EXTREME ENVIRONMENTS: HOW HPC SIMULATION HELPS EXTRACTING VALUABLE RESOURCES

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Mining One

Extracting Resources

The mining industry has an image problem – Sustainability – A global skills crisis – Decarbonisation, Electric Vehicles and Green Steel – Digital Twins

The World Needs Resources

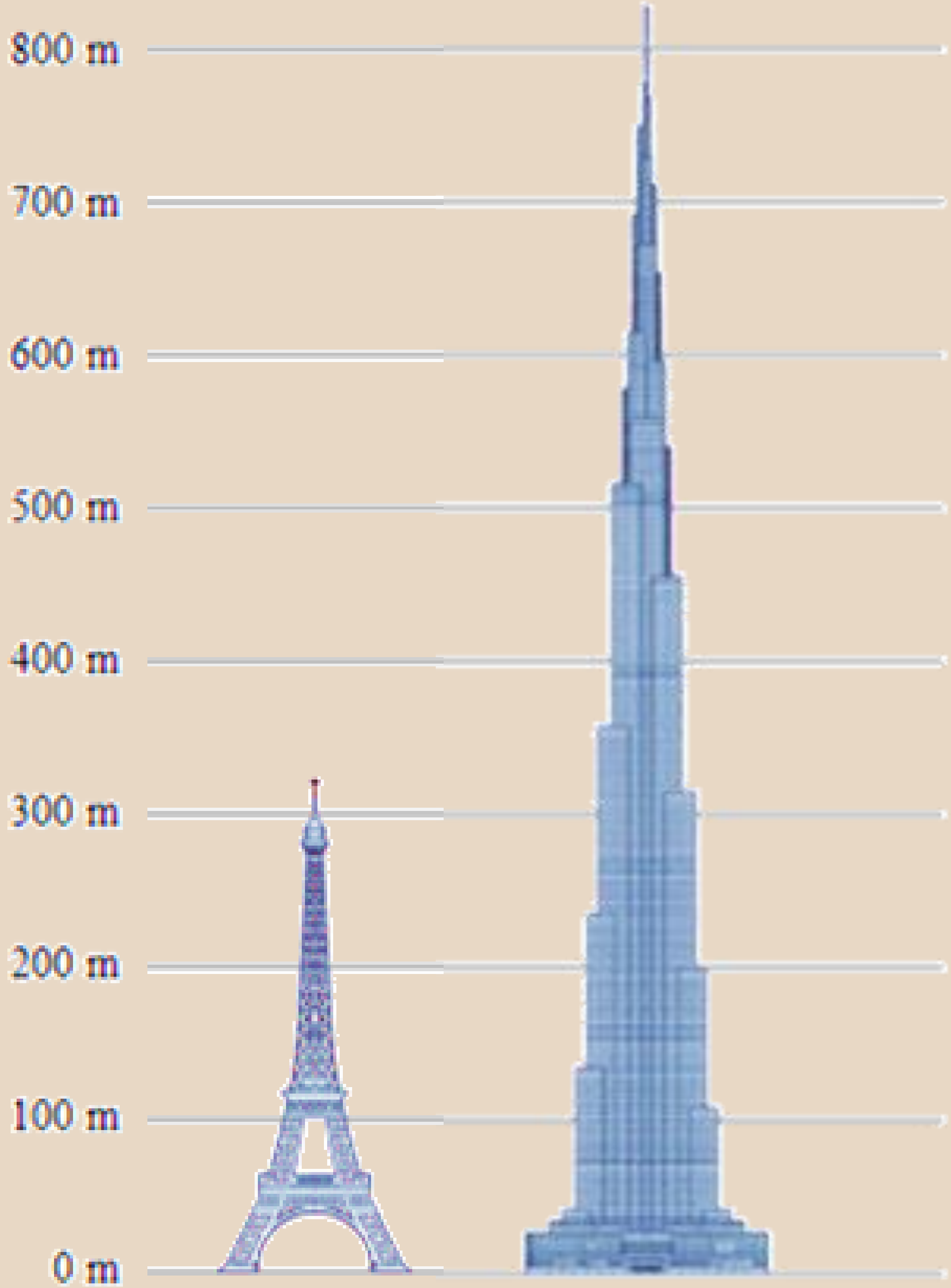
Extreme Environments

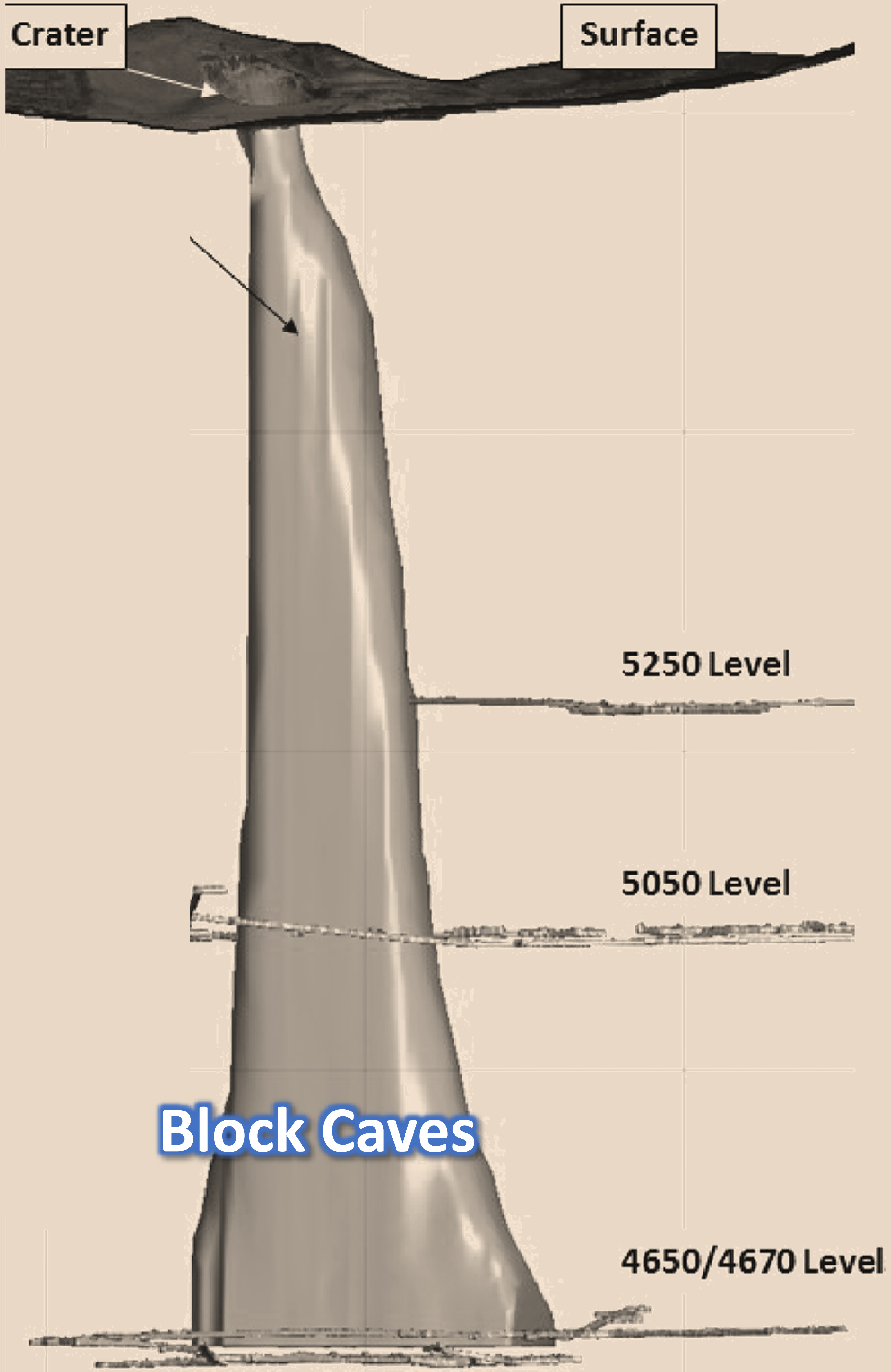
4000m Altitude – or 1200m below the surface – Scale

Extreme Environments – 4000m Altitude

The World's highest altitude Abaqus Training?

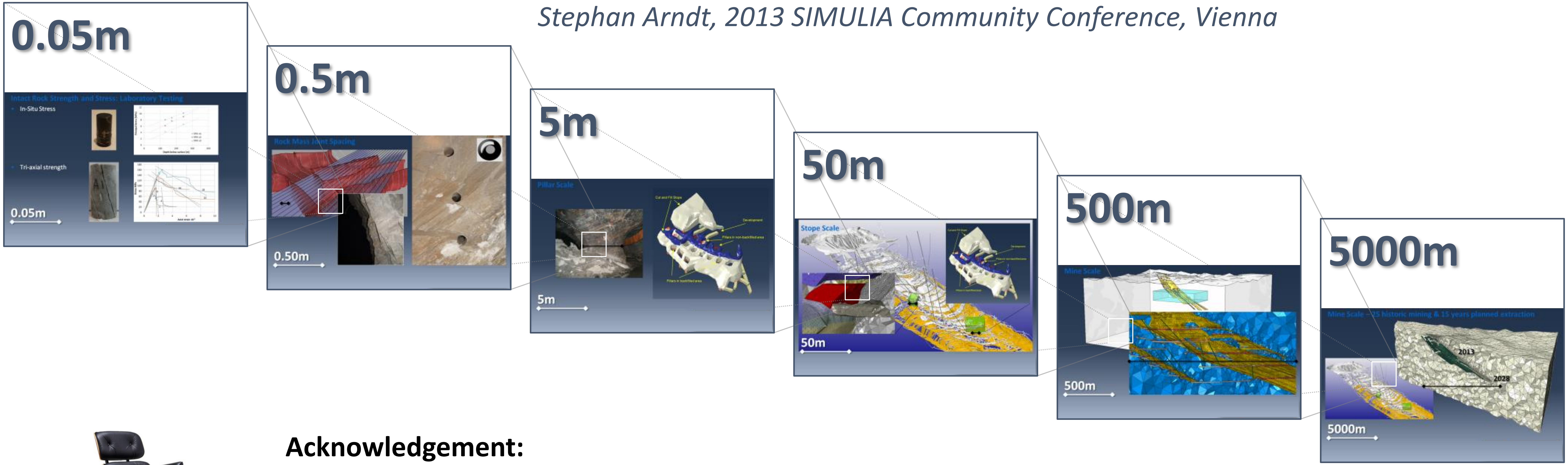
1200m Deep … and Beyond





Extreme Environments – Scale

Forecasting Seismicity, Stability and Stress in Underground Mining
Stephan Arndt, 2013 SIMULIA Community Conference, Vienna



Acknowledgement:

Powers of Ten beta
Based on the film by Charles and Ray Eames.
An Eames Office website.

http://www.powersof10.com

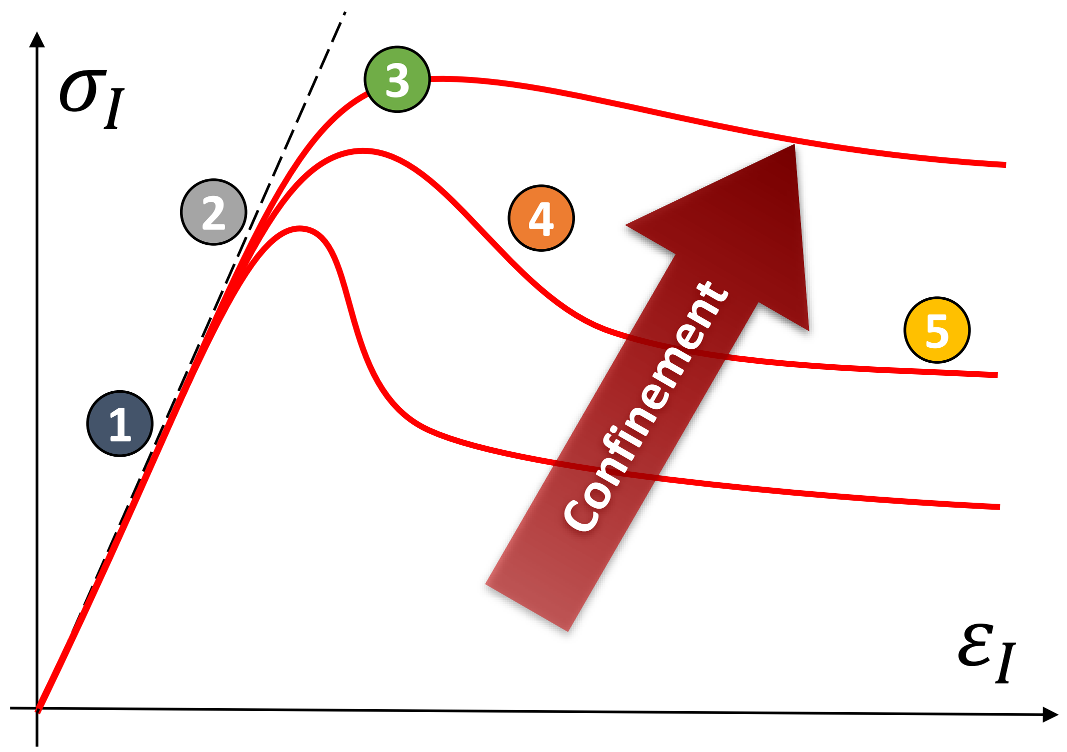
Simulation

Modelling Rock Mass in High Stress: IUCM – Rock Anisotropy in Constitutive Models

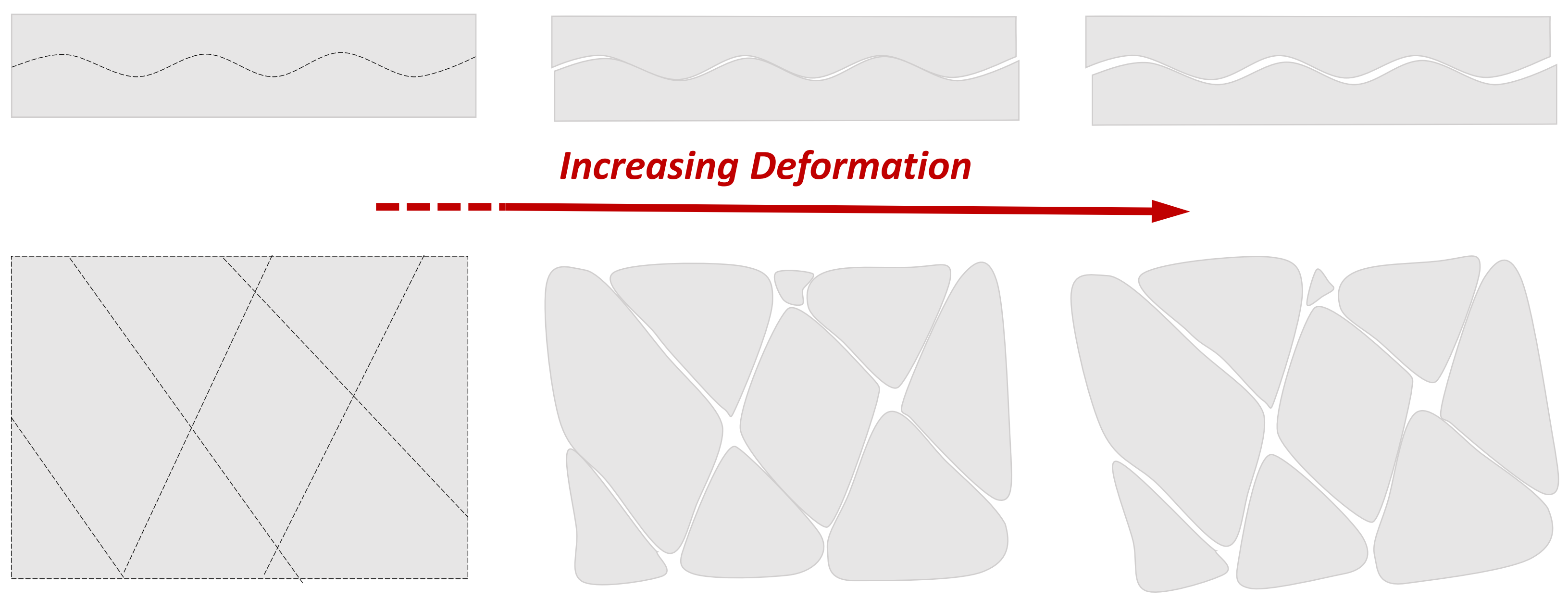
Modelling Rock Mass in High Stress: IUCM

