



# COBRAMSEG 2024

XXI Congresso Brasileiro de Mecânica dos Solos e Eng. Geotécnica  
X Simpósio Brasileiro de Mecânica das Rochas  
X Simpósio Brasileiro de Engenheiros Geotécnicos Jovens

GEOTECNIA PARA O  
DESENVOLVIMENTO  
SUSTENTÁVEL

## Rock Mechanics Best Practice in Underground Mine Operations - Data, Design Tools and Monitoring -

**ROCKENG**

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President & Principal Consultant

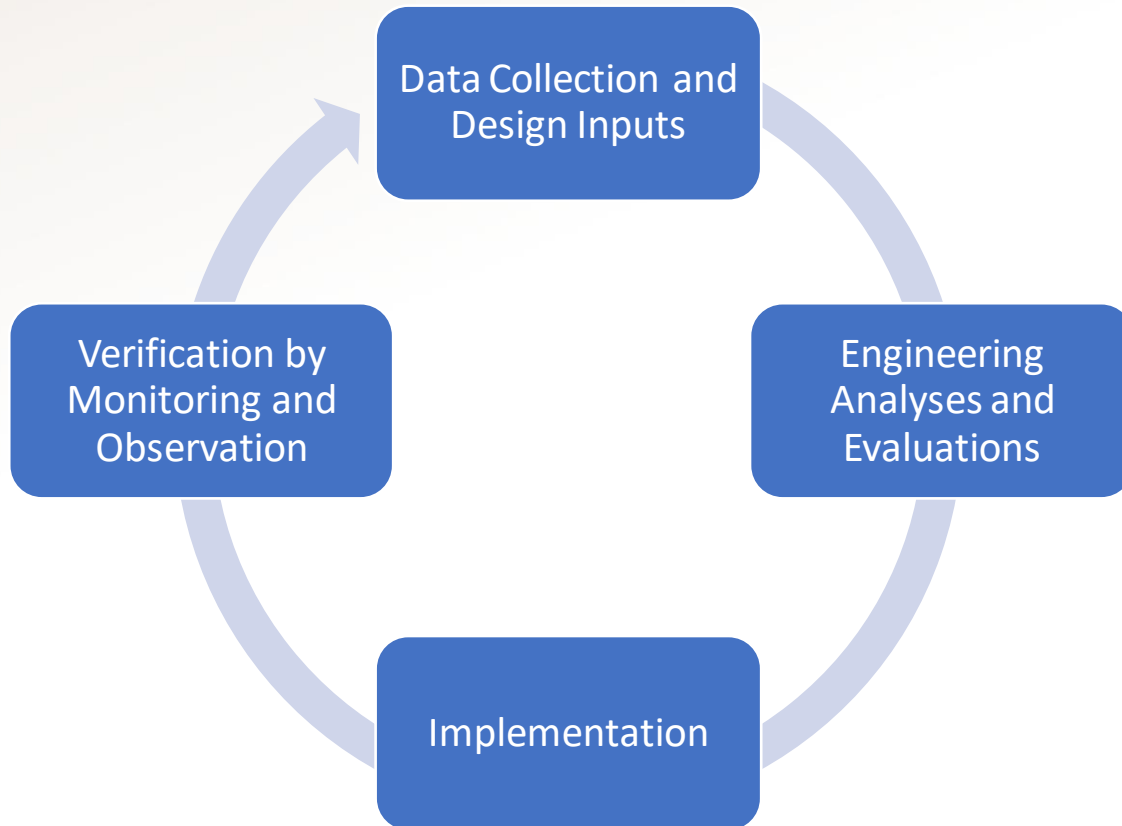
Realização



Organização



# Contents



1. Foundational Data Needs
  - Technically justified data collection plans
  - Confidence in geomechanical inputs
  - Ground behavior model
  - A focus on in situ stress – a significant design unknown
2. Geomechanical Design for Underground Mines
  - Susceptibility vs. mechanistic design
  - Performance based design
    - Ground support design
    - Infrastructure management
    - High stress and seismic hazard management
3. Summary of Best Practices (*which should be common practices*)

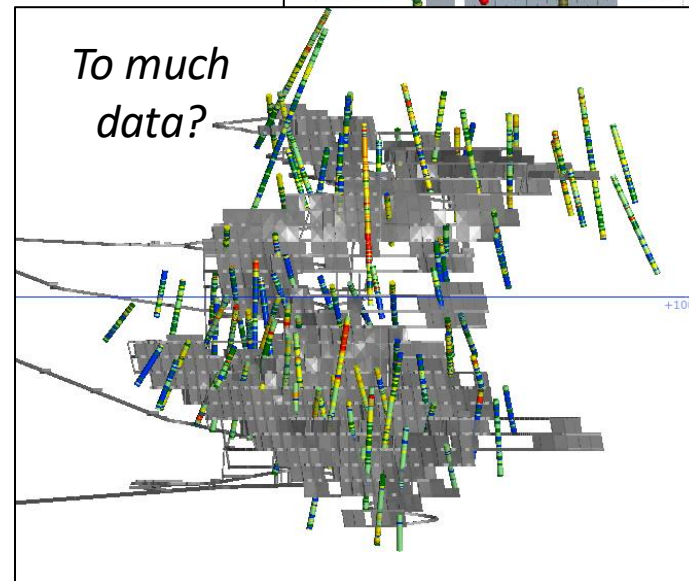
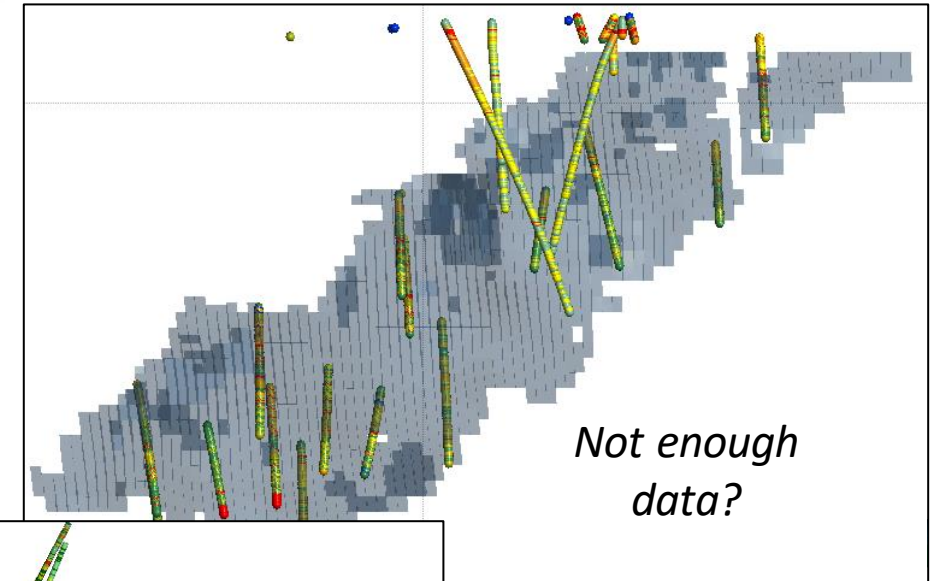
# Foundational Data Collection

- Geotechnical data and site characterization are the foundation of geomechanical design
  - Stope & ground support design
  - Excavation planning & siting
  - Ground support quality assurance
  - Geotechnical risk management
  - Etc.
- Inadequate geotechnical data collection introduces risk to geomechanical mine design and ground control execution.
  - Safety (injury/fatality)
  - Economic (production inefficiencies, equipment damage, dilution, etc.)
  - Asset (resource recovery)



