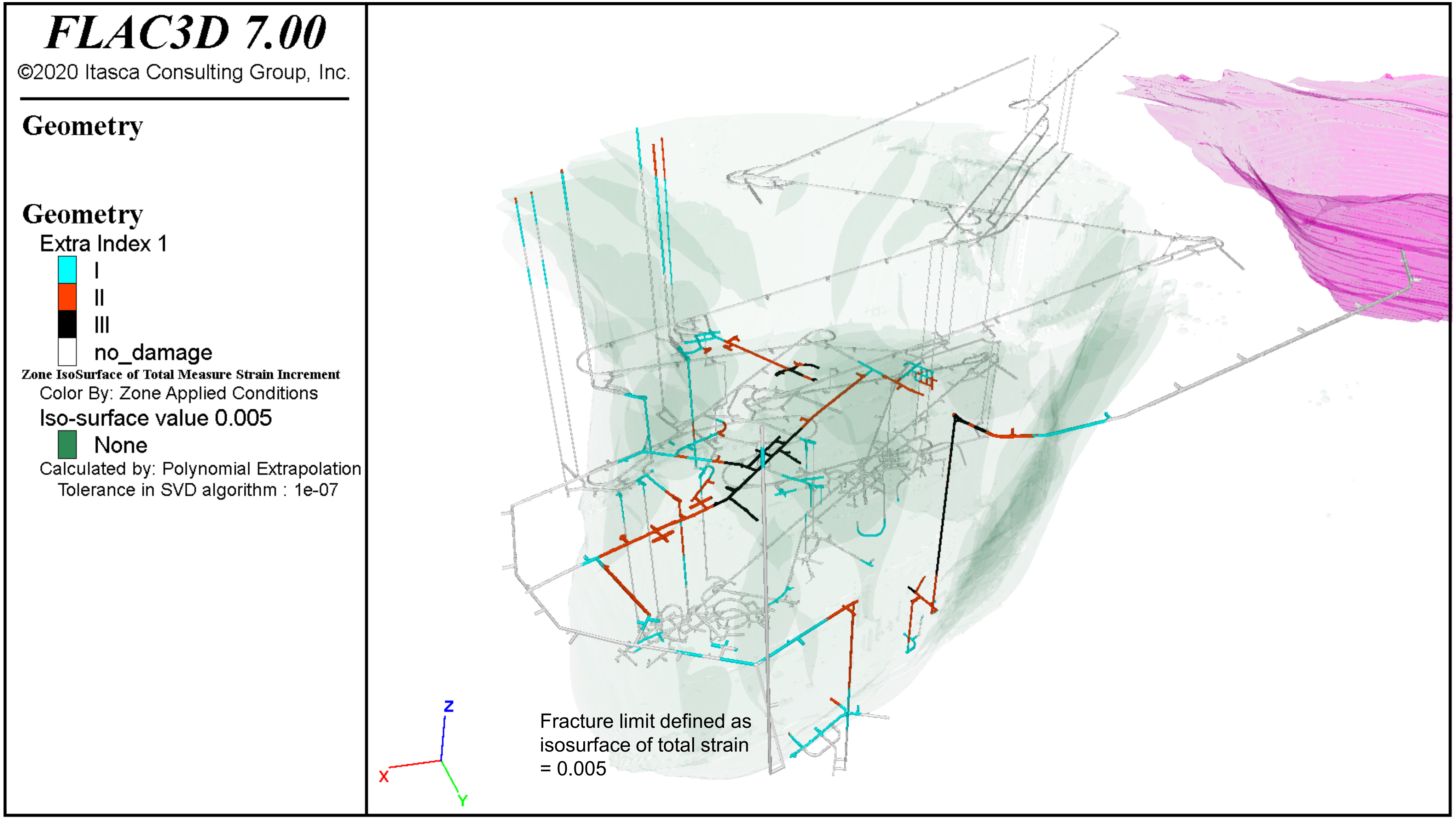
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