Stress – Strain

1) **Elastic**
2) **Fracturing**
   (onset of in-elastic behaviour)
3) **Peak strength**
4) **Softening**
5) **Broken**
   (residual strength)



Dilation

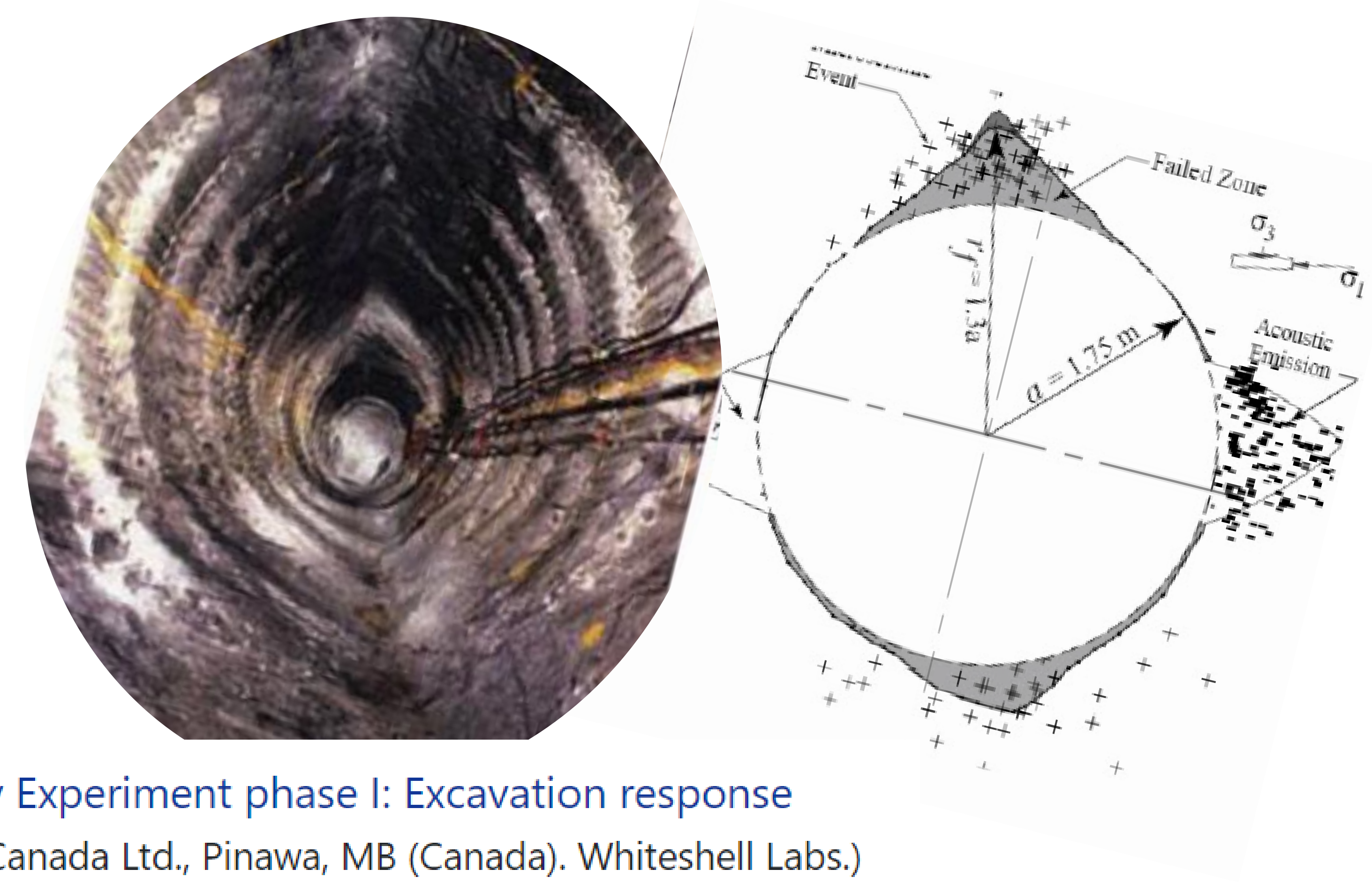


Mine-by-experiment

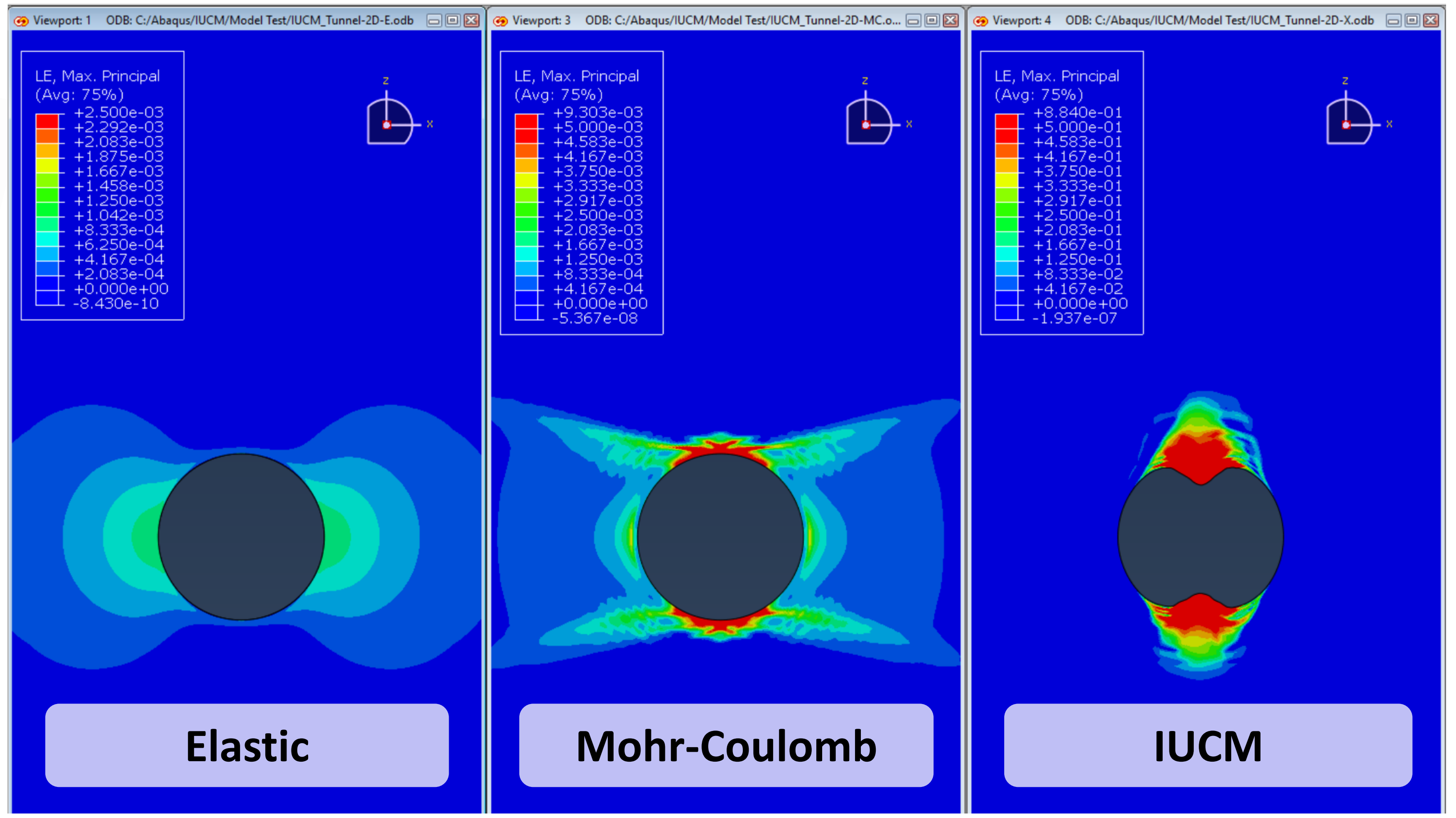
Cai et at. (2004)

Hajiabdolmajid et al. (2002)

Read, Martin (1996)

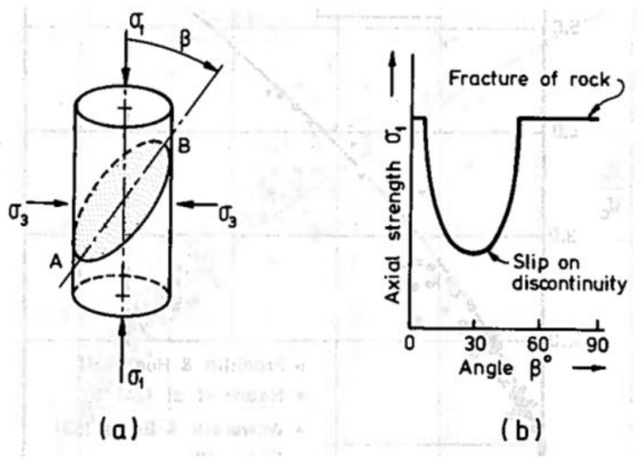


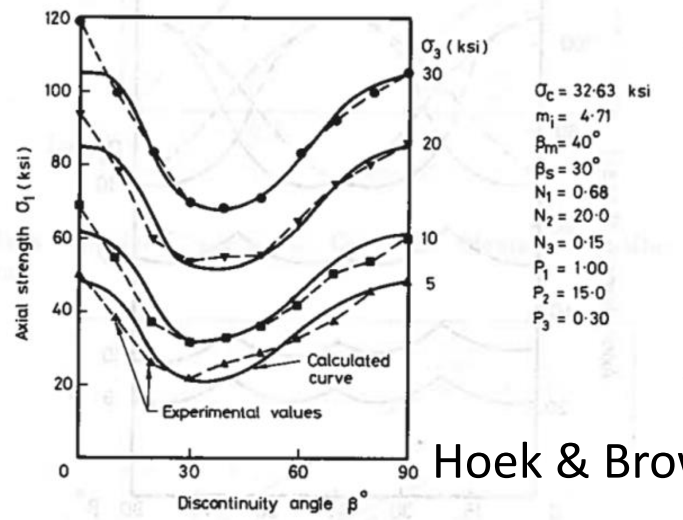
IUCM



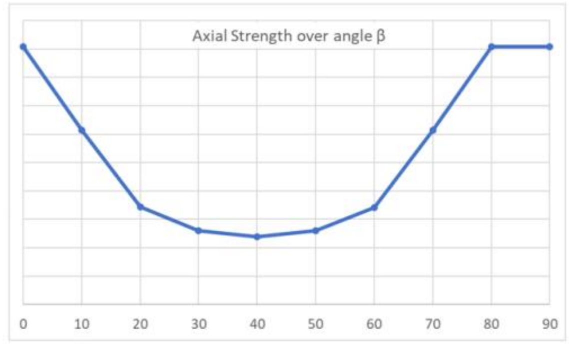
PDF Technical summary of AECL's Mine-by Experiment phase I: Excavation response
Read, R.S.; Martin, C.D. (Atomic Energy of Canada Ltd., Pinawa, MB (Canada). Whiteshell Labs.)
Atomic Energy of Canada Ltd., Pinawa, MB (Canada). Whiteshell Labs
1996