# Foundational Data Collection

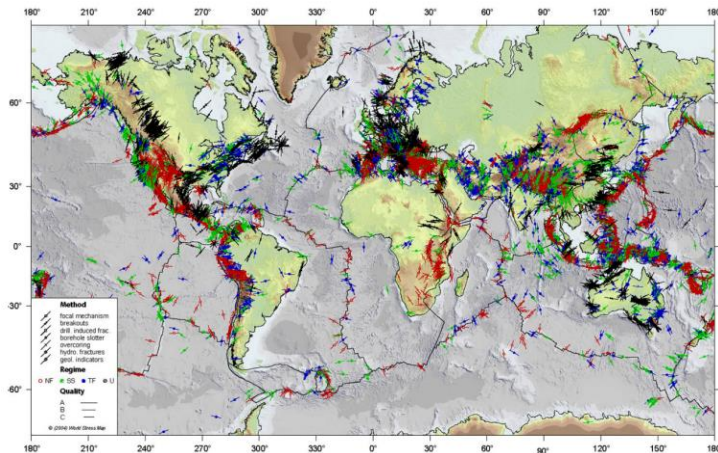
- Key Challenge:
  - No formal guidelines for appropriate levels of geomechanical data collection
- Underground mine projects and operations must strive to collect data:
  - With quantity that is adequate for site specific needs
  - That is targeted to ensure maximum added value



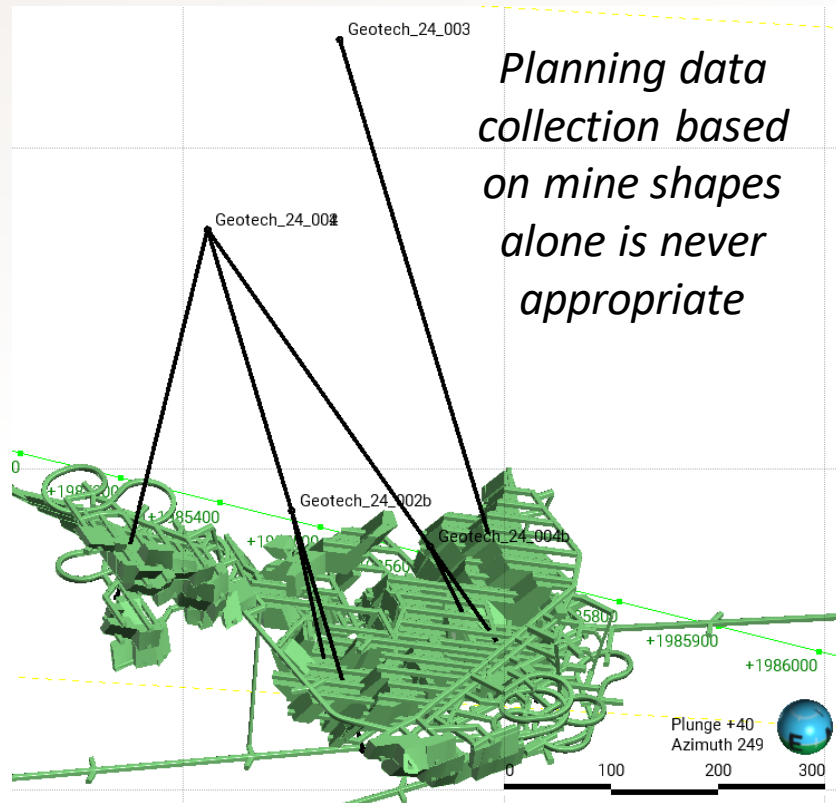
- There is no one size fits all, but there is a consistent set of characterization themes
  - ✓ Geological model
  - ✓ Structural model (fault-scale)
  - ✓ Structural fabric (joint-scale)
  - ✓ Hydrogeology model
  - ✓ Intact rock strength
  - ✓ Strength of structures
  - ✓ Rock mass characterization
  - ✓ In situ stress
- Effective and efficient collection of suitable geomechanical data requires:
  - Understanding of the site-specific geological conditions
  - Foresight regarding anticipated ground behavior mechanism
  - Understanding of data needs relative to project stage

## Best Practice

Establish technical justification of data collection plans based on anticipated ground conditions and ground reaction foresight

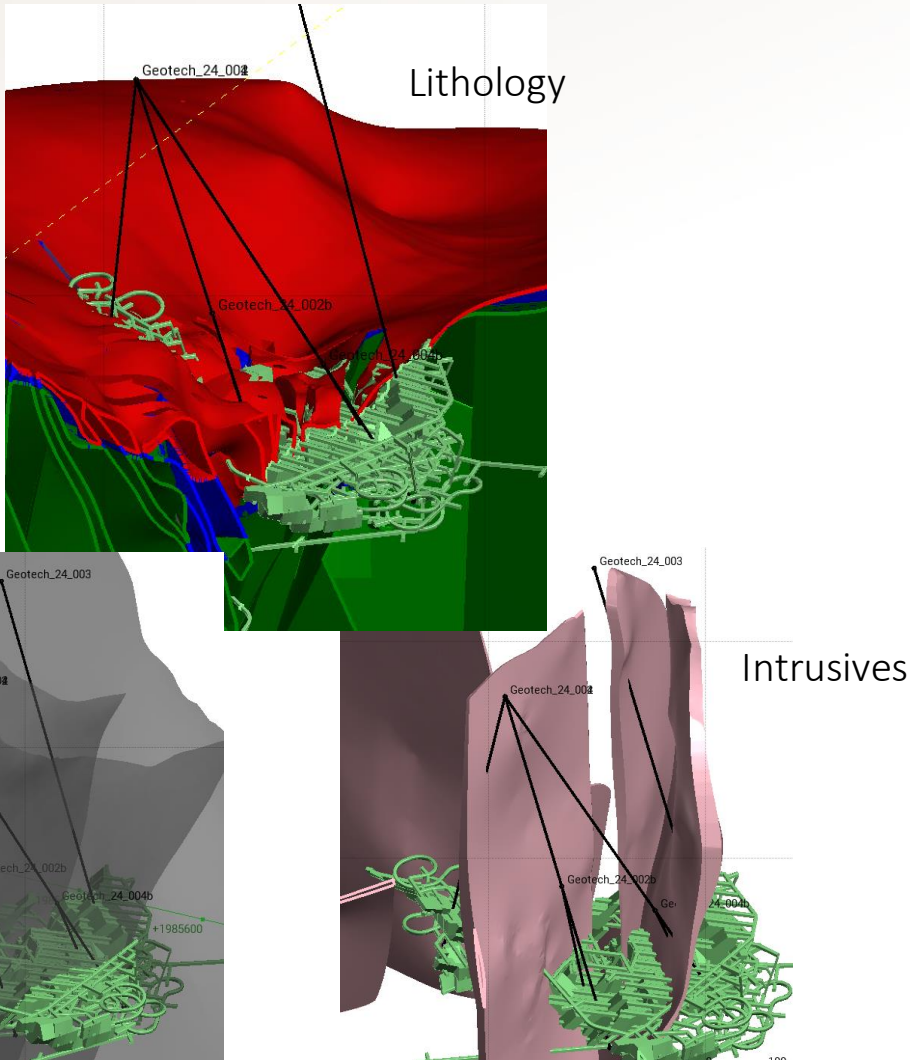


# Reliance on Geological Data and Models



- Geology is the primary control on geomechanical conditions
- Geology explains spatial variability in ground conditions, as controlled by:
  - Lithology
  - Structures
  - Alteration
- Major structural trends are commonly linked to joint-scale fabric
- Geological boundaries should be relied on to establishing appropriate geotechnical domains
- Geomechanical data collection should be targeted according to geological controls on critical failure mechanisms