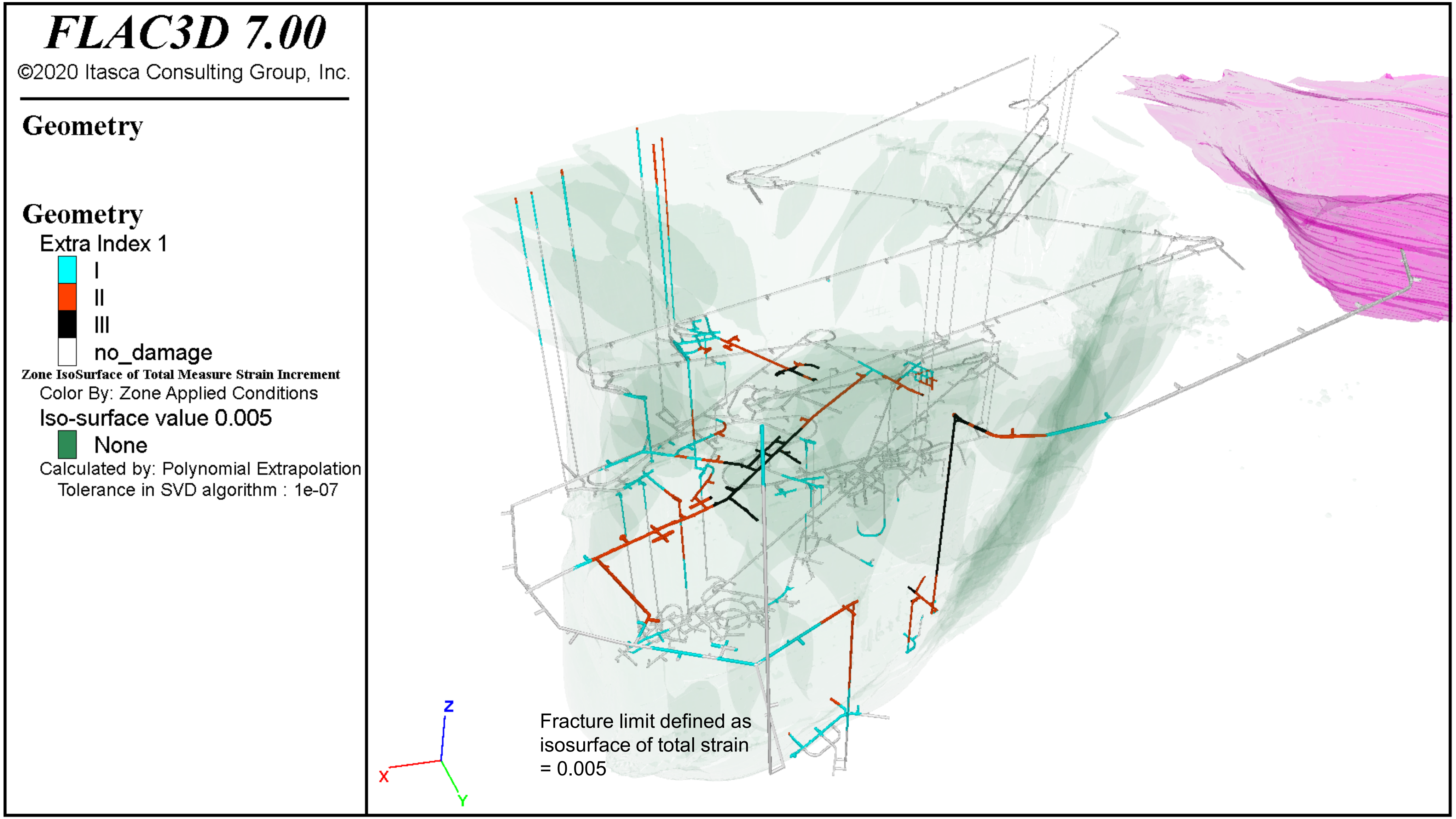
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