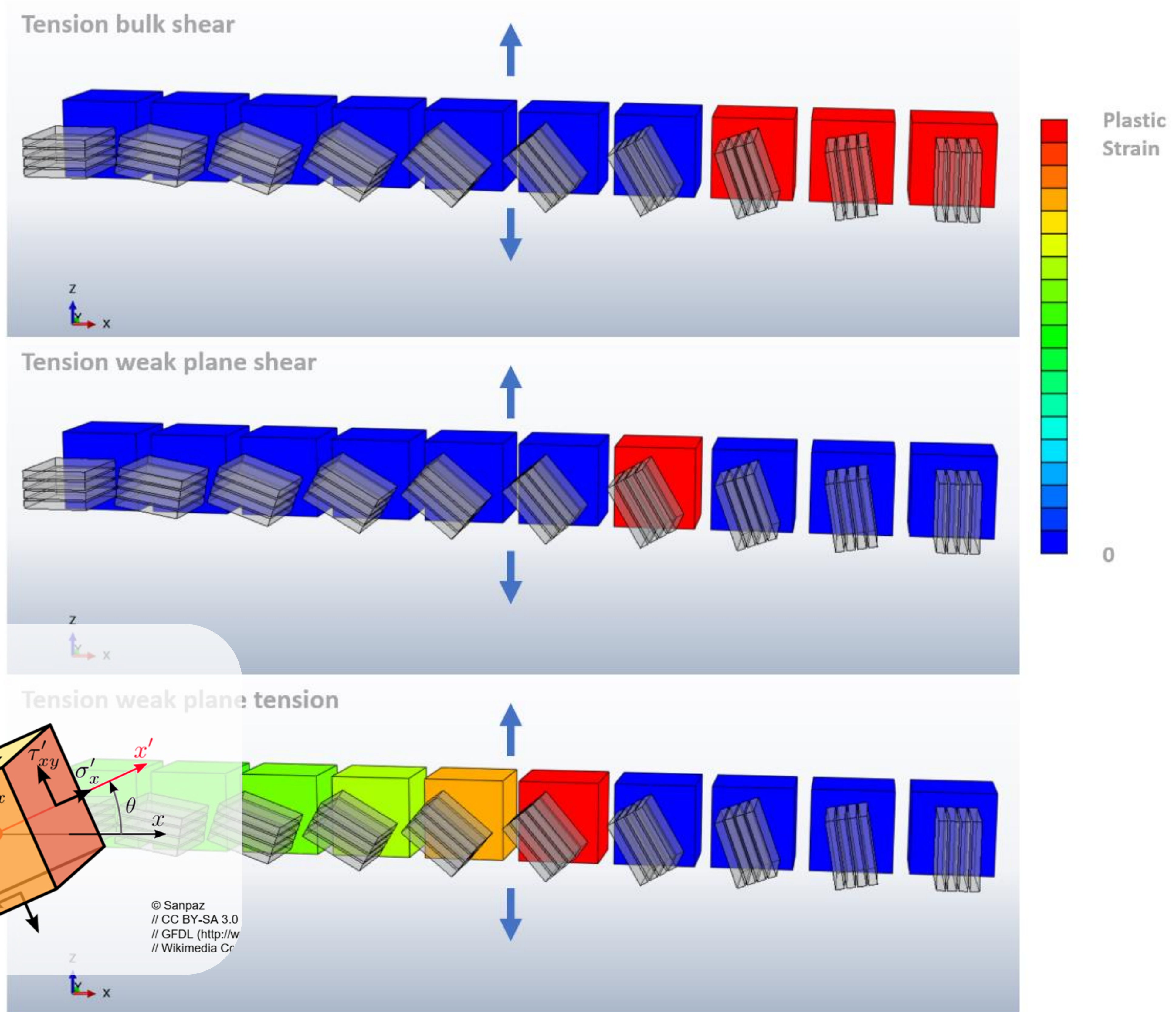
Rock Anisotropy in Constitutive Models

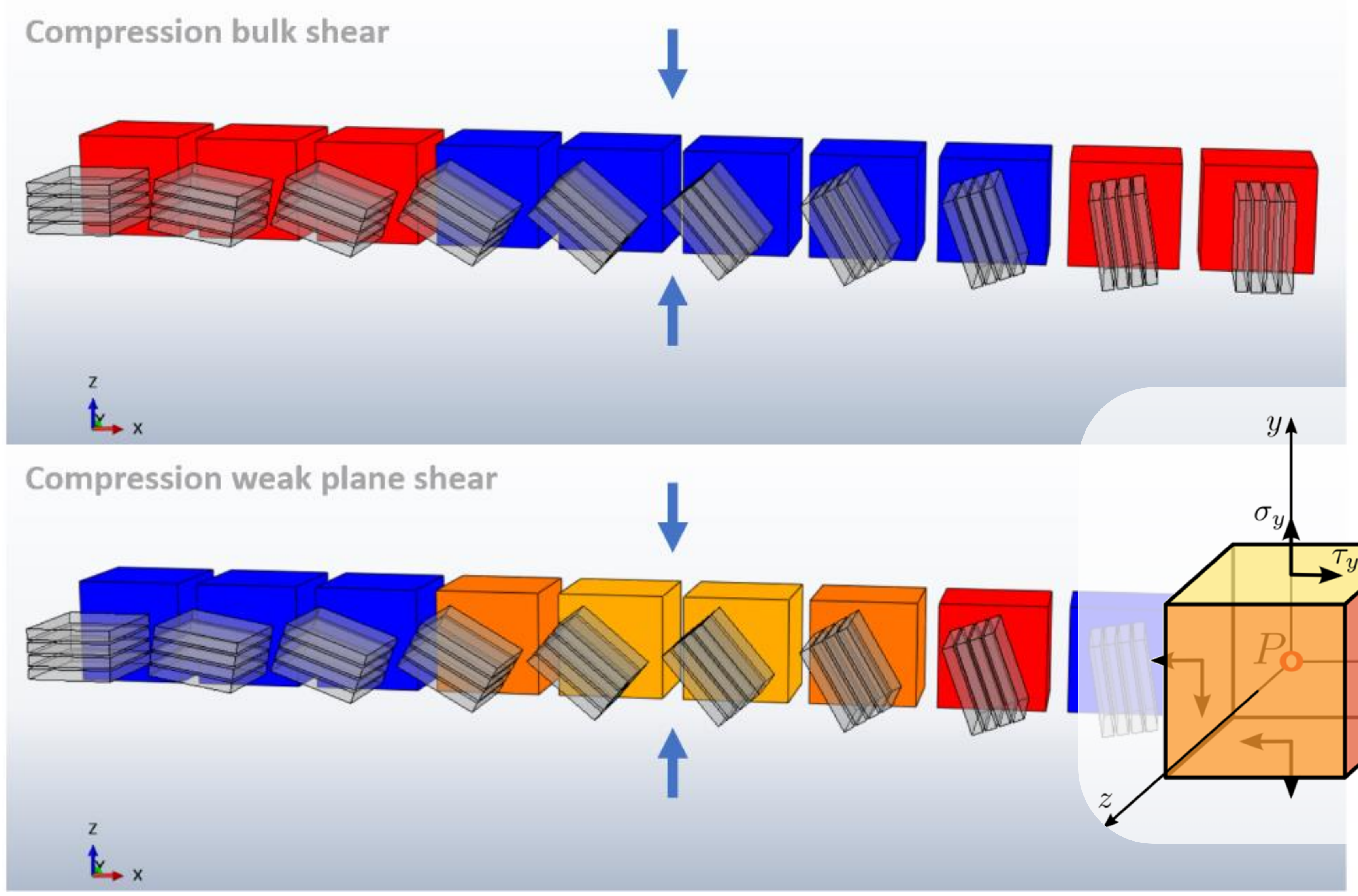


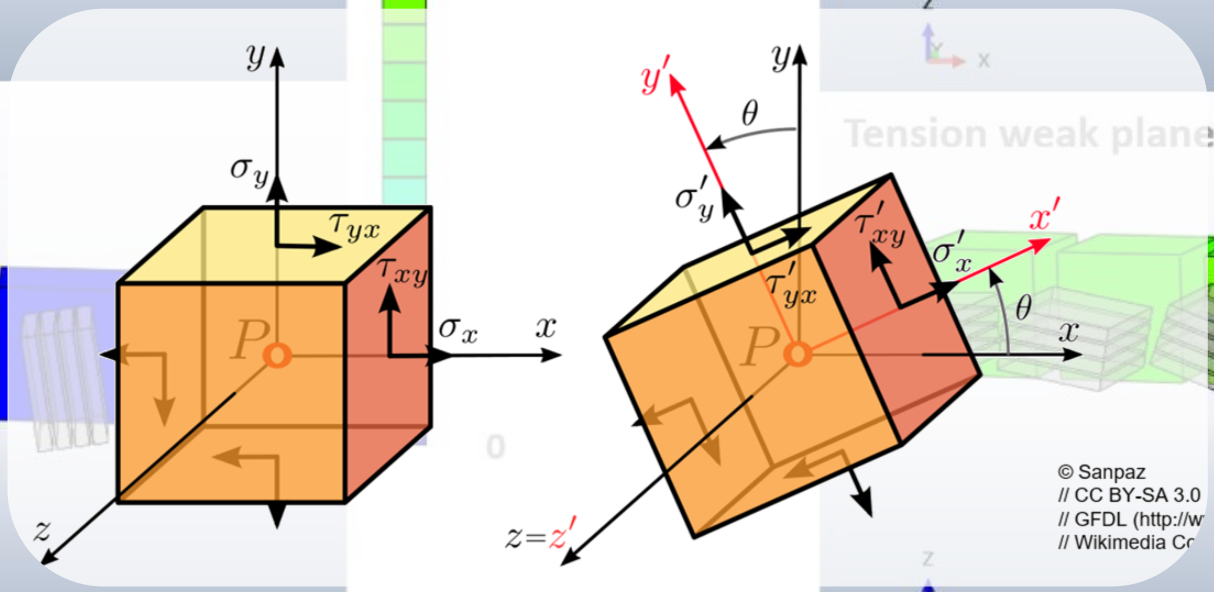


Hoek & Brown (1980)









https://www.linkedin.com/pulse/how-rock-anisotropy-works-numerical-models-stephan-arndt/
https://www.linkedin.com/pulse/principal-stress-transformations-stephan-arndt-e7jbc/

Improved Unified Constitutive Model – IUCM

IUCM Features (Vakili 2016)

- *Non-linear Hoek-Brown*
- *Brittle to ductile transition*
- *Confinement-dependent strain-softening*
- *Non-linear evolution of dilation*
- *Elastic stiffness softening*
- *Strength anisotropy (weak plane)*
- *Available as a constitutive model library (**VUMAT**) for Abaqus / Simulation Manager*

1. Initialise the pre-mining stresses in the model.
2. Obtain the current minor and major principal stresses for each finite difference zone (or element in the finite element method).
3. Obtain minor principal stress increment ($\Delta\sigma_3$) by adding and subtracting 0.1% of the current σ_3 magnitude,

$$\sigma_3^1 = \sigma_3 - 0.001\sigma_3 \quad (1)$$

$$\sigma_3^2 = \sigma_3 + 0.001\sigma_3 \quad (2)$$

4. Calculate constants for the Hoek-Brown criterion based on equations provided by Hoek et al. [35],

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \quad (3)$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right) \quad (4)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} + e^{-\frac{20}{3}}\right) \quad (5)$$

5. Obtain the major principal stress increment ($\Delta\sigma_1$) from the generalised Hoek-Brown failure criterion [35] and from the measured change in the minor principal stress ($\Delta\sigma_3$),

$$\sigma_1^1 = \sigma_3^1 - \sigma_c\left(m_b\frac{\sigma_3^1}{\sigma_c} + s\right)^a \quad (6)$$

$$\sigma_1^2 = \sigma_3^2 - \sigma_c\left(m_b\frac{\sigma_3^2}{\sigma_c} + s\right)^a \quad (7)$$

6. Obtain the slope (ψ) of the incremental stress envelope,

$$\tan\psi = \frac{\sigma_1^1 - \sigma_1^2}{\sigma_3^1 - \sigma_3^2} \quad (8)$$

7. Calculate instantaneous friction angle (φ) from ψ,

$$\varphi = \sin^{-1}\left(\frac{\tan\psi - 1}{\tan\psi + 1}\right) \quad (9)$$

8. Calculate instantaneous cohesion,

$$C = \frac{\sigma_1^1(1 - \sin\varphi) - \sigma_3^1(1 + \sin\varphi)}{2\cos\varphi} \quad (10)$$

9. Calculate un

$$\sigma_t = \frac{s\sigma_c}{m_b} \quad (11)$$

10. To avoid th ... hich correspond ... ion, compare th ... (11) and the ma ... wer value.

Computers and Geotechnics

(Vakili 2016)

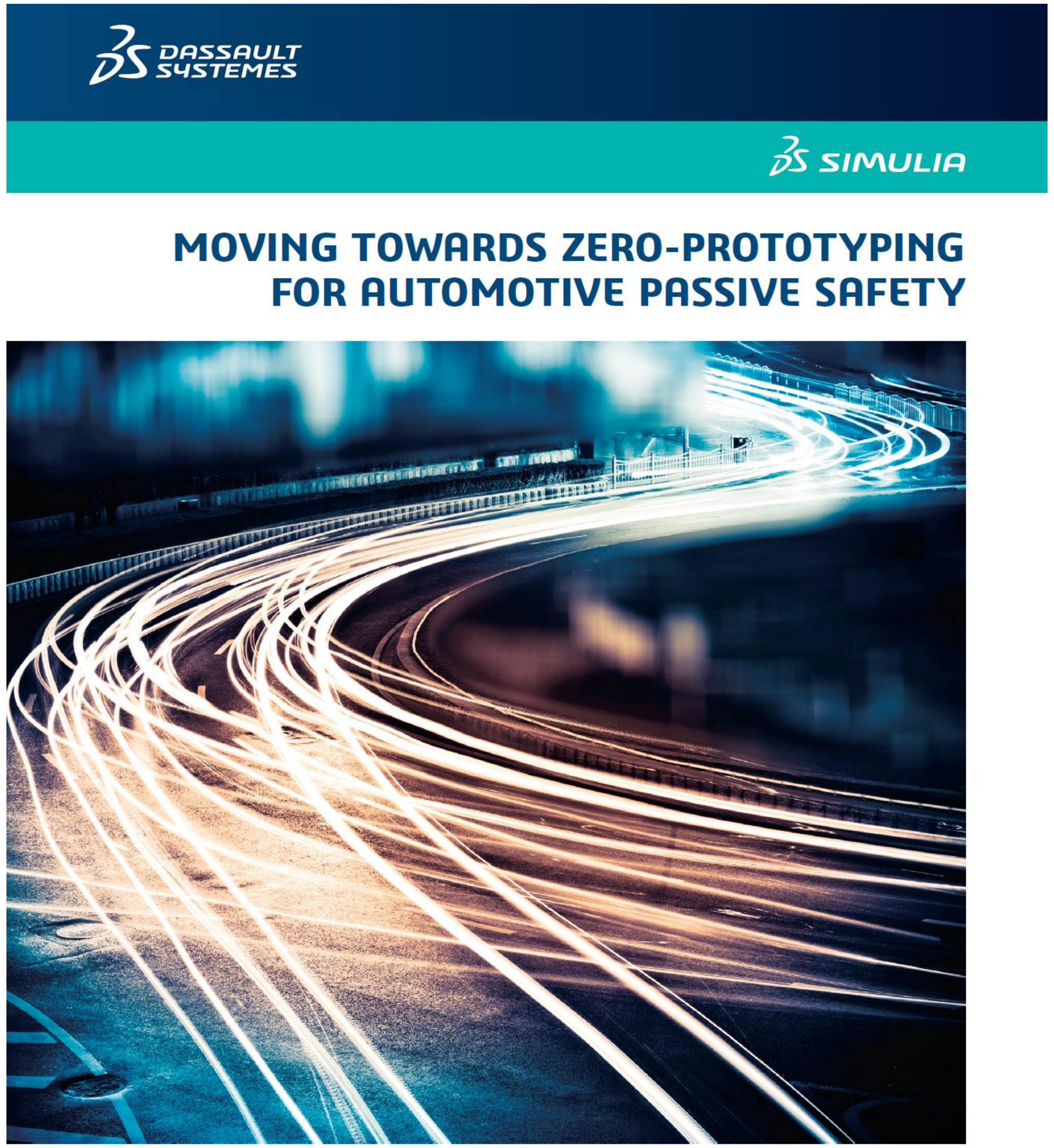
```
// IUCM (Vakili, 2016)
// -------------------
// 3: sigma3 variation (dS = +/- 0.001) - formulas use [MPa] (!)
dS3_1 = abs(0.999 * eigVal[3]) / c_1MPa;
dS3_2 = abs(1.001 * eigVal[3]) / c_1MPa;

// 4: Hoek-Brown constants
if (p_gsi > 99.9) prop_gsi = 99.9;
prop_hbmb = p_mimax * exp((prop_gsi - 100.) / (28. - 14. * p_disfac));
prop_hbs = exp((prop_gsi - 100.) / (9. - 3. * p_disfac));
prop_hba = 0.5 + 1. / 6. * (exp(-prop_gsi / 15.) + exp(-20. / 3.));

// 5: generalised Hoek-Brown failure criterion
dS1_1 = dS3_1 + p_sigci * pow(prop_hbmb * (dS3_1 / p_sigci) + prop_hbs, prop_hba);
dS1_2 = dS3_2 + p_sigci * pow(prop_hbmb * (dS3_2 / p_sigci) + prop_hbs, prop_hba);

// 6: slope of HB curve, current friction & cohesion
dS_tanPsi = (dS1_2 - dS1_1) / (dS3_2 - dS3_1);

// 7: instantaneous friction angle
prop_phi = asin((dS_tanPsi - 1.) / (dS_tanPsi + 1.));

// 8: instantaneous cohesion
dS_sinPhi = sin(prop_phi);
prop_coh = (dS1_1 * (1. - dS_sinPhi) - dS3_1 * (1. + dS_sinPhi)) / (2. * cos(prop_phi));

// 9: uniaxial tensile strength
prop_ten = prop_hbs * p_sigci / prop_hbmb;

// 10: maximum tensile strength & bracket friction angle (ap
if (prop_phi <= c_minA) prop_phi = c_minA;
if (prop_phi >= c_maxA) prop_phi = c_maxA;

s_tmax = prop_coh / tan(prop_phi);
if (prop_ten > s_tmax) prop_ten = s_tmax;
```

Abaqus User Subroutine

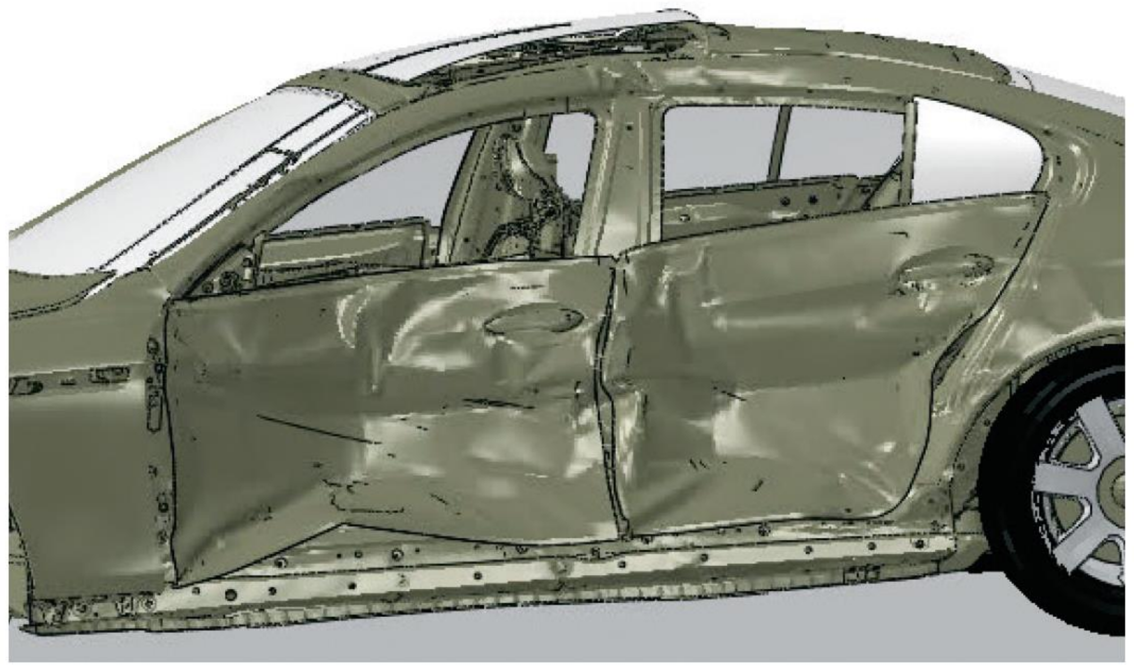
"What you see is what you get"