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Faults

# Anticipation of Failure Mechanisms

## Heavily Jointed Rock

## Jointed Rock

## Massive Rock

Low Stress



Unravelling



Discrete block failure

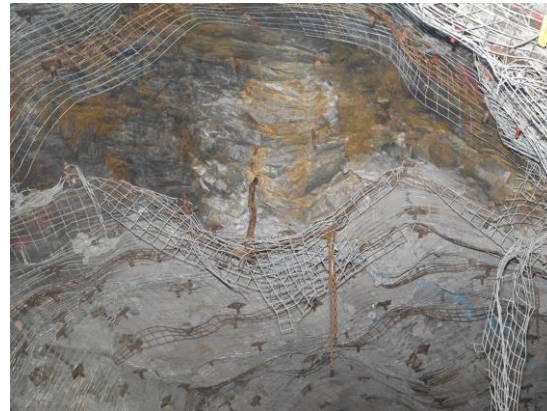


Stable

High Stress



Sliding, crushing,  
squeezing






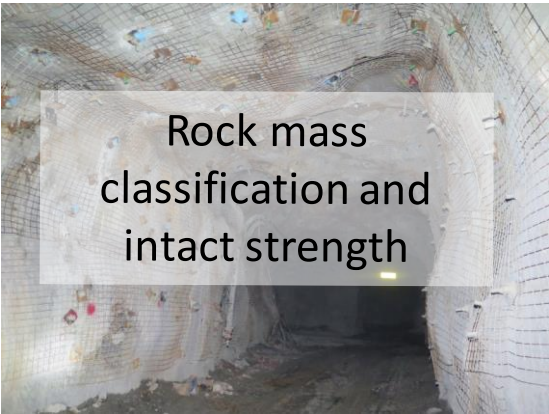
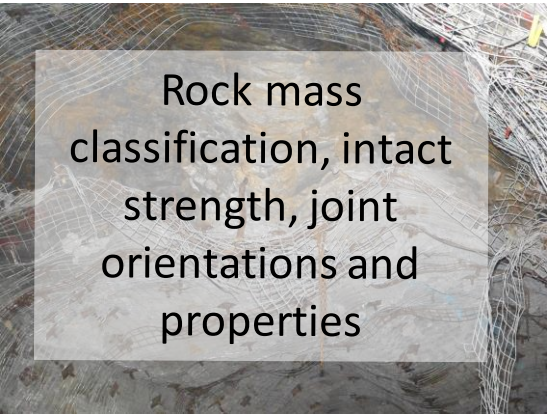

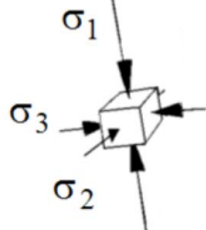
Joints clamped, spalling  
and crushing



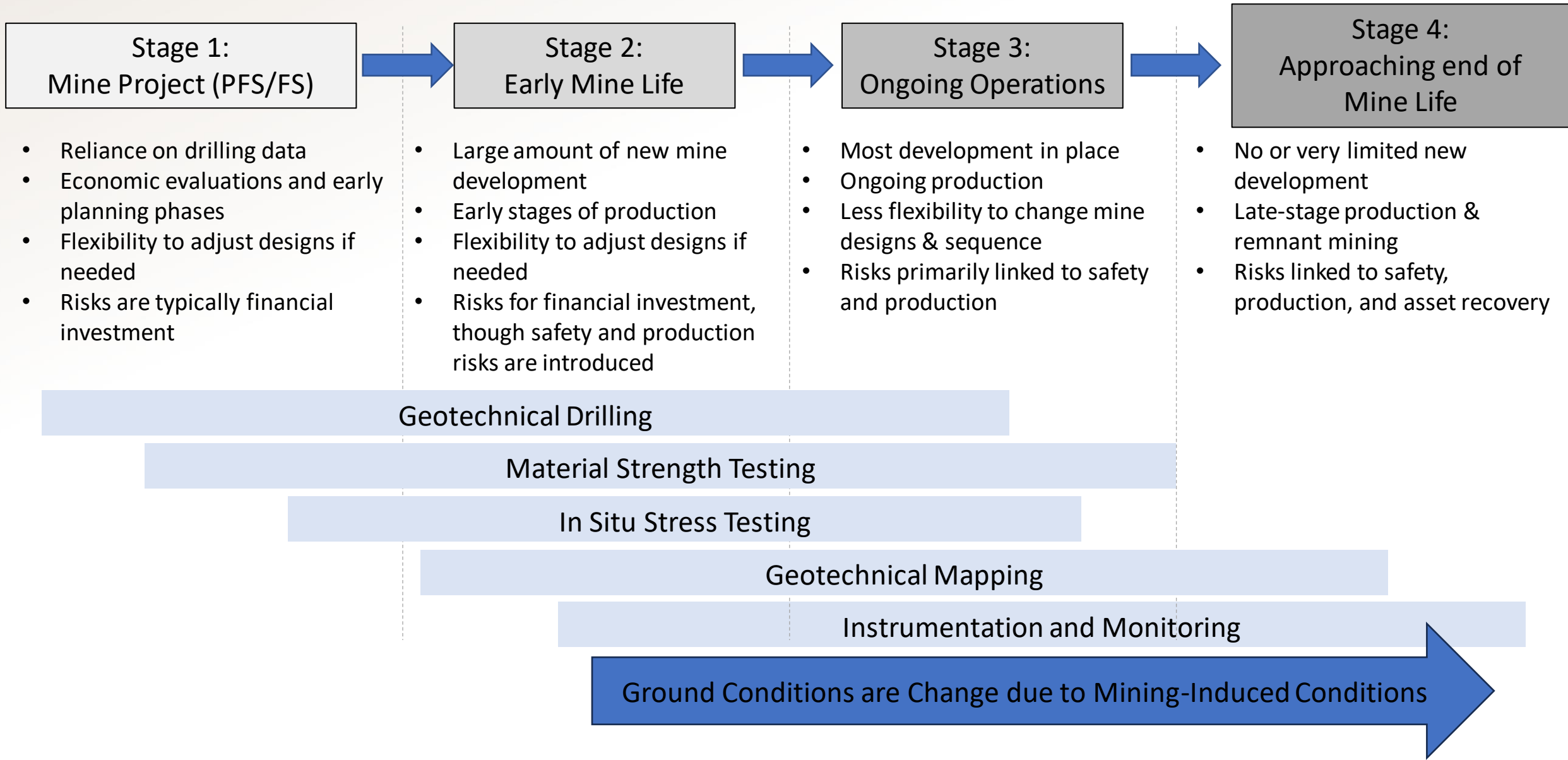
Spalling and crushing



# Anticipation of Failure Mechanisms

|             | Heavily Jointed Rock  | Jointed Rock   | Massive Rock   | Dominating Boundary Conditions  |
|-------------|---|--|--|---|
| Low Stress  |  <p>Rock mass classification</p> <p>Unravelling</p>                              |  <p>Joint orientations &amp; properties</p> <p>Discrete block failure</p>  |  <p>Rock mass classification</p> <p>Stable</p>        | <p>Hydrogeology</p> <p><i>Pore pressure</i></p> <p><i>Fluid flow in fractures</i></p> <p><i>Dissolution</i></p> |
| High Stress |  <p>Rock mass classification and intact strength</p> <p>Squeezing, crushing</p> |  <p>Rock mass classification, intact strength, joint orientations and properties</p> <p>Joints clamped, spalling and crushing</p> |  <p>Intact strength</p> <p>Spalling and crushing</p> | <p>In situ stress</p>       |