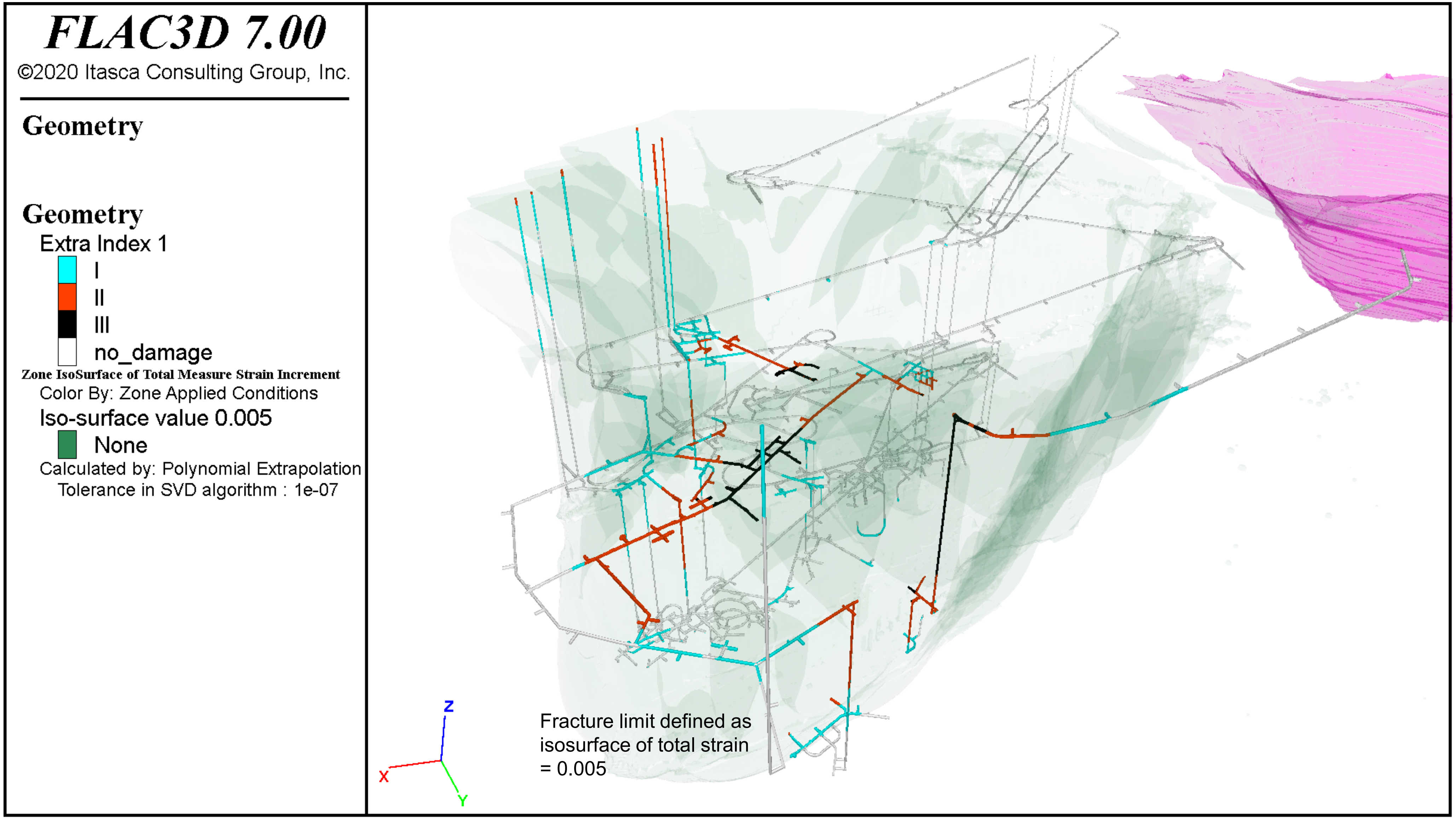
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