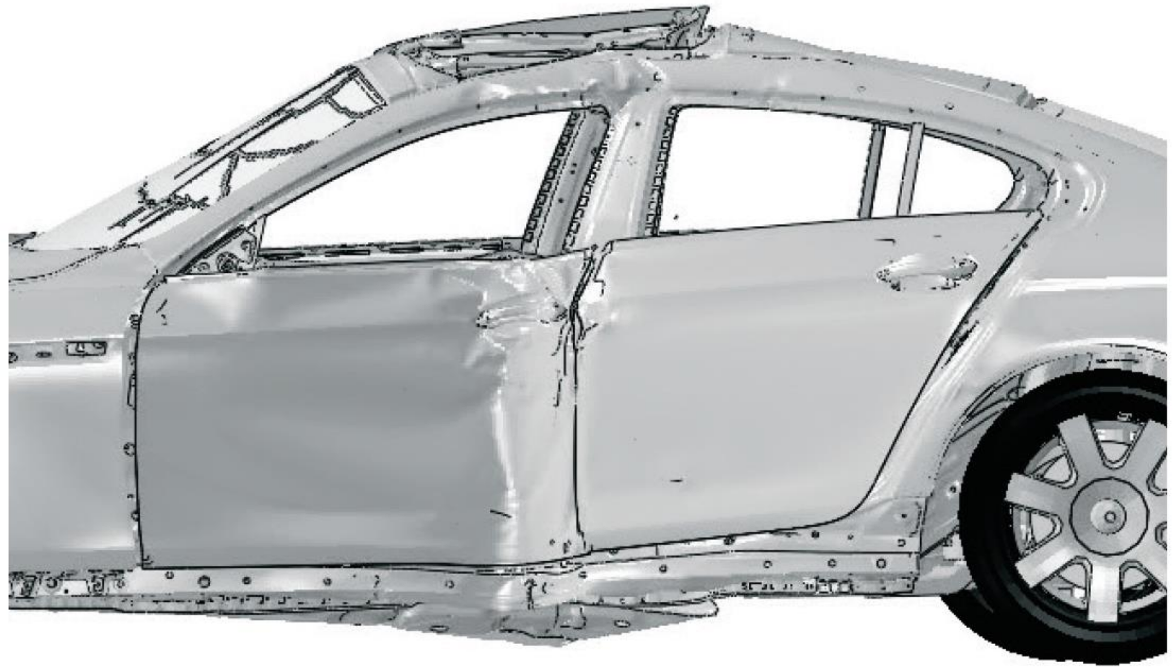
Zero Prototypes

Zero Prototypes

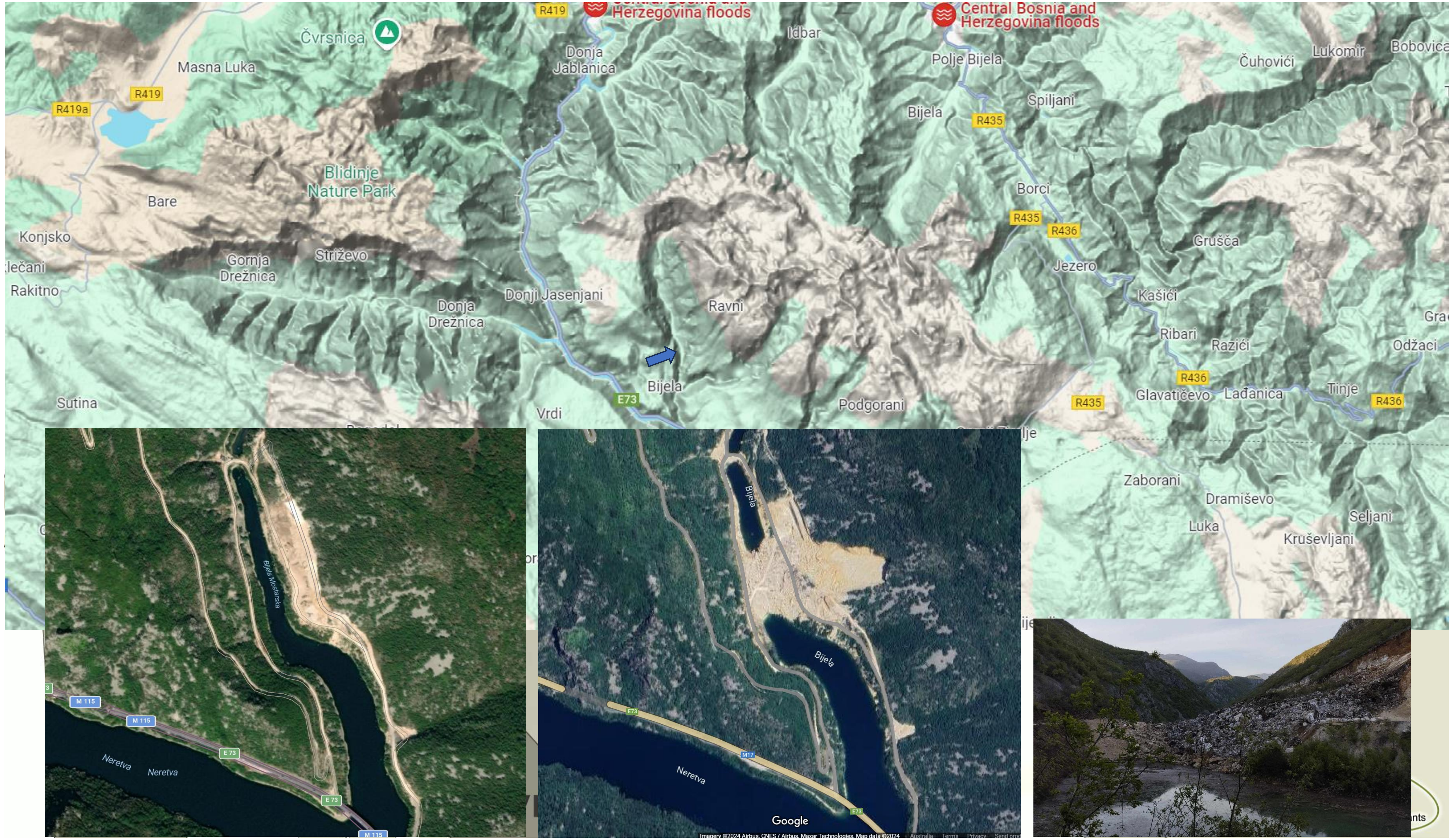


Courtesy BMW/SIMULIA





Real World ‘Prototypes’



Workflows

Slope Stability – Solution Pathway – Pore Pressure – Underground Workflows – StopeX and SlopeX

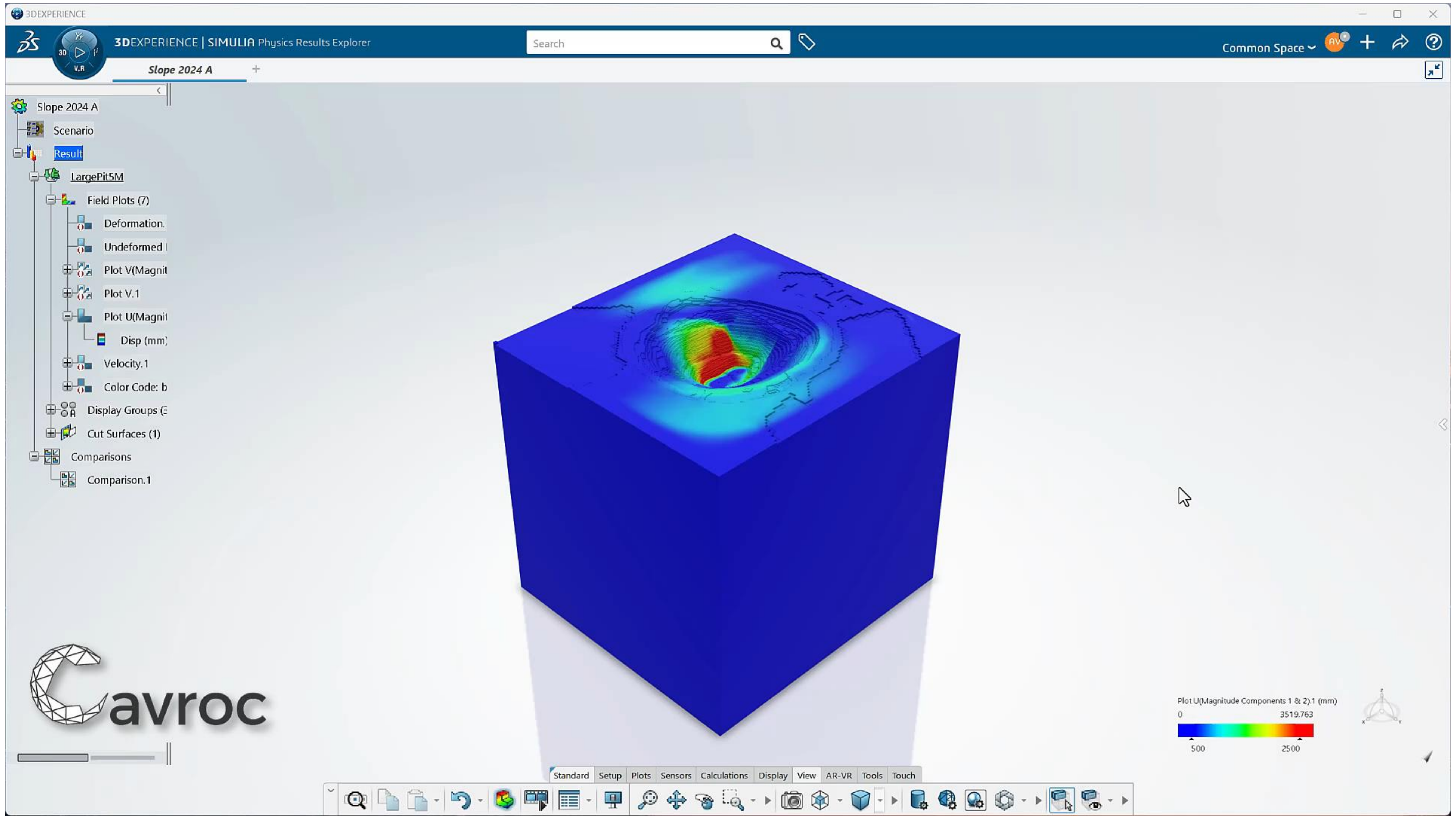
Slope Stability

Stability analysis is a central element of the slope design process*

- ***Safety*** *(zero harm & protecting the environment)*
- ***Project economics*** *& reducing financial risk*
- ***Sustainability*** *(energy consumption, waste)*

Accurate 3D Numerical Modelling can contribute significantly to these objectives.

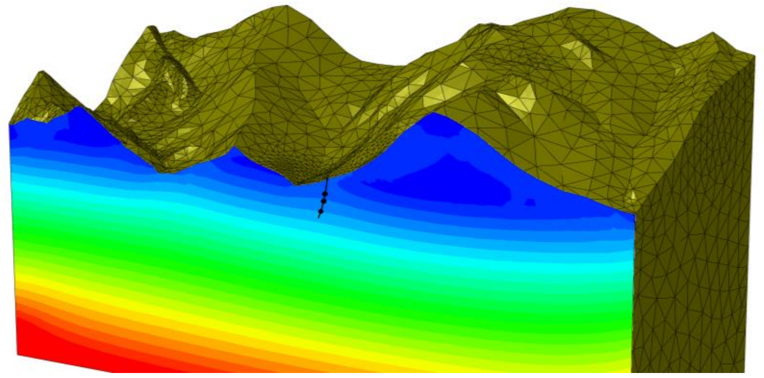
** "Guidelines for Open Pit Slope Design", Read (Ed.) 2009. CSIRO Publishing.*



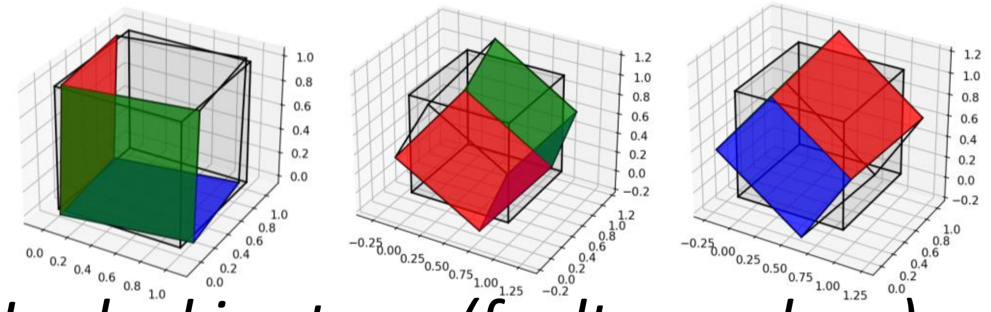
Tectonic Stress and Model Equilibrium

There are many cases where no analytical solution for the initial condition of the stress field exists, requiring an equilibrium step:

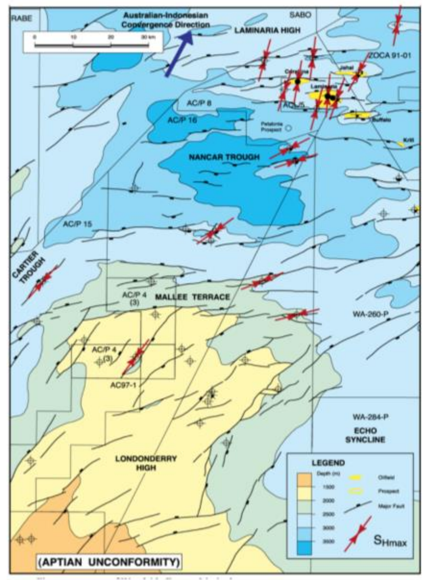
1) *The model contains surface topography*

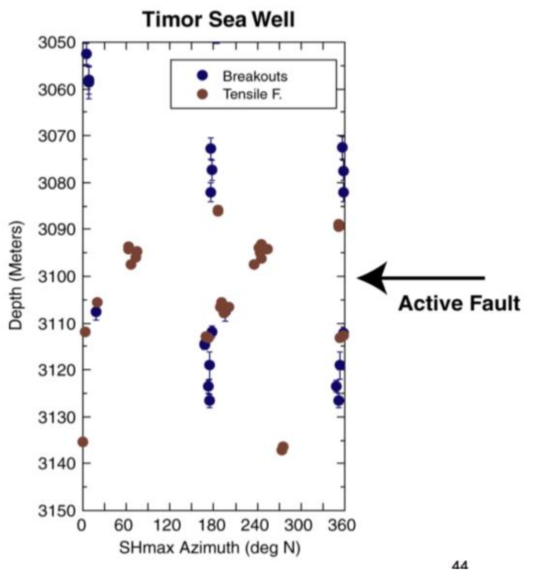


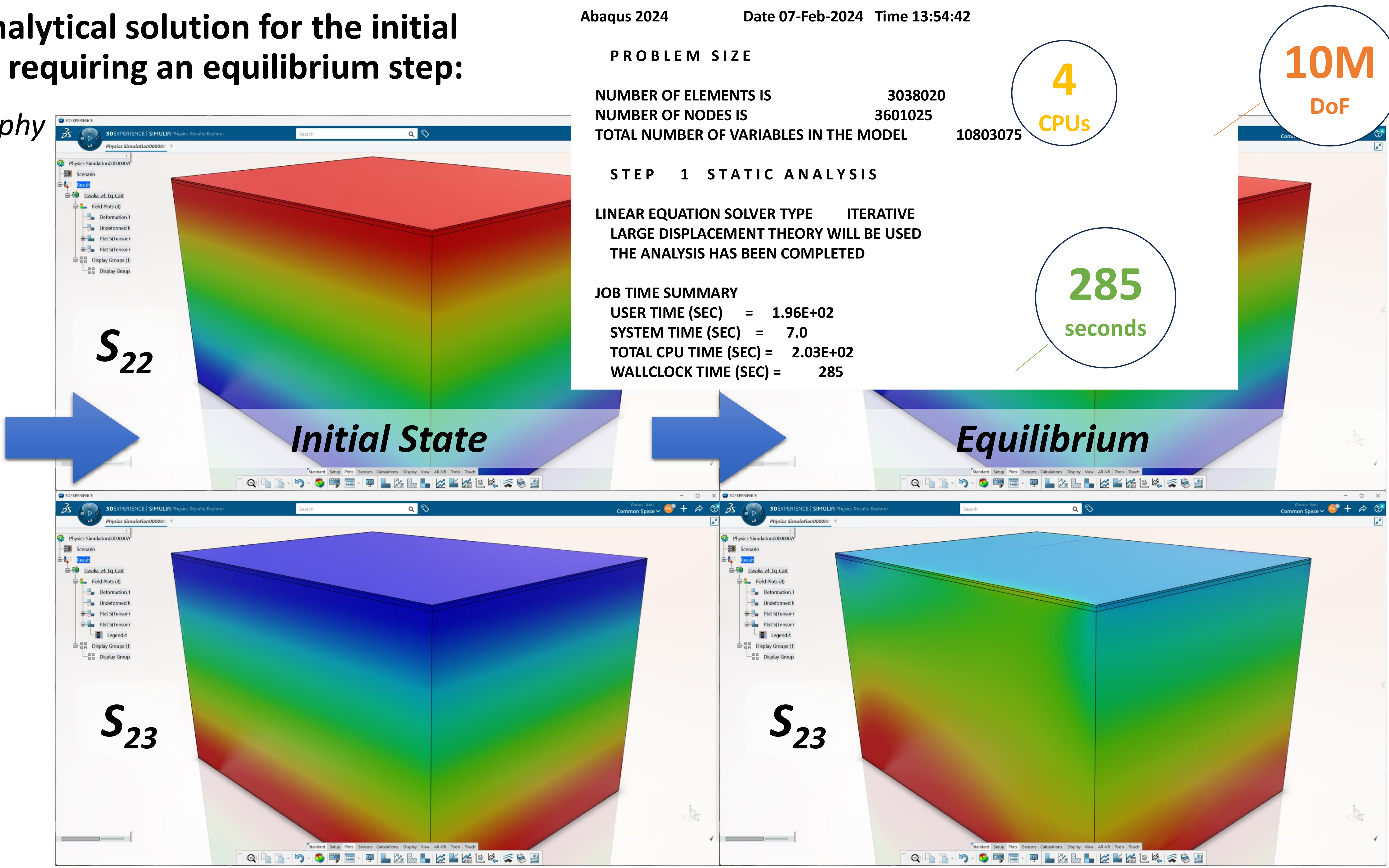
2) *The principal stress orientations are not horizontal and vertical*