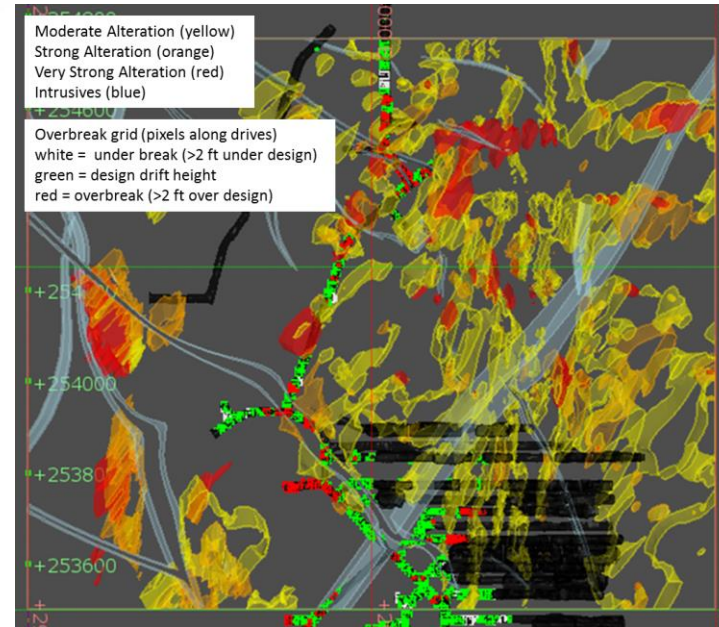
# Data Collection Guidelines By Project Stage



# Best Practice



Establish and maintain a ground behavior model

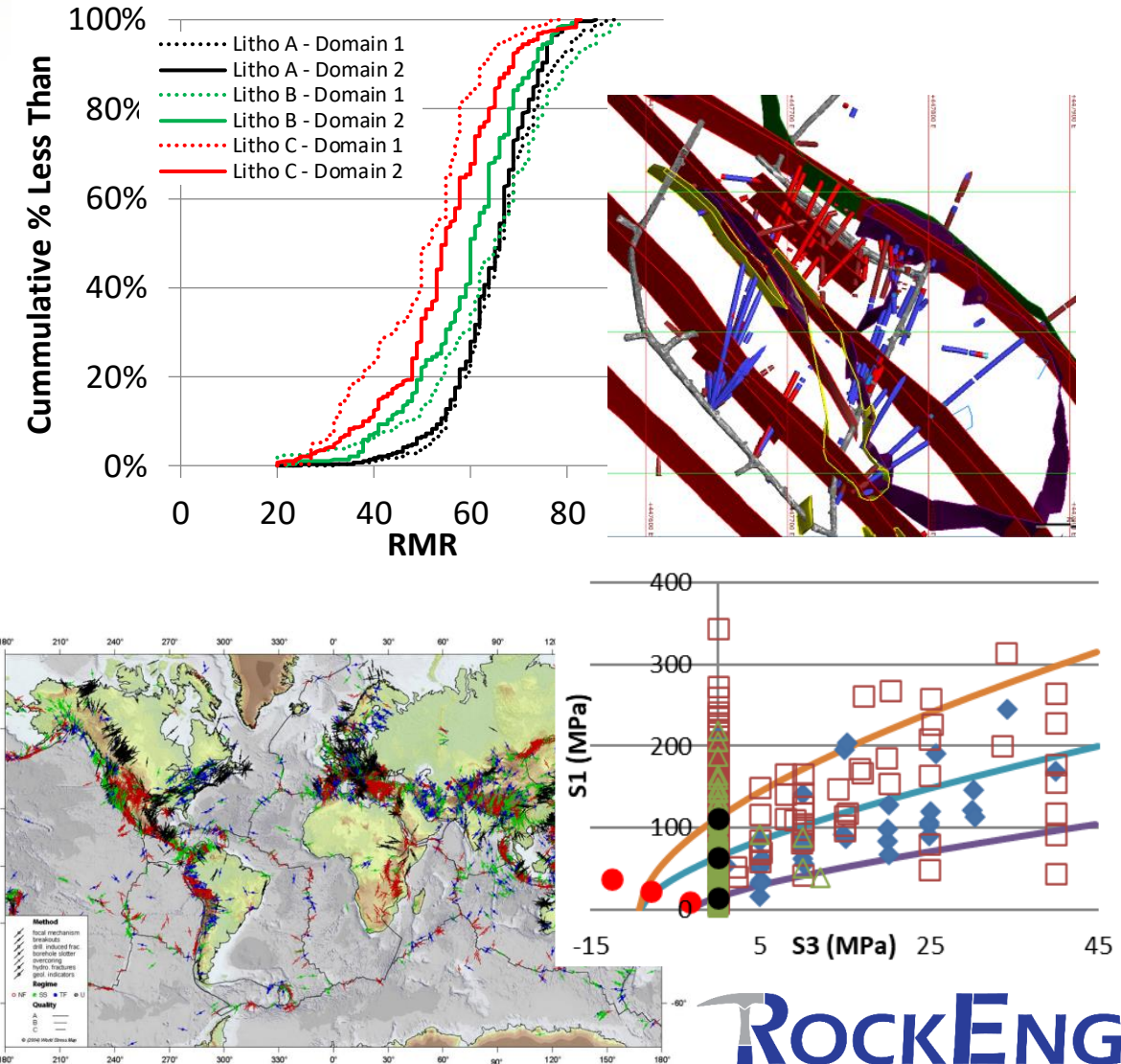
- Data collection culminates with the development and maintenance of a ‘ground behaviour model’ (Palleske et al. 2017)
- Three-dimensional compilation of:
  - Raw geotechnical data (mapping, core logs, laboratory results)
  - Domained rock mass conditions
  - Geology
  - As-built excavation and design geometries
  - Instrumentation data
  - Ground support performance
  - Damage and mechanism mapping
  - Falls of ground or failures
  - Water



*The process of developing a ground behavior model allows the geomechanical engineer to also **develop an intimate understanding of site-specific conditions, and thus formulate a conceptual model of the site geomechanics.***