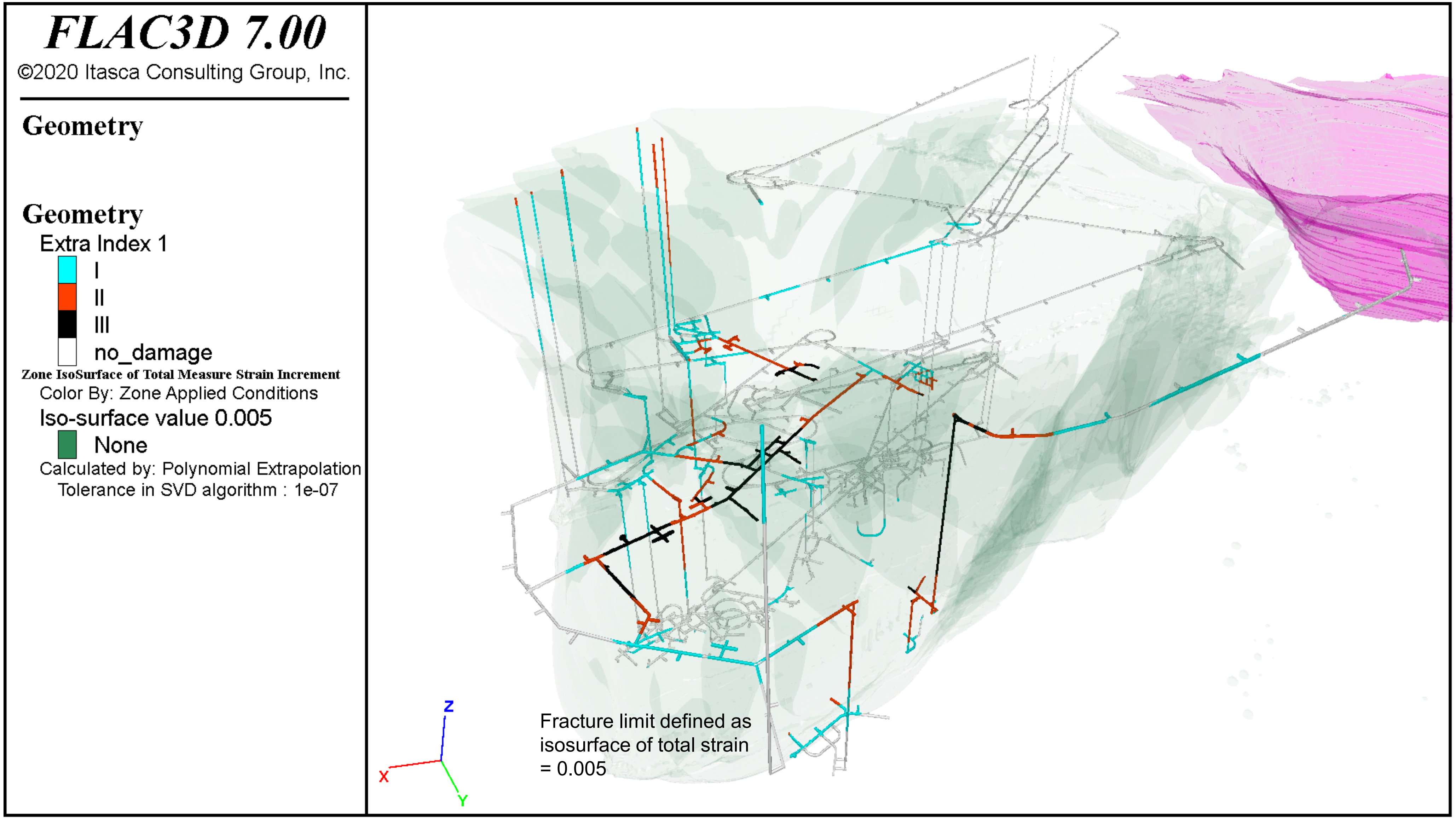
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