3) *Locked in stress (faults, geology)*

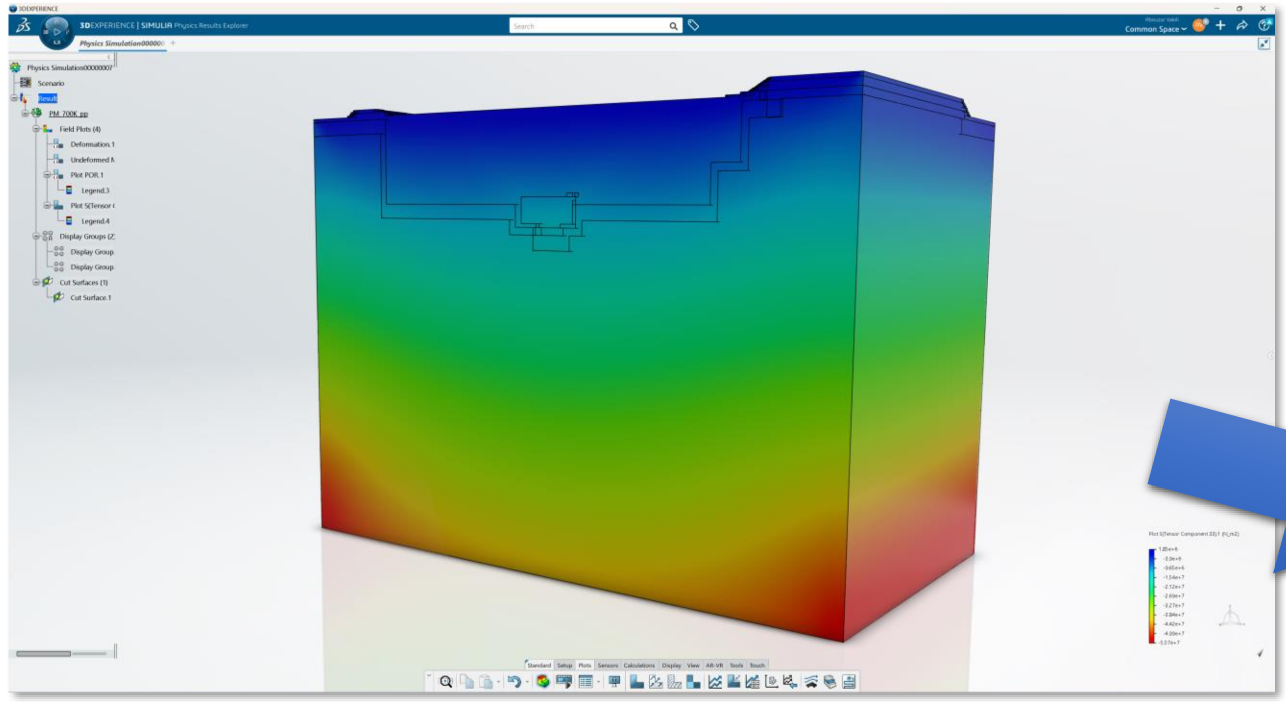




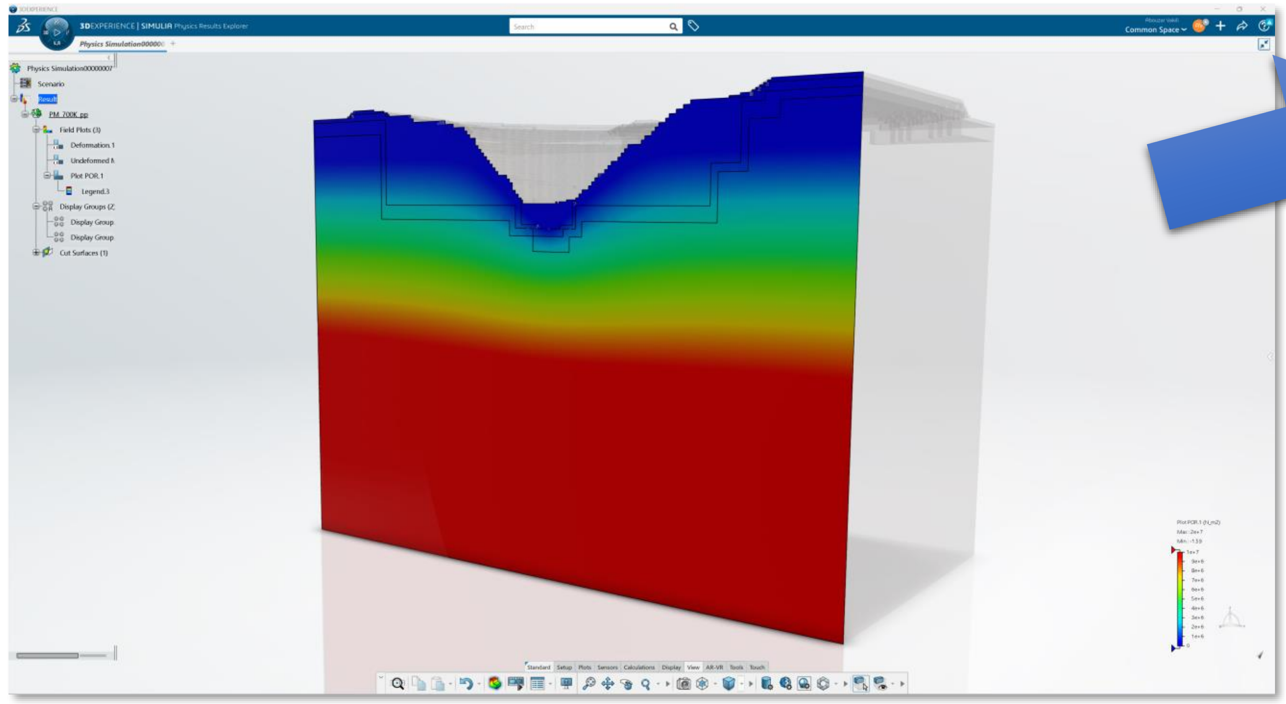


Solution Pathway: Equilibrium to Instability

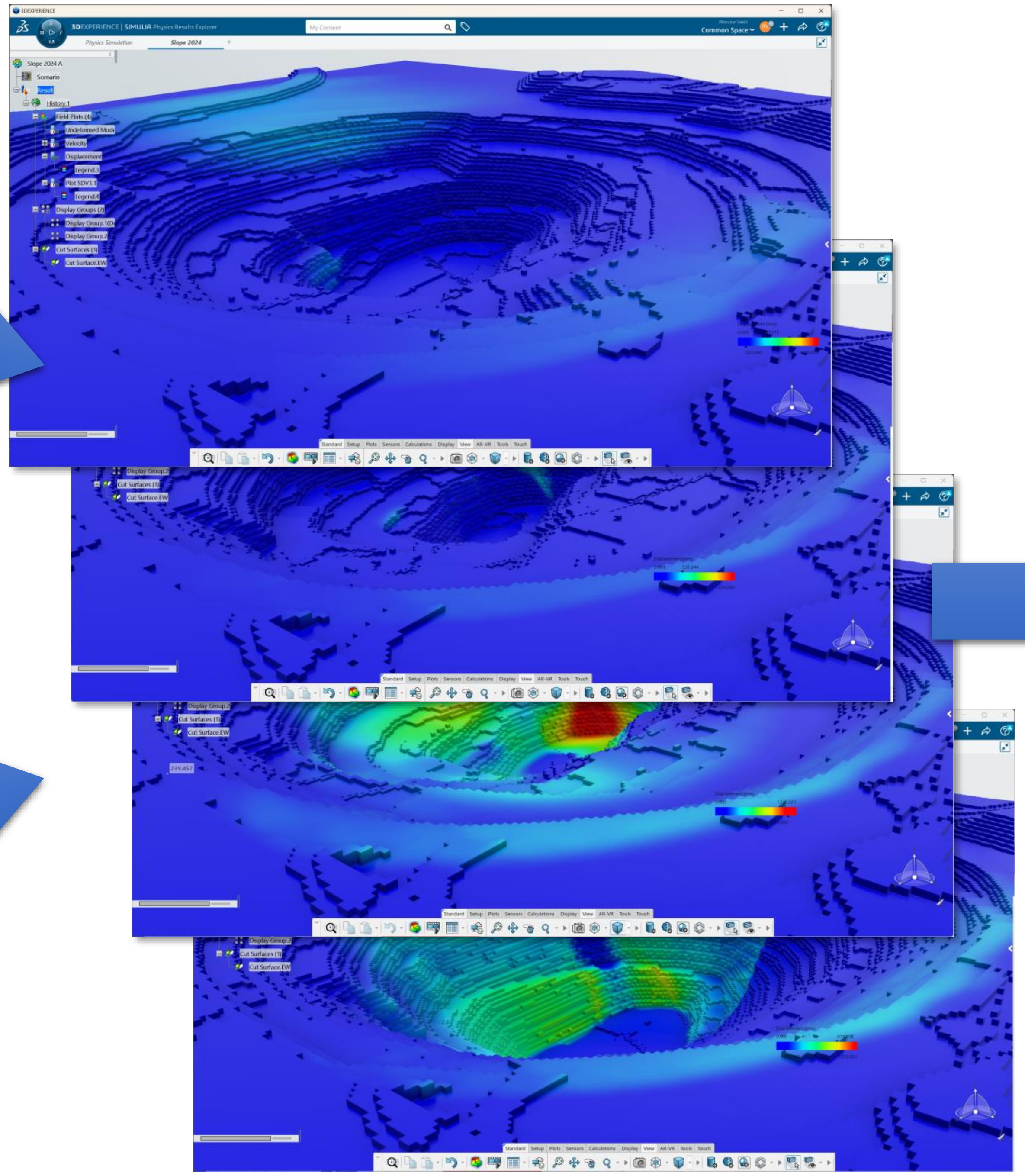
Initial Stress & Equilibrium



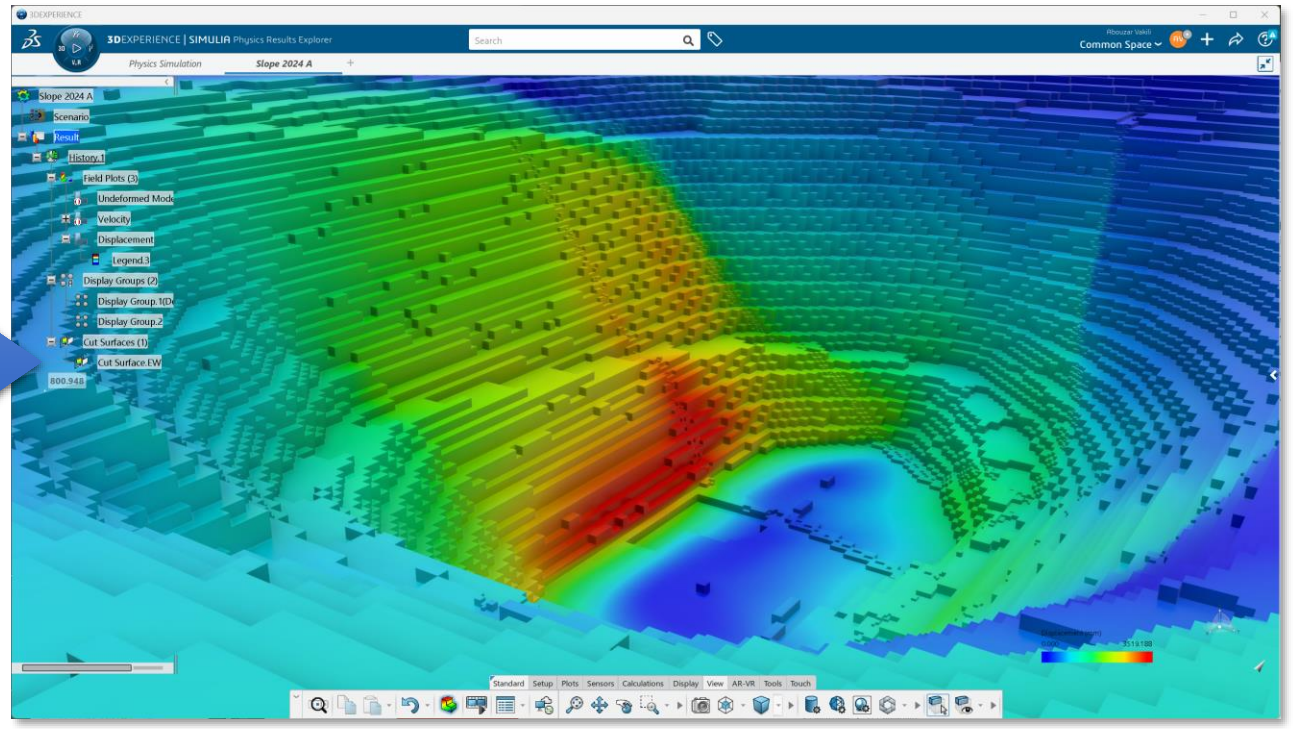
Pore Pressure(s)