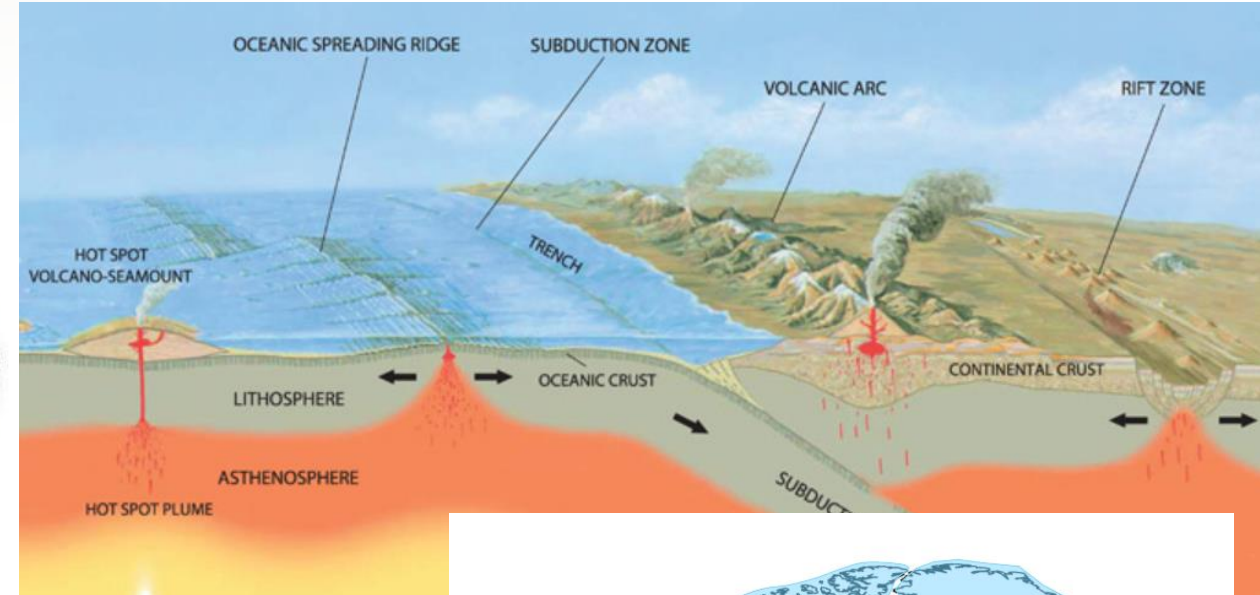
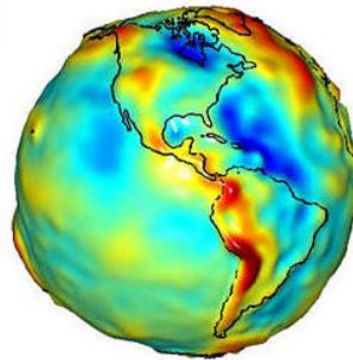
# Geomechanical Design Inputs

| Design Inputs                                   | Typical Data Sources   | Confidence  |
|---|--|---|
| Mine shapes                                     | surveys, designs   | <div style="text-align: center;"> <p>Highest</p>   <p>Lowest</p> </div> |
| Geological domain model                         | mapping, core logging, geophysics                                      |   |
| Geotechnical domain model                       | laboratory testing, mapping, core logging, instrumentation, literature |   |
| Loading conditions (most commonly stress state) | in situ testing (instrumentation), literature                          |   |

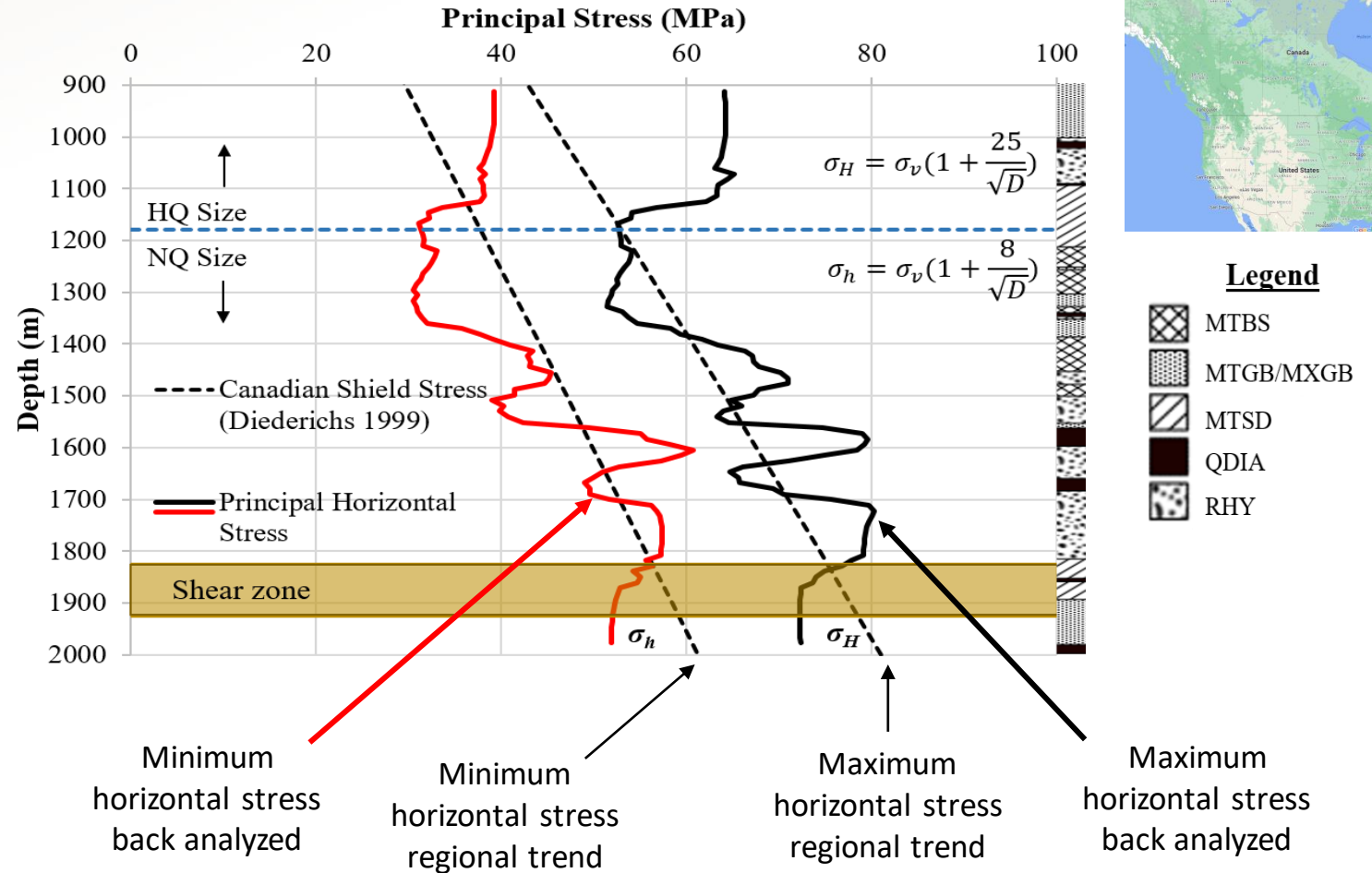
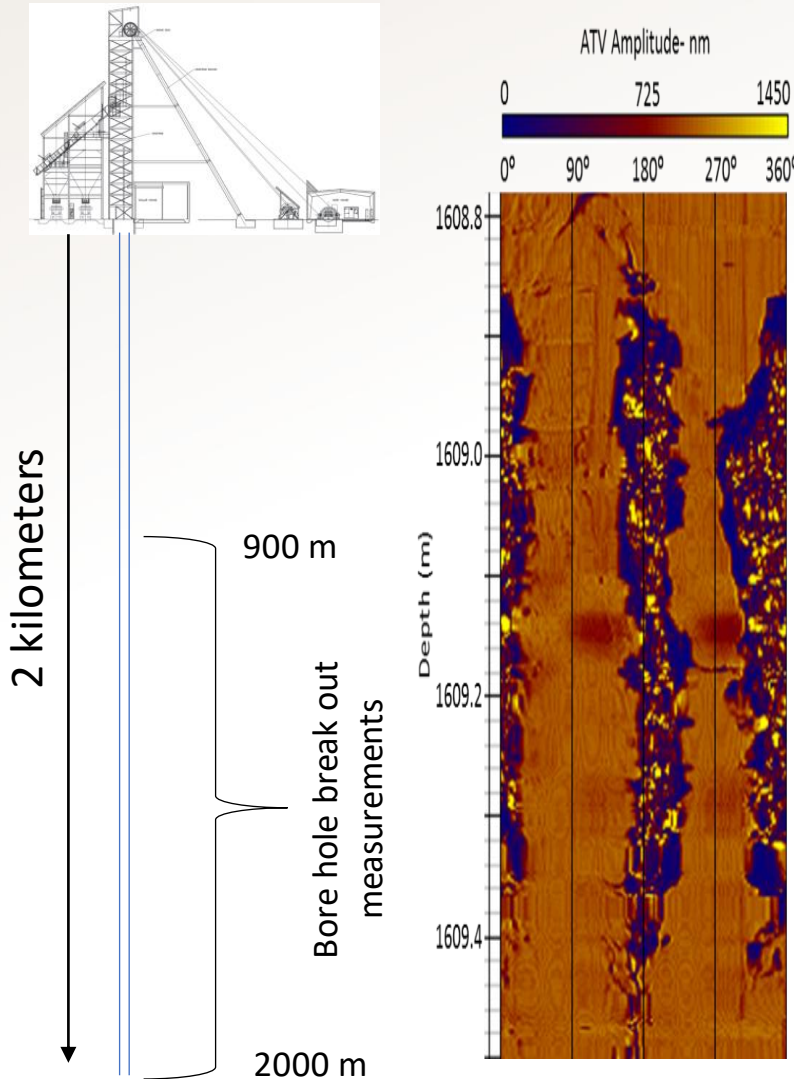