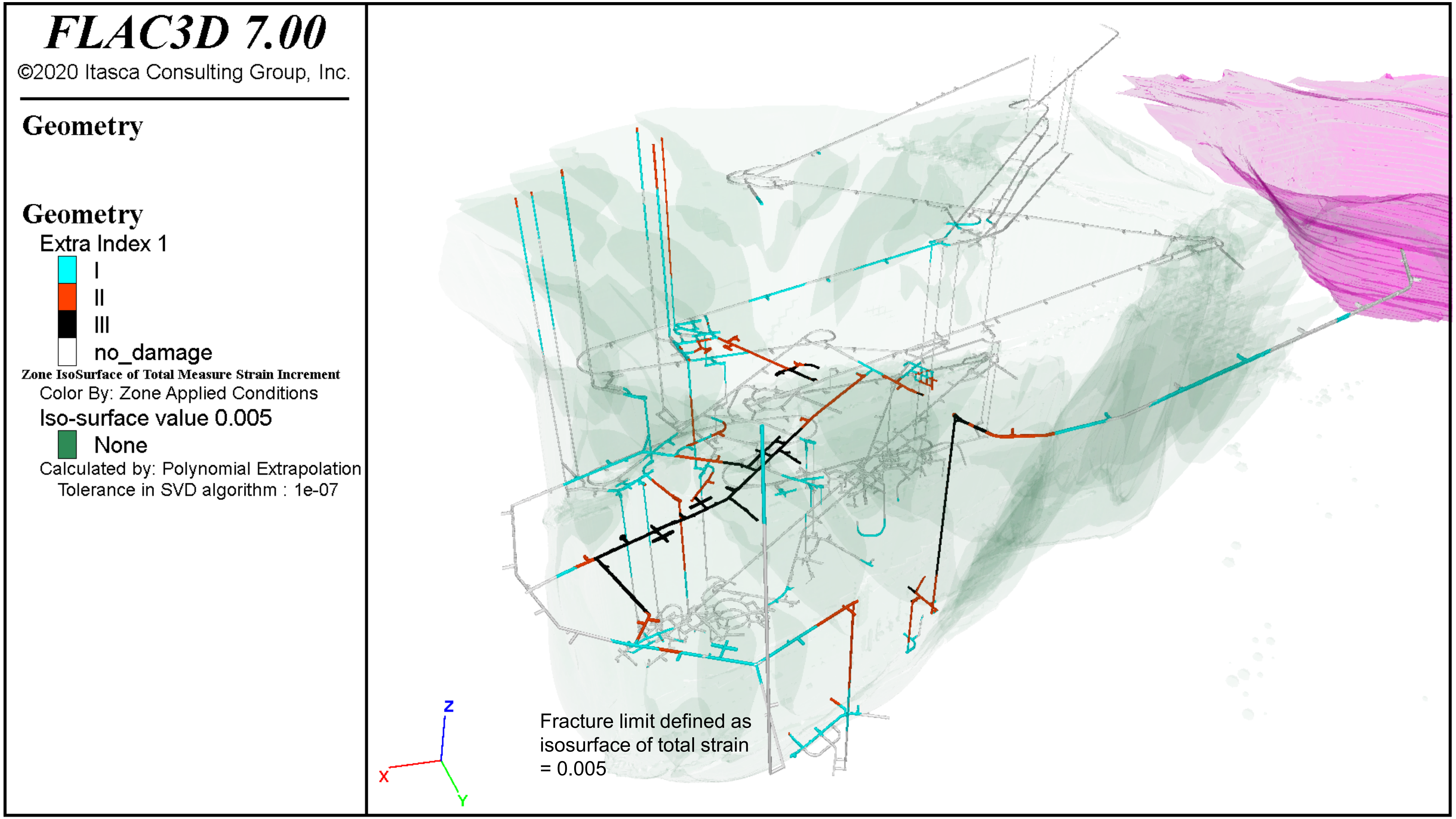
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