Pit Excavation Sequence



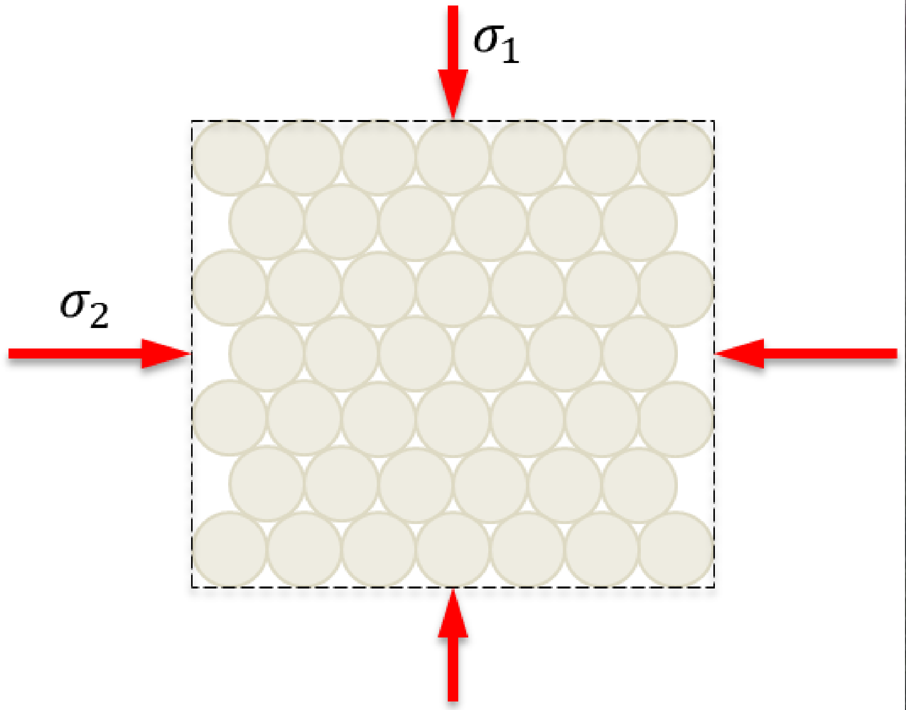
Shear Strength Reduction



Pore Pressure

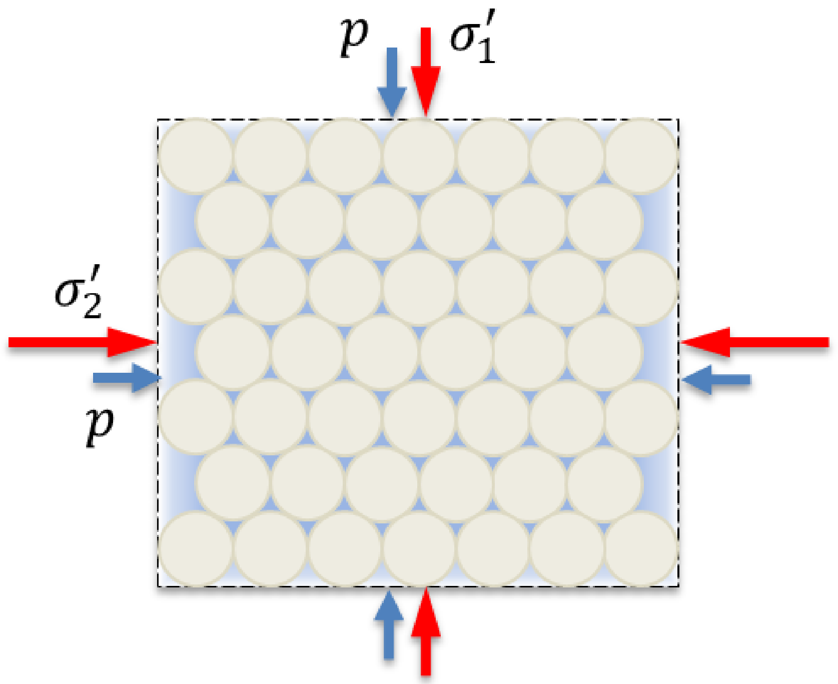
Dry Medium

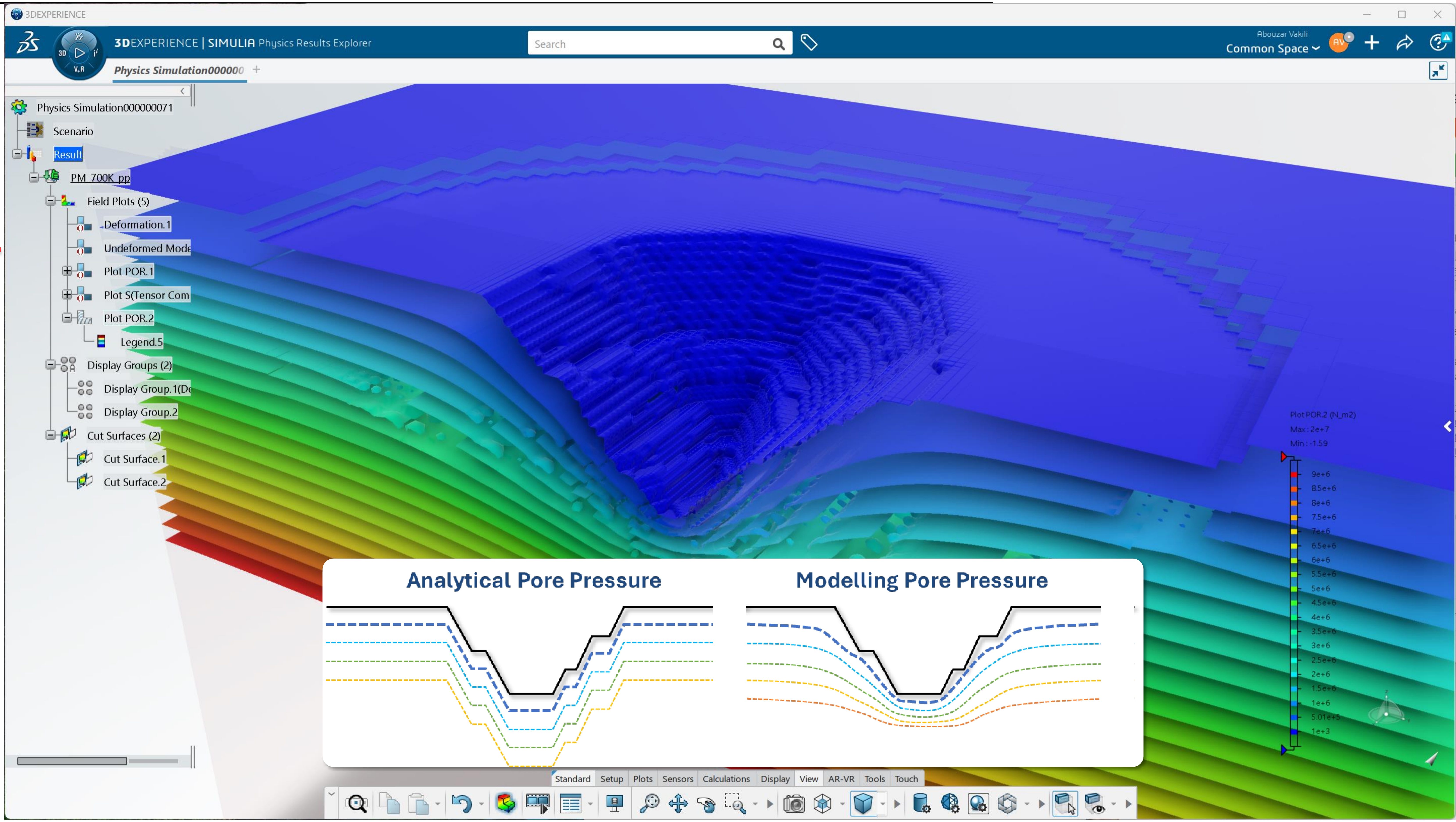
Stress acting on the matrix



Saturated Medium

Stress acting on matrix and fluid

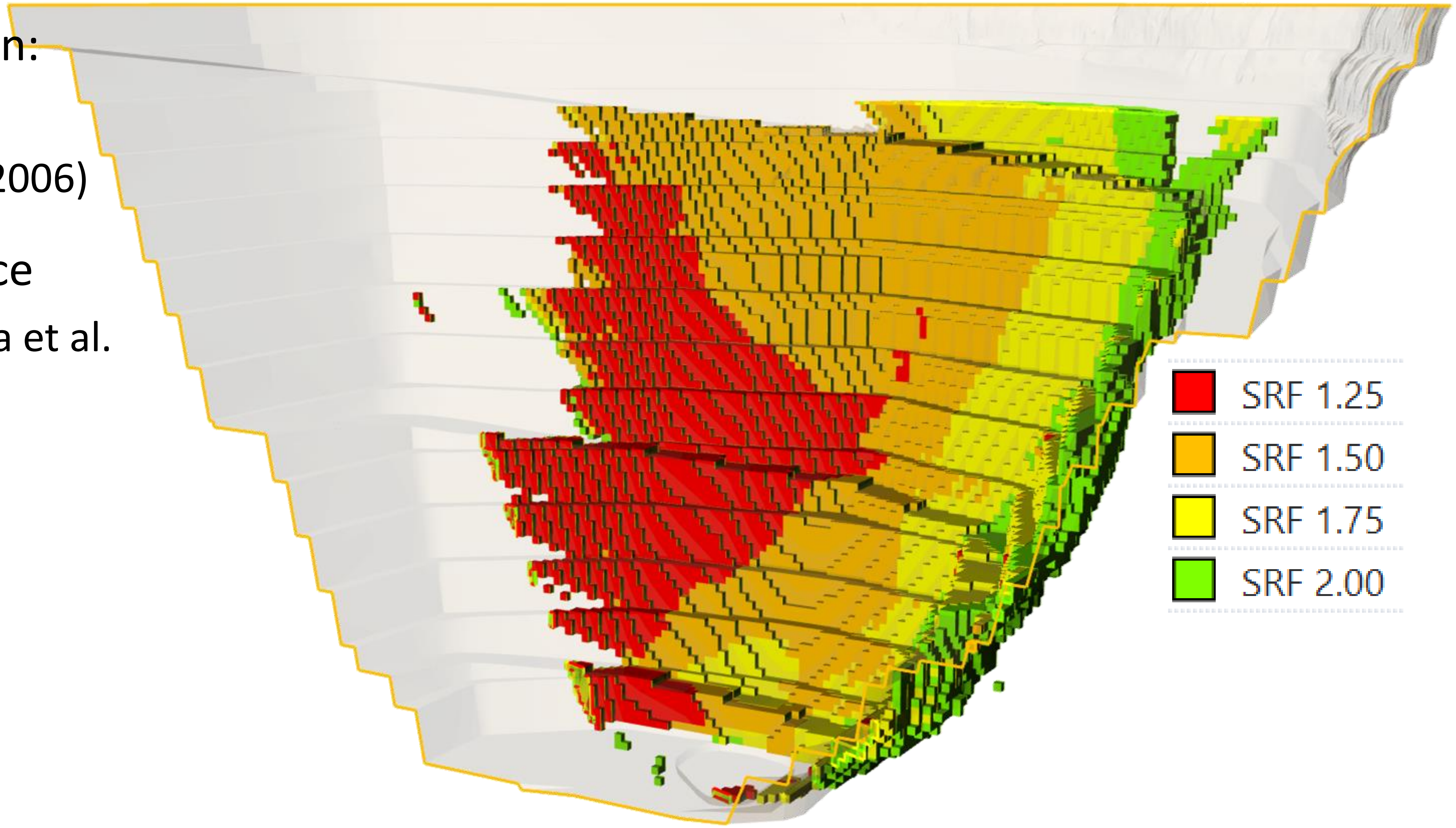




Reliability-Based Design Access Criteria

Reliability-Based Design Access Criteria (RBDAC)

- **Failure volume and location** are required inputs for the economic risk assessment of inter-ramp & overall pit slope designs (Creighton et al. 2022)
- Risk-consequence approach to open pit slope design: *"Risk criteria are therefore set on the basis of consequences of potential failures"* (Terbrugge et al. 2006)
- Consider design acceptance criteria using confidence classification and consequence categories (Macciotta et al. 2020)



Underground Workflow

- Mine Geometry
- Geology & Faults
- Extraction Sequence
- In-situ Stress
- Rock Mass Parameters

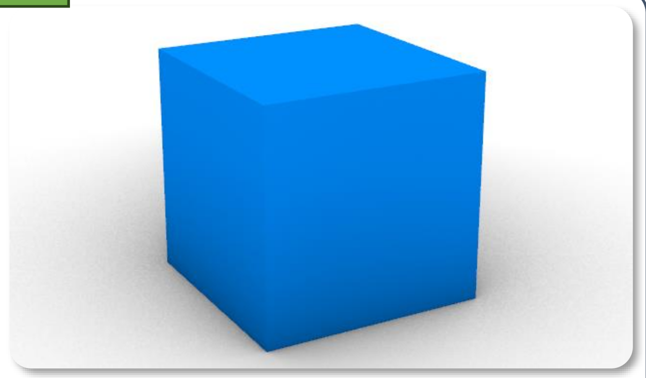
(not a real picture)

StopeX

Cavroc StopeX

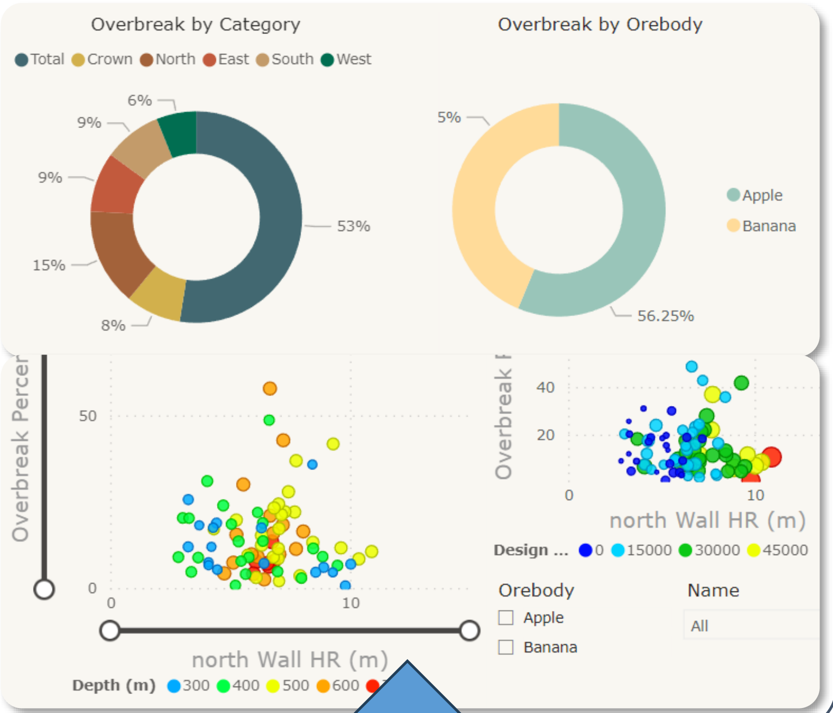
Abaqus FEA

Simulation Manager

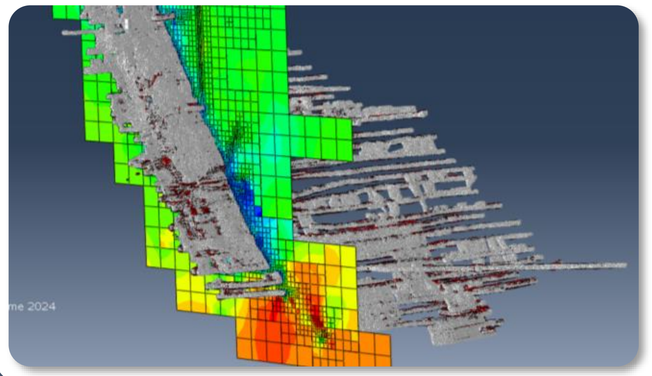


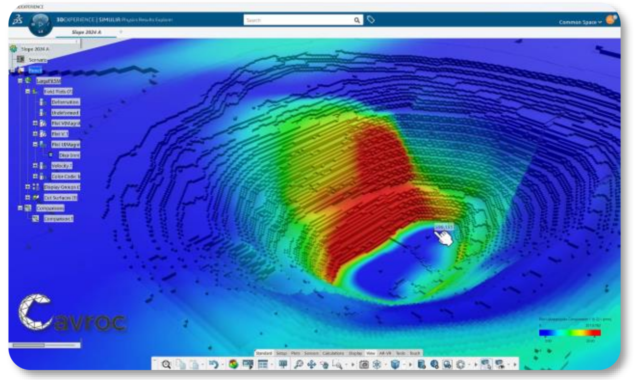
Other Solvers

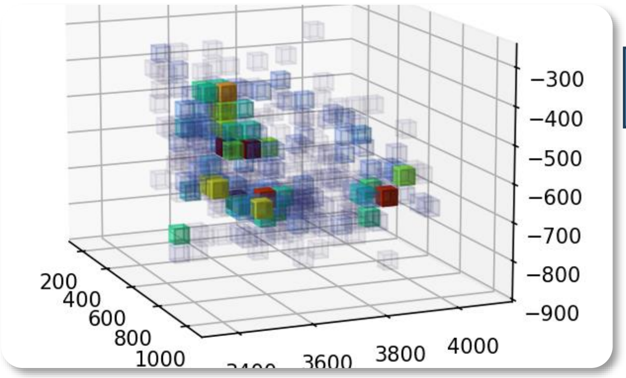
Dashboards



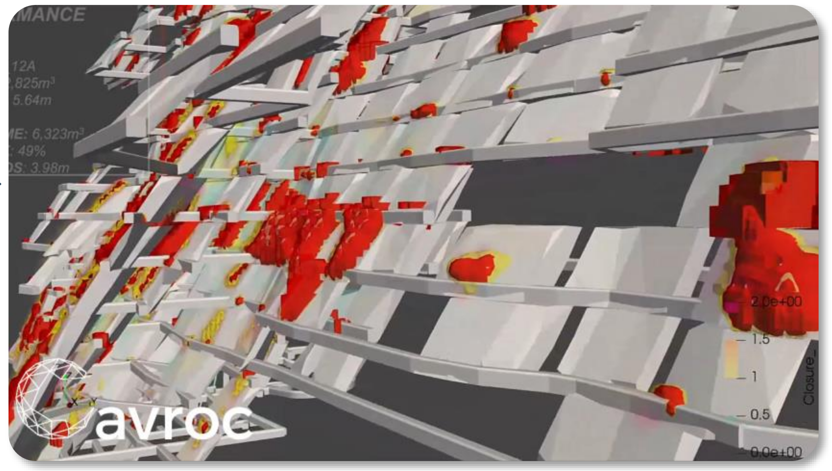
Visualisation & Results Processing (Python)