# Biggest Unknown: Boundary Conditions

- Stress state is impacted by geological numerous factors:
  - Gravity,
  - Topography
  - Paleo- and active plate tectonics
  - Glacial loading
  - Erosional events
  - Local heterogeneities, fabric and discontinuities

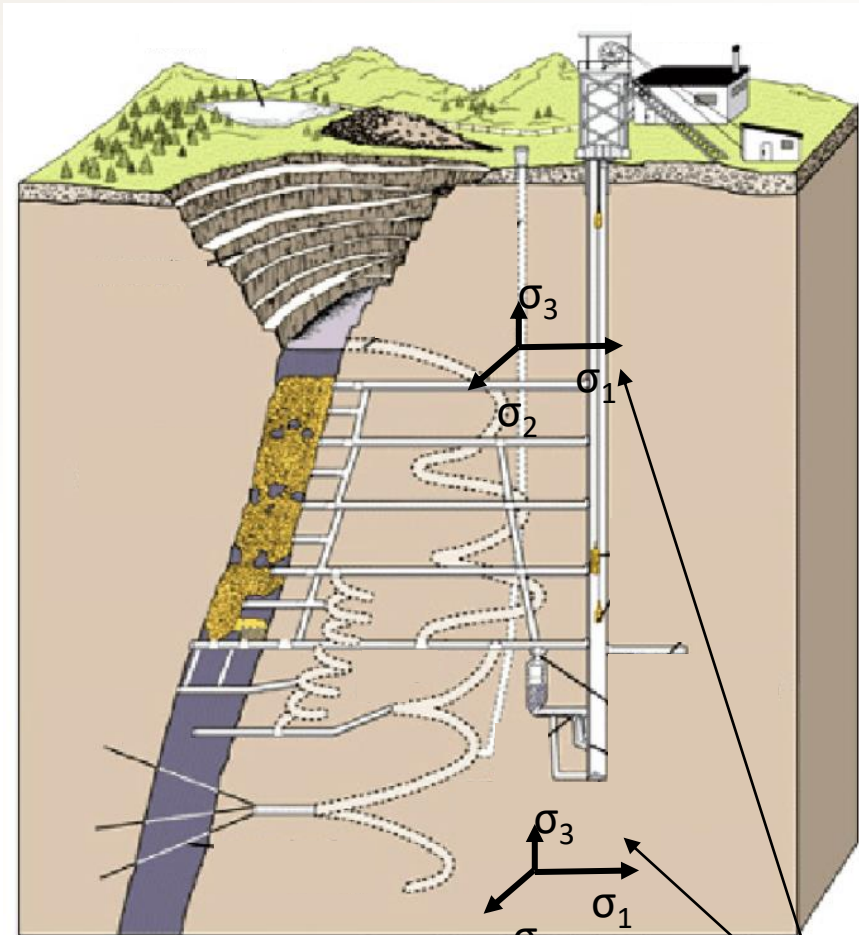


# Example: In Situ Stress Complexity

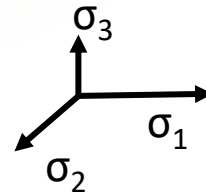


LeRiche, A. et al. 2017

# Simplified Stress States



Regional Trends



**Most Common Method:** Define stress state according to averaged orientations and gradients.

| Component  | Magnitude (MPa)       | Trend (°) | Plunge (°) |
|------------|-----------------------|-----------|------------|
| $\sigma_1$ | $1.8 \times \sigma_3$ | 020       | 00         |
| $\sigma_2$ | $1.2 \times \sigma_3$ | 110       | 00         |
| $\sigma_3$ | $0.027z$              | 000       | 90         |