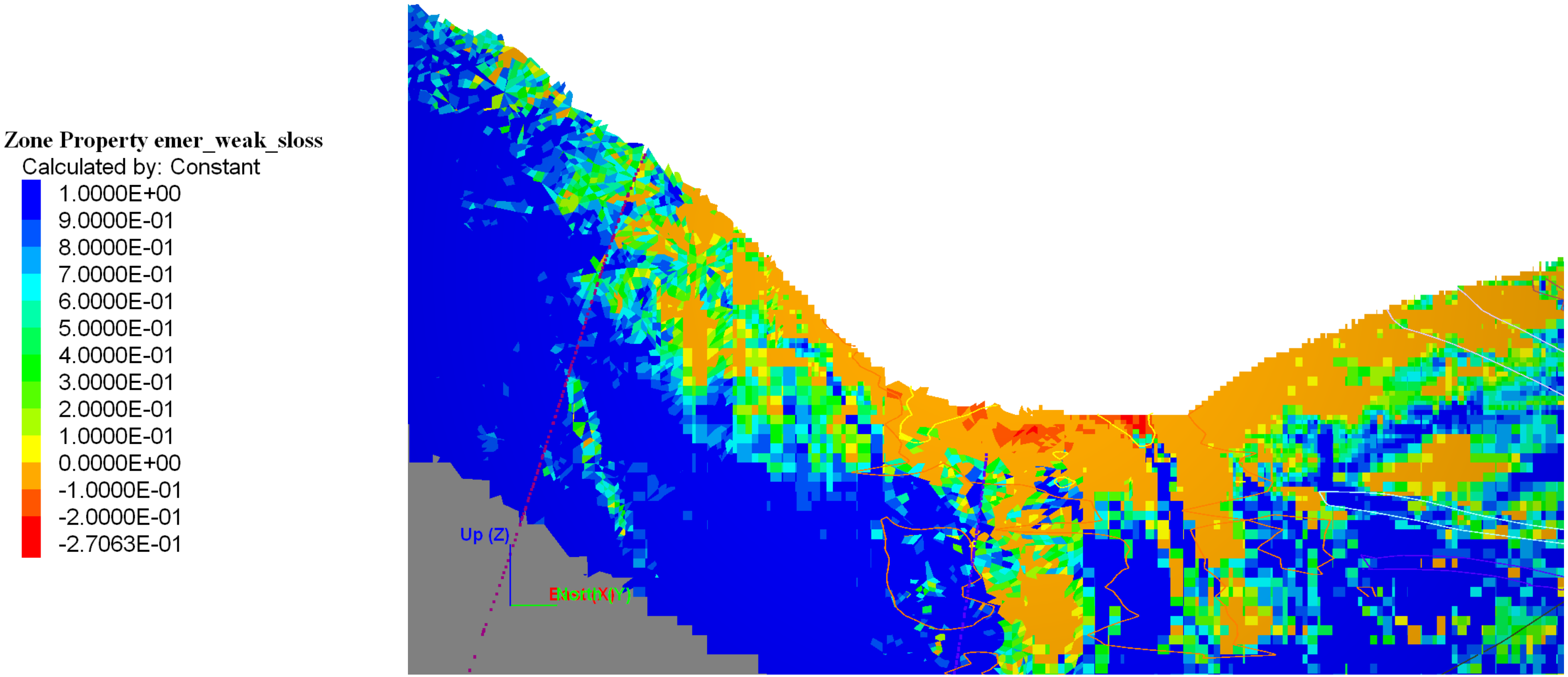
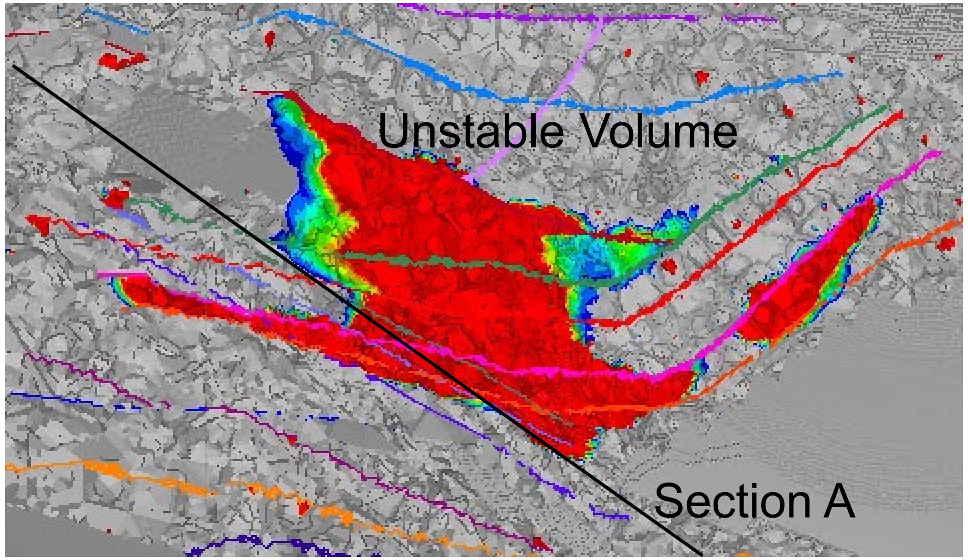
UG_infra