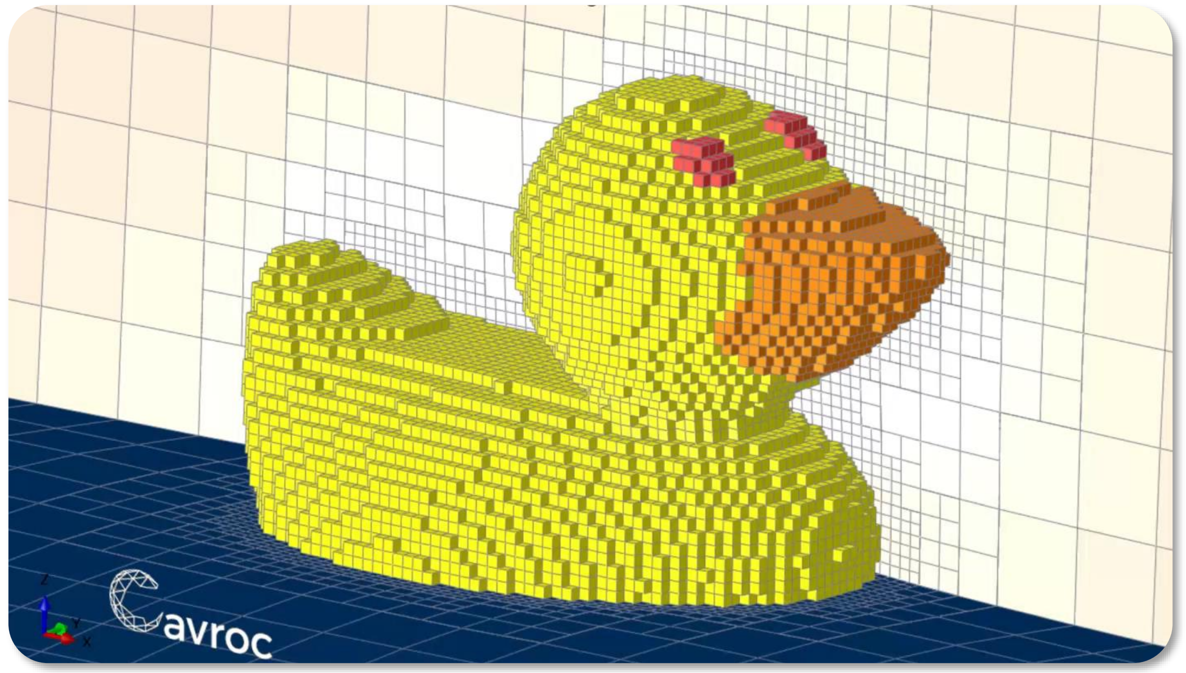


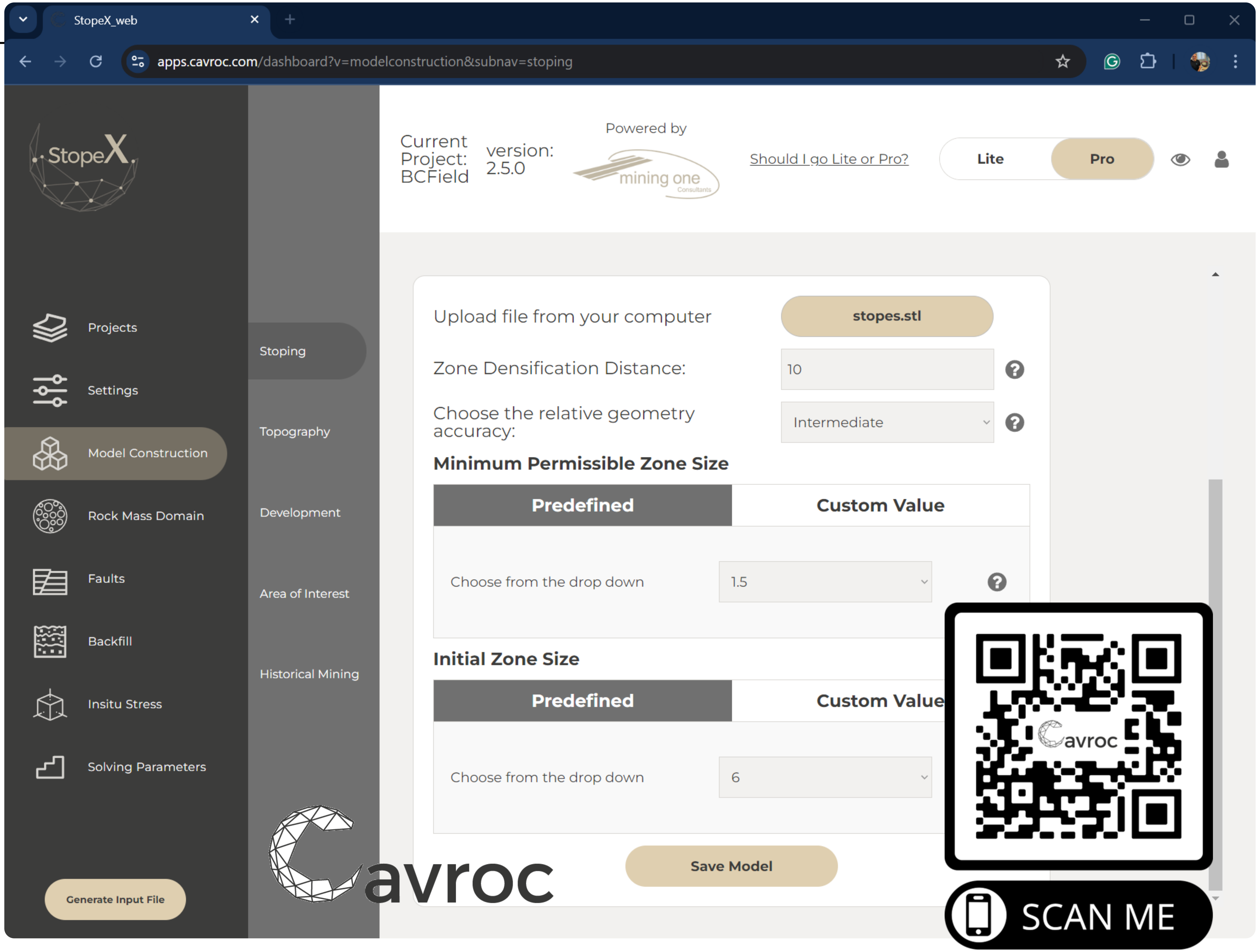
Cavroc RocboX



StopeX & SlopeX

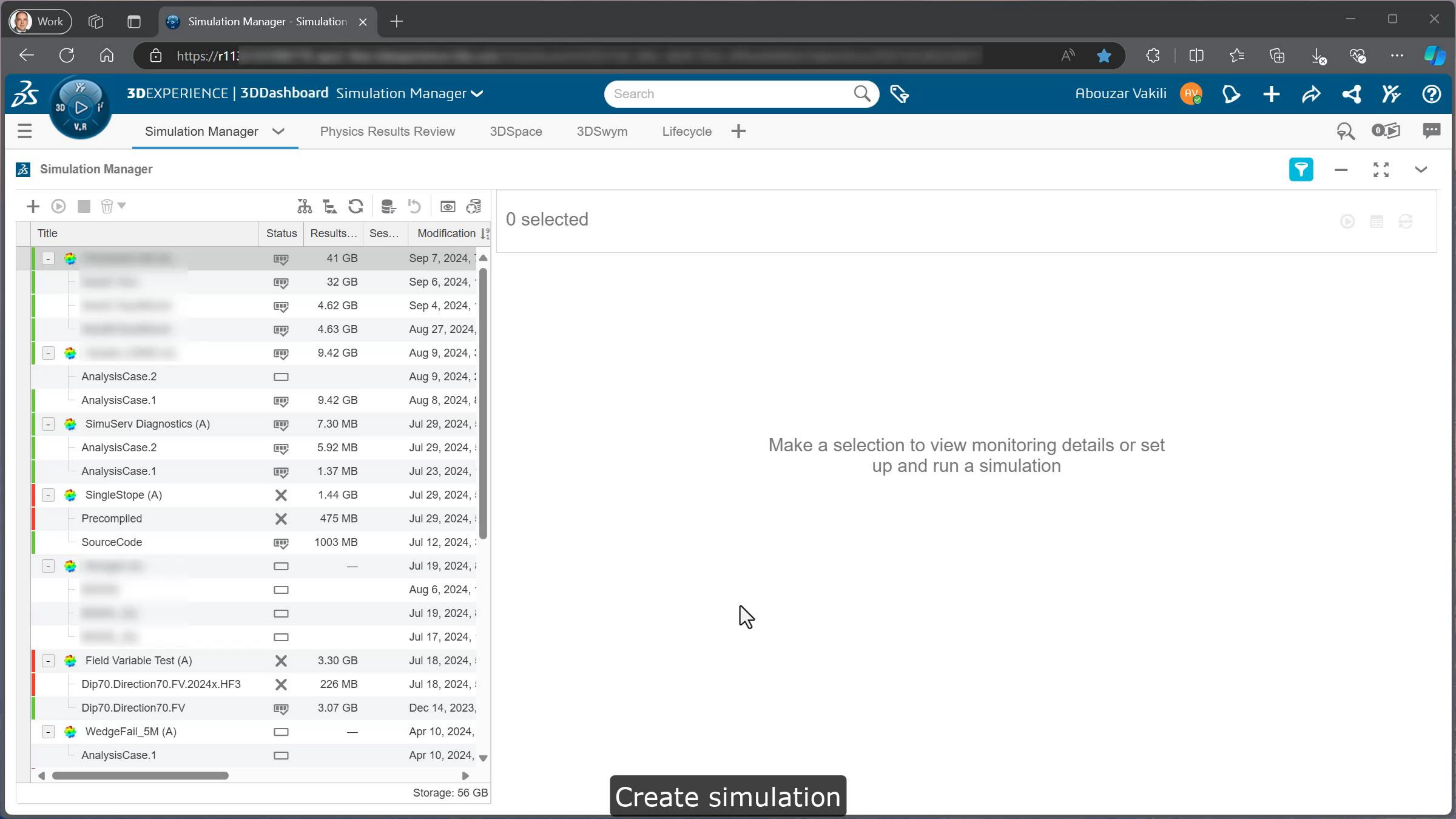
- **Web-based** user interface
- **Rapid** model construction (~hours)
- Automated **octree** meshing
- Guided, best-practice, **workflows**
- Cavroc forum: **support & discussions**
- **IUCM** constitutive model for rock mass
- Supporting multiple **solvers**
- RocboX stope **performance** intelligence





3DEXPERIENCE platform

Simulation Manager – Physics Results Explorer – Scalability – Virtual Reality


Simulation Manager - Simulation
3DEXPERIENCE | 3DDashboard Simulation Manager
Search
Abouzar Vakili
Simulation Manager
Physics Results Review
3DSpace
3DSwym
Lifecycle
Simulation Manager
Title
Status
Results...
Ses...
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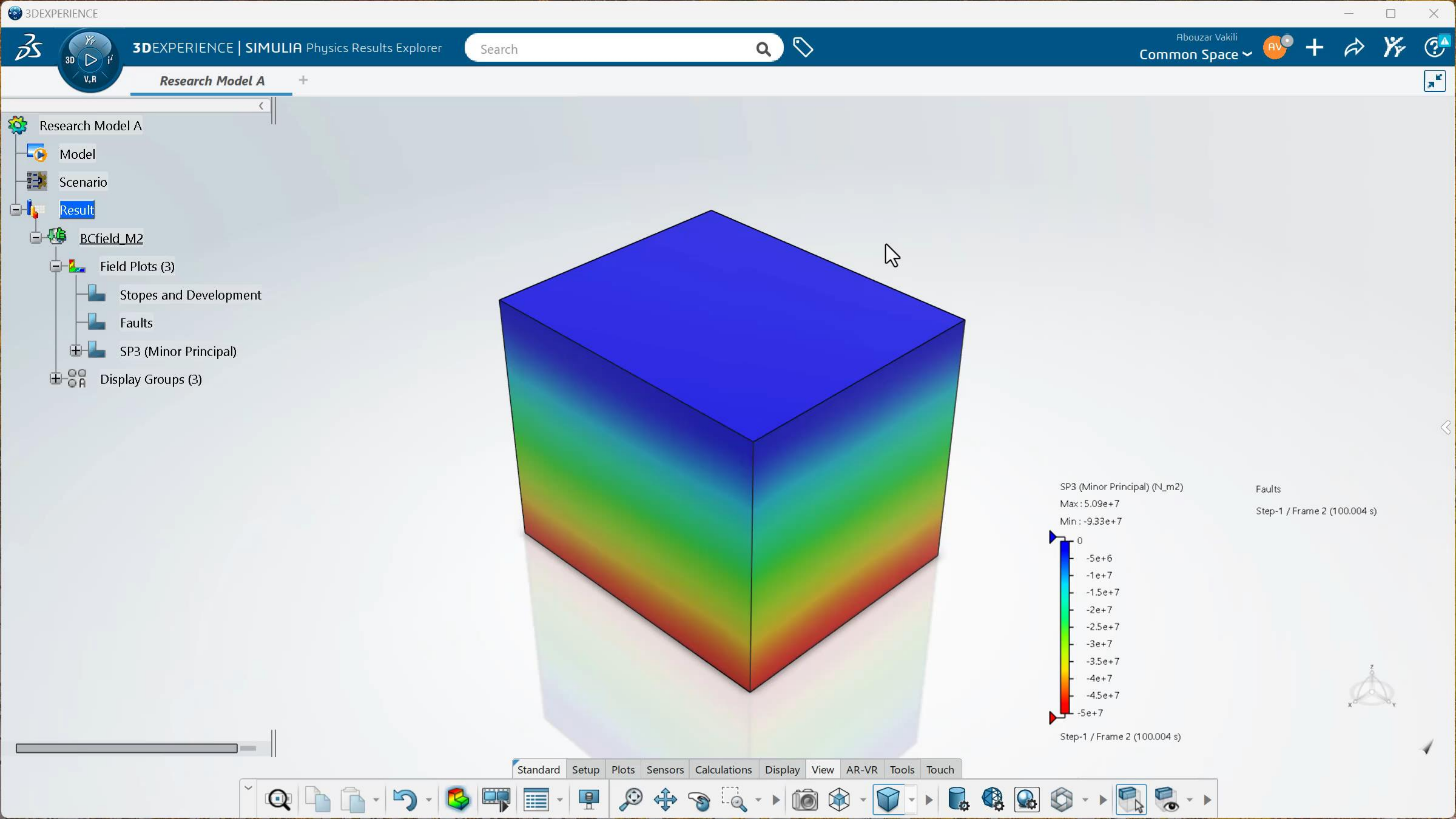
Create simulation