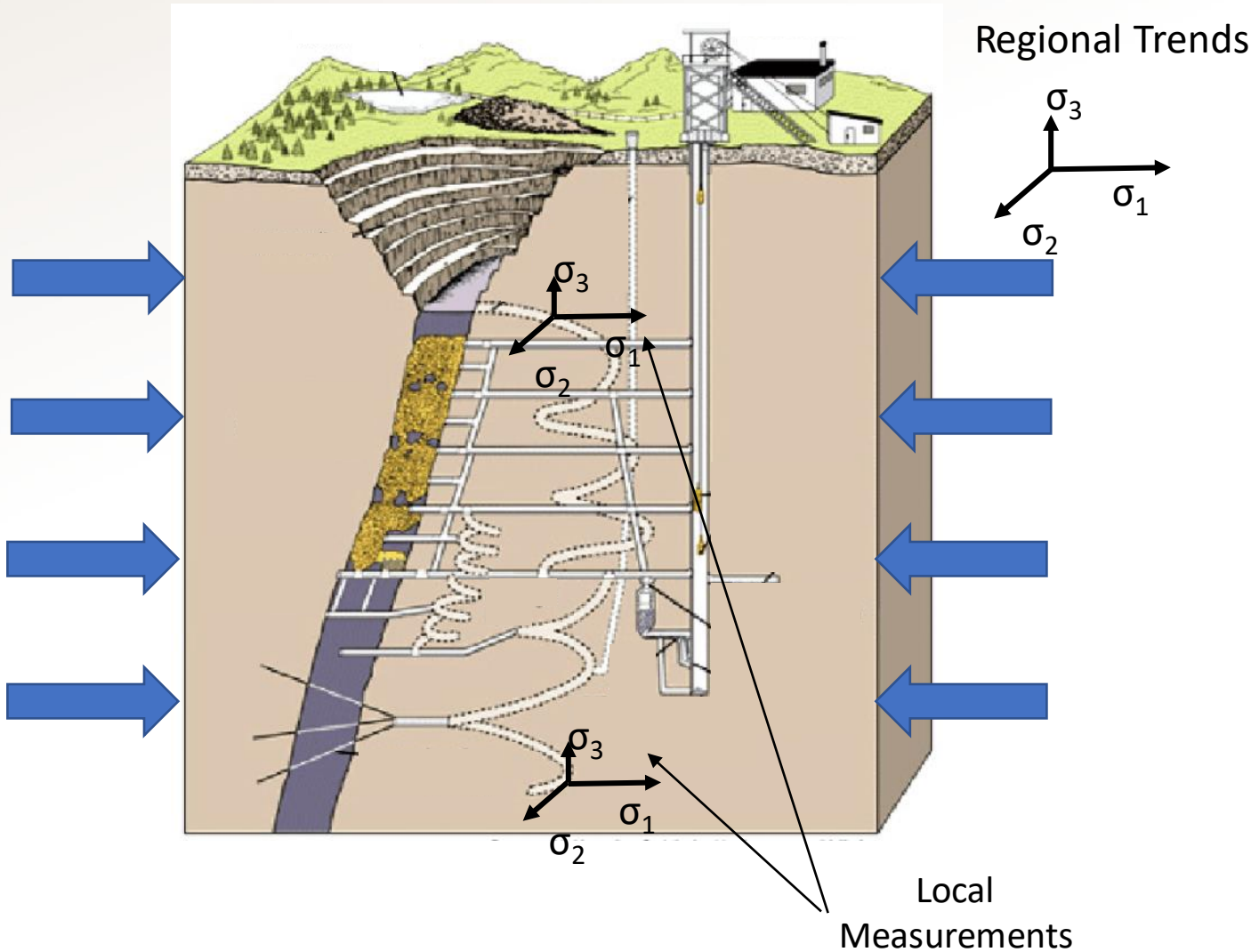
Fixed magnitude increase with depth

Constant tensor orientation

Local Measurements

# Best Practice

## Strain-Based Initialization of Geologically Realistic In Situ Stress States

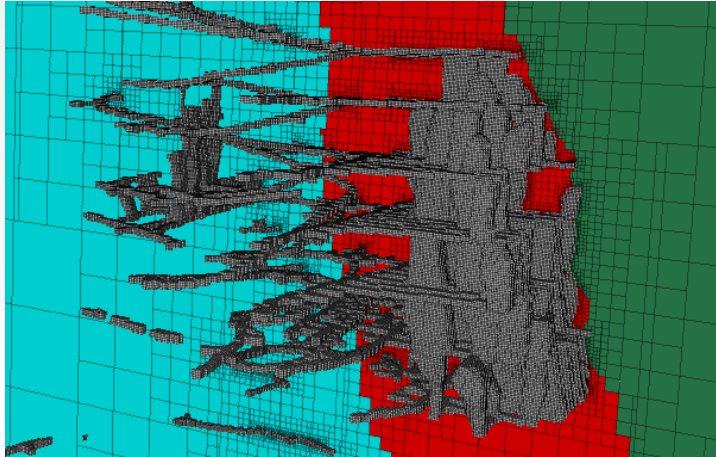





- Requires numerical modelling
- Strain is induced within the numerical model is reasonably consistent with the site geological history
- Produces geologically realistic stress tensor distributions
  - Spatial variance in magnitude and orientation of the stress state

*Kalenchuk, 2022a*



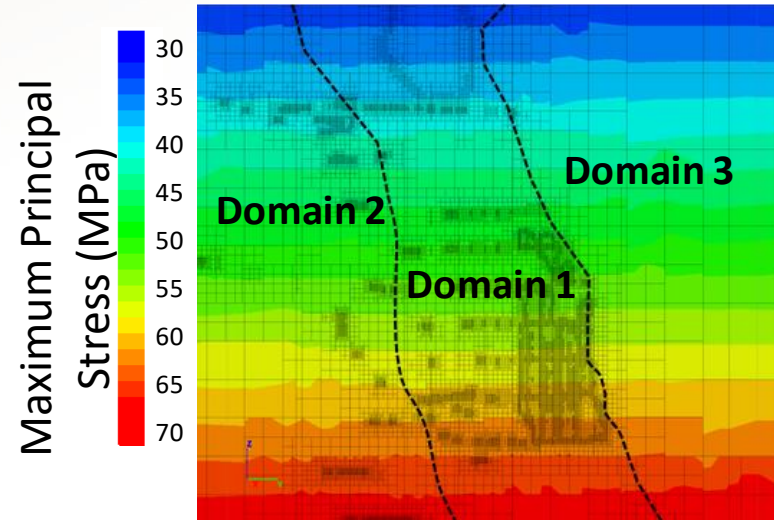
# Realistic In Situ Stress Characterization Requires Global Mine-Scale Modelling



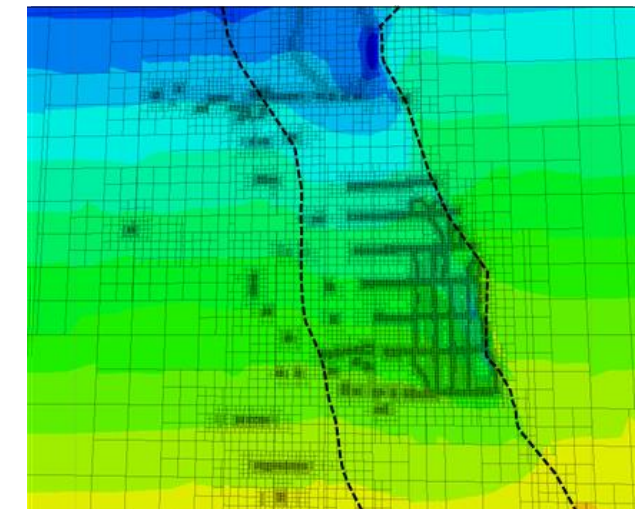
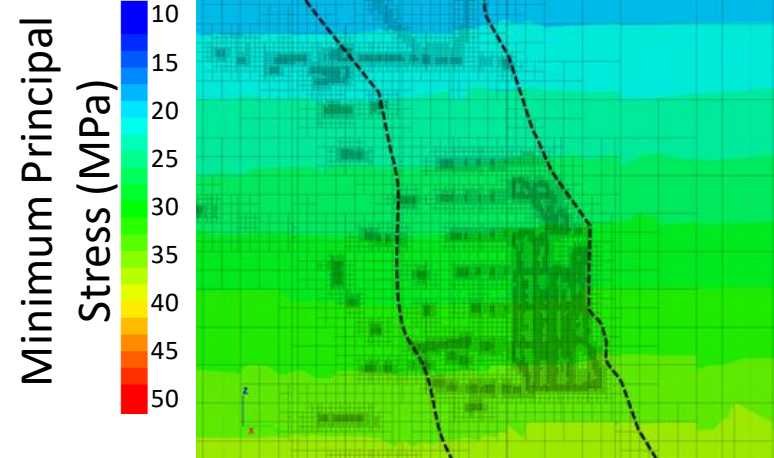
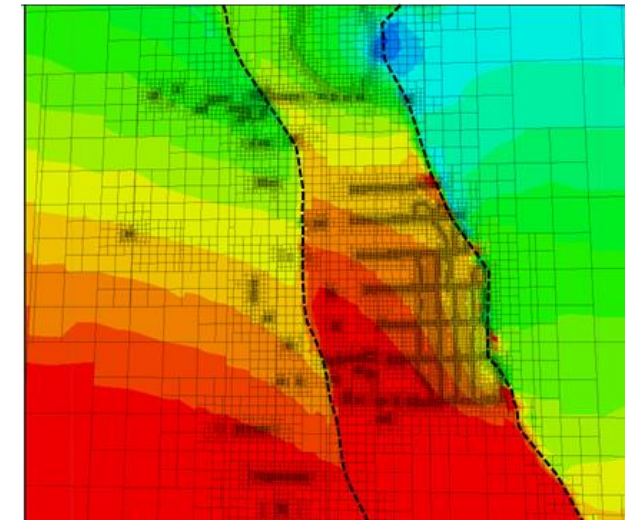
| Domain   | UCS (MPa) | $m_i$ | $E_i$ (GPa) | GSI |
|--|-----------|-------|-------------|-----|
|  1 | 154       | 25    | 54          | 61  |
|  2 | 94        | 17    | 58          | 62  |
|  3 | 36        | 10    | 30          | 46  |

Vertical cross section through mine workings showing major lithology domains

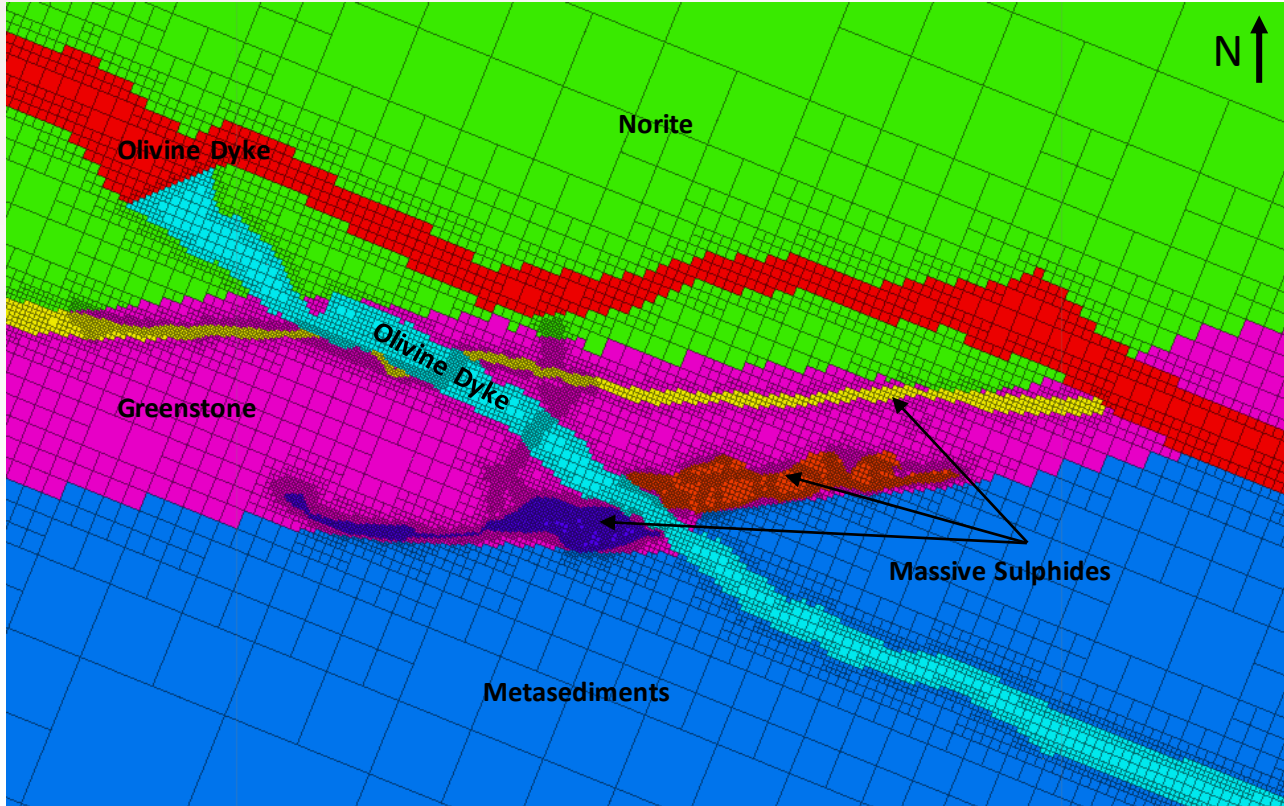
Uniform Depth Gradient



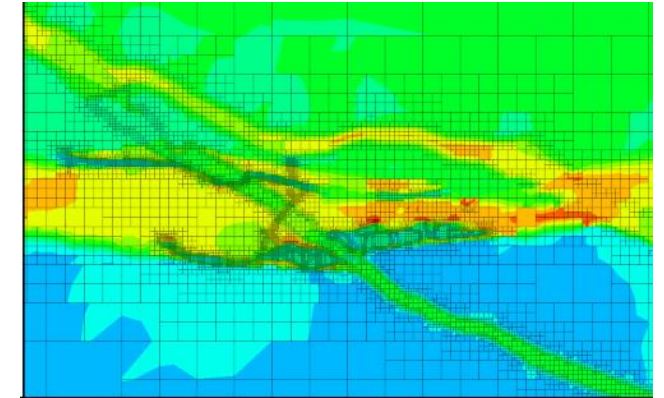
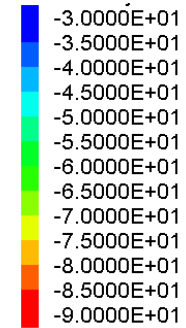
Strain-Based Stress Initialization



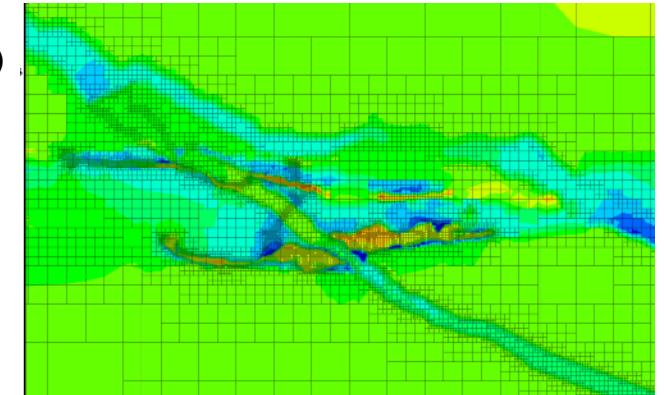
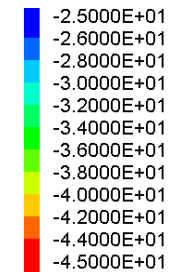
# Realistic In Situ Stress Characterization Requires Global Mine-Scale Modelling



$\sigma_1$  (MPa)  
 (compression negative)



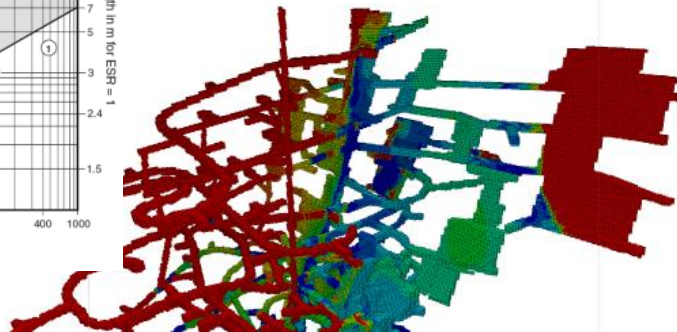