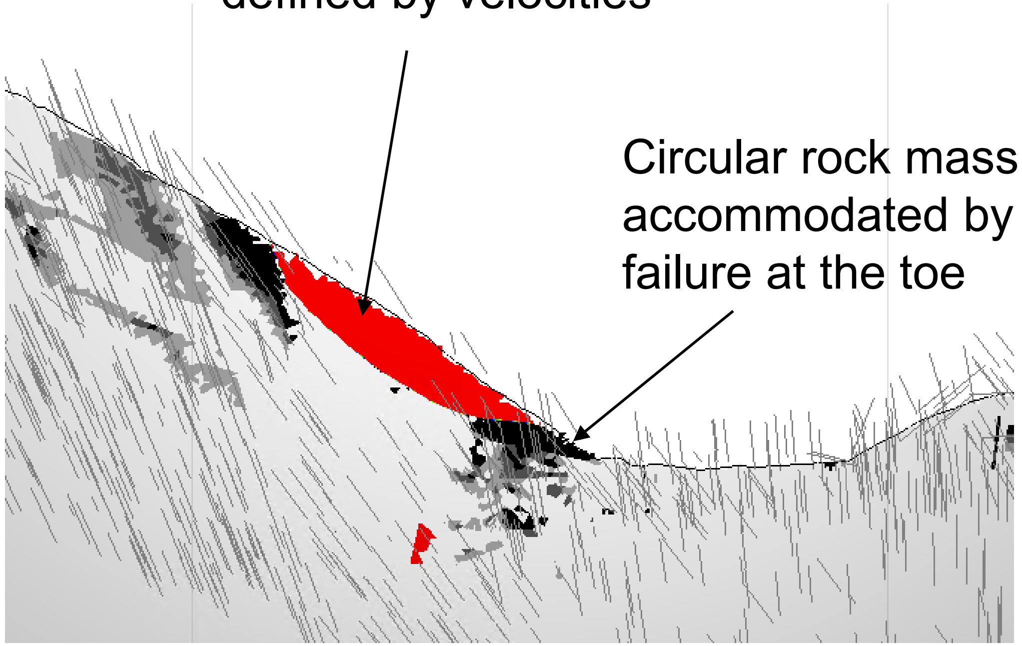
Rock mass degradation behind a slope



Rock mass degradation behind a slope

Potential failure of the slope
(volume in red)





Section A

Some other important components of *IMASS*

- Density adjustment based on zone-based volumetric strain
- Weakness planes defined by Ubiquitous Joints
- Option between one or two residual envelopes
- Tracking stresses at failure

- *IMASS* uses the latest Itasca constitutive model framework and techniques for apex correction, automatic testing, and property update and management.

Installation and usage

- *IMASS* is built into *FLAC3D 7.0* and *3DEC 7.0*
- Invoking the model:

```
model config imass
zone cmodel assign imass
zone initialize density [_density]
zone property in_stren_gsi [_gsi]
zone property in_stren_ucsi [_ucs]
zone property in_stren_mi [_mi]
zone property in_mod_youngintact [_young]
zone property in_weak_multecrit [_mult]
```

These are the only properties required to have all default behaviors active

Table 2: IMASS material property names

	Flags/Inputs	Calculated	Emergent
Peak strength	flag_stren_mod(off) *in_stren_gsi* *in_stren_mi* *in_stren_ucsi*	calc_stren_global calc_stren_tension calc_stren_ucsrm calc_stren_mb calc_stren_s calc_stren_a	
Modulus	*in_mod_youngintact*	calc_mod_youngrm calc_mod_poisson	emer_mod_young
Strength weakening	flag_weak_barton(on) flag_weak_tencut(on) in_weak_multecrit in_weak_chmbr(4.33) in_weak_char(1.0) in_weak_phib(30) in_weak_sloss(1.0) in_weak_tabletension	calc_weak_ecrit calc_weak_zsize	emer_weak_sloss emer_weak_esplastic emer_weak_istenweak emer_stren_mcfric emer_stren _mccoh emer_stren _mcten
Dilation/ bulking & modulus softening	flag_bulking_denadj flag_bulking_modsoft in_bulking_den in_bulking_dil in_bulking_targetvsi in_bulking_maxtotvsi(2/3)		emer_bulking_mcdil emer_bulking_den emer_bulking_totvsi
Stress at failure	flag_sfail_failtrack(off)		emer_sfail_pmax emer_sfail_plungepmax emer_sfail_trendpmax emer_sfail_pmid emer_sfail_plungepmid emer_sfail_trendpmid emer_sfail_pmin emer_sfail_plungepmin emer_sfail_trendpmin
Ubiquitous joint	flag_uj_usejoints(on) in_uj_jcoh in_uj_jdil in_uj_jfric in_uj_jten in_uj_jdip in_uj_jddirection(on) in_uj_jnx in_uj_jny in_uj_jnz		emer_uj_esplastic

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)
  - Characterization of the upper- and lower-bound for the equivalent roughness (R) (especially for porosities below 15%)
  - Refinement of the dilation model consistent with the upper- and lower-bound R and how it transitions between those values with increasing rock mass porosity

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.

Questions & Answers

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