3DEXPERIENCE
3DEXPERIENCE | SIMULIA Physics Results Explorer
Search
Abouzar Vakili
Common Space
Research Model A
Research Model A
Model
Scenario
Result
BCfield_M2
Field Plots (3)
Stopes and Development
Faults
SP3 (Minor Principal)
Display Groups (3)
SP3 (Minor Principal) (N_m2)
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Faults
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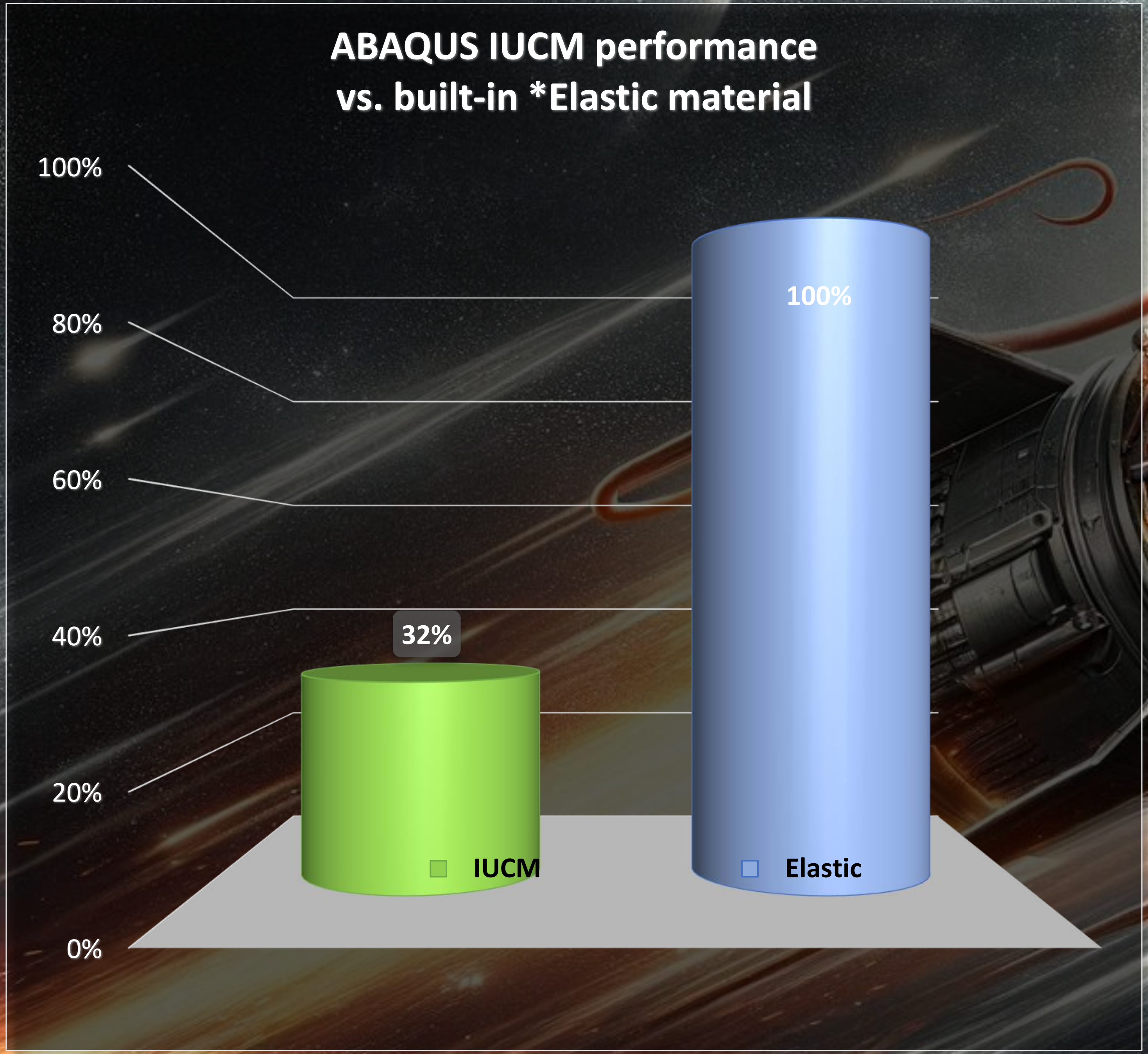
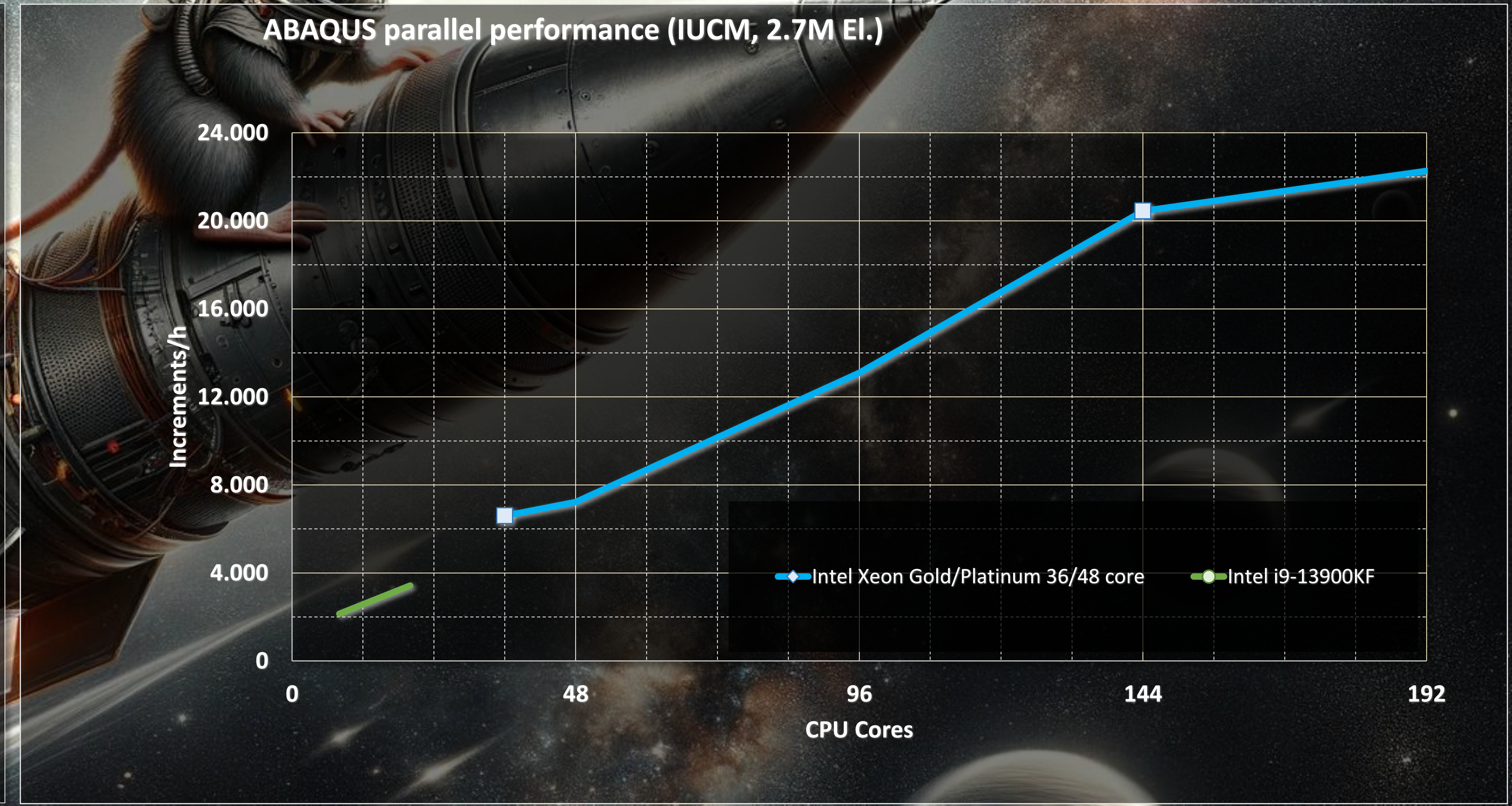
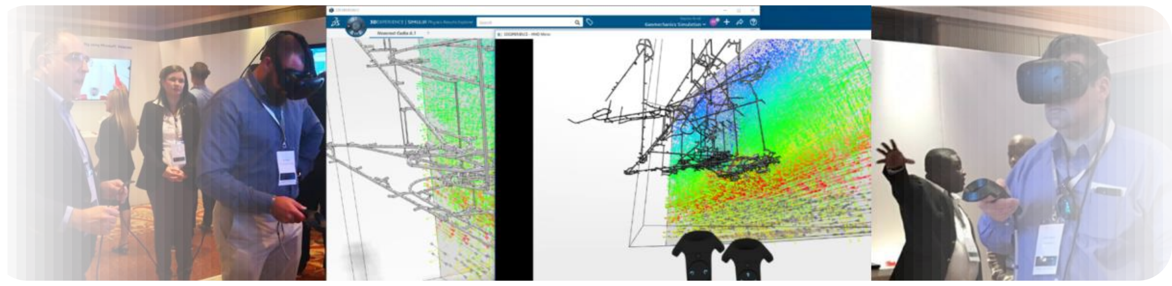
Setup
Plots
Sensors
Calculations
Display
View
AR-VR
Tools
Touch

Travelling at the speed of light

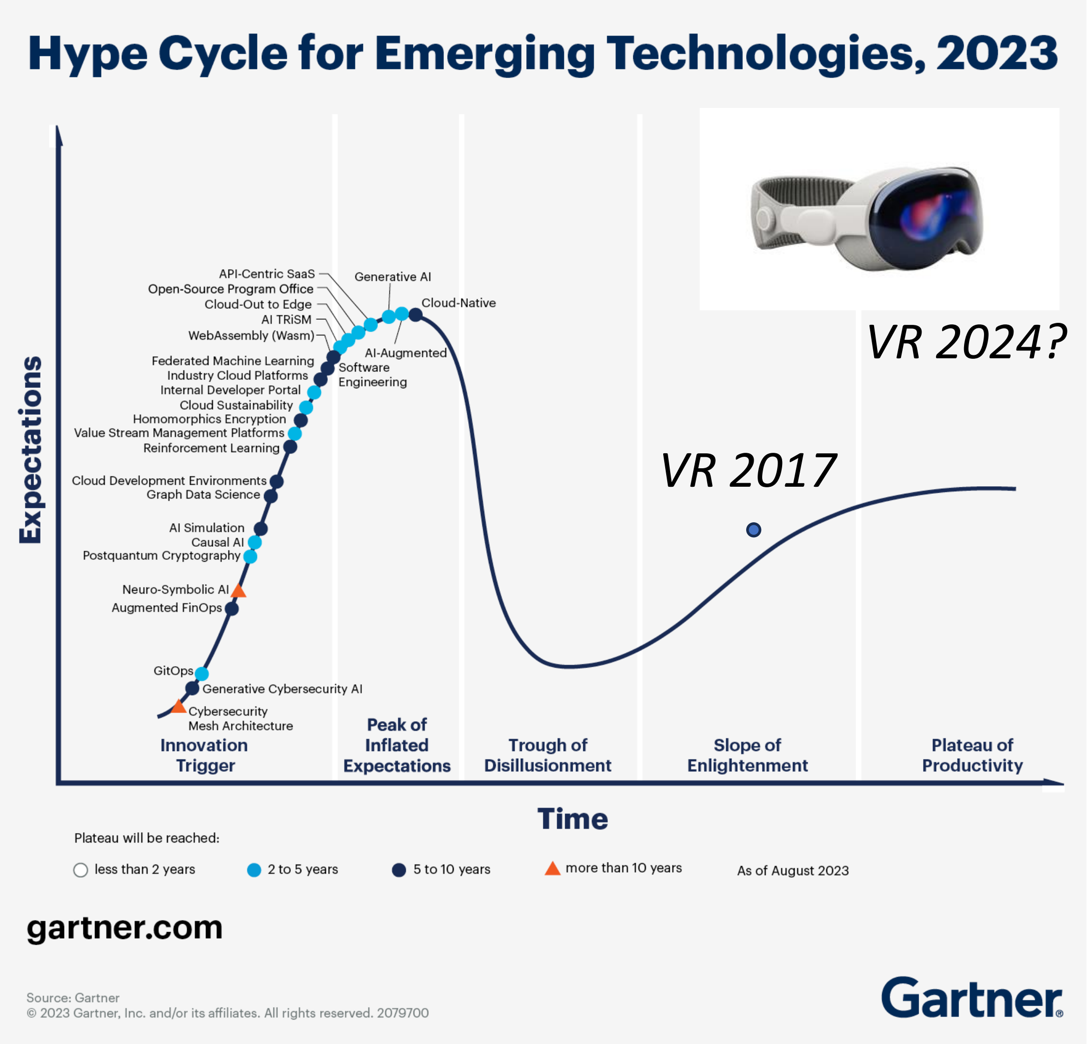




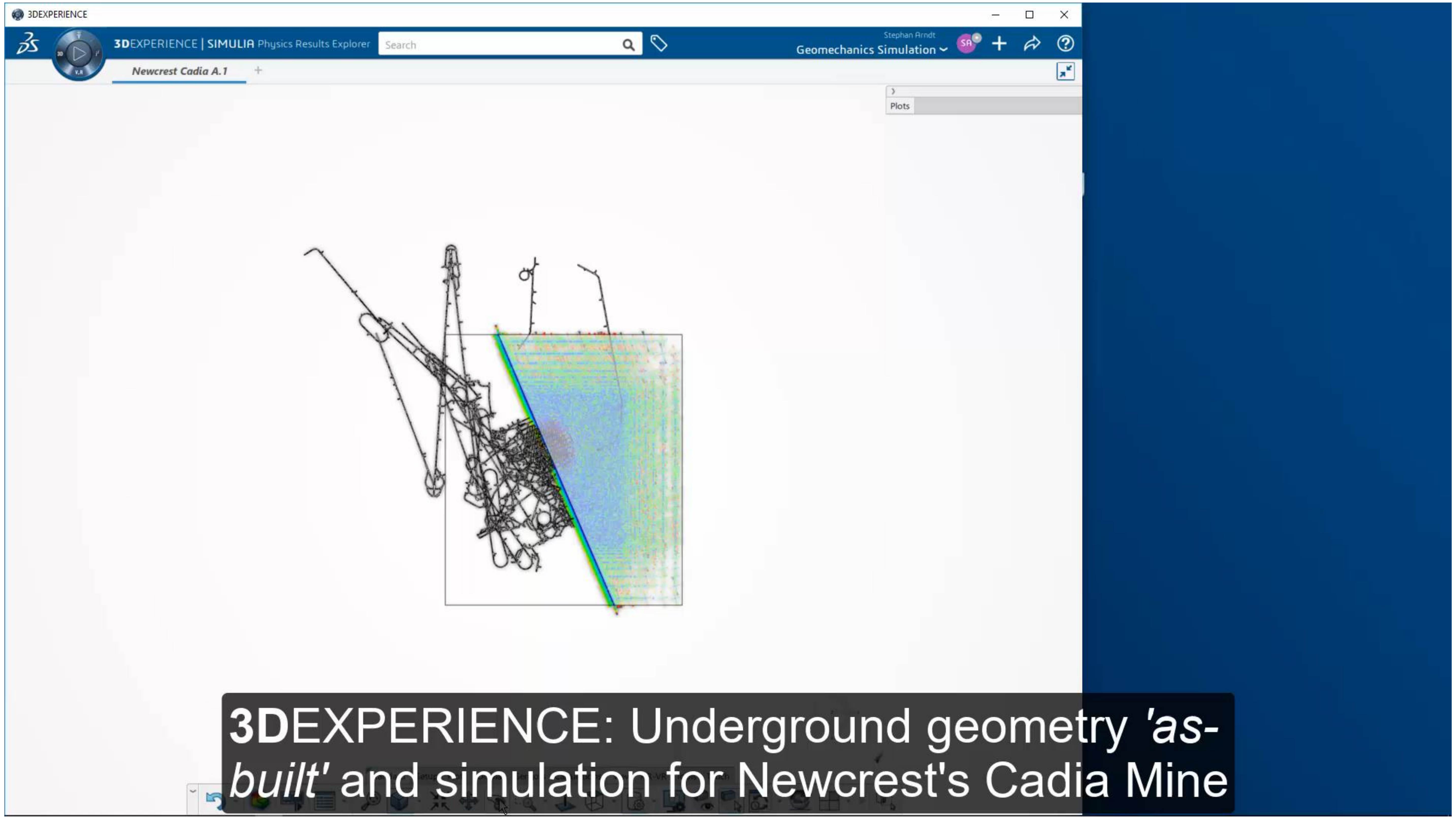
Virtual Reality



Technology Firm Gartner famously booted Virtual Reality (VR) off its “Emerging Technologies” Hype Cycle graph in 2018



Noteworthy: the dominance of AI in 2023



https://youtu.be/u7cfXFDGnac?si=hDpdORjCSLPHBU5q

https://www.linkedin.com/pulse/virtual-reality-where-business-value-stephan-arndt/

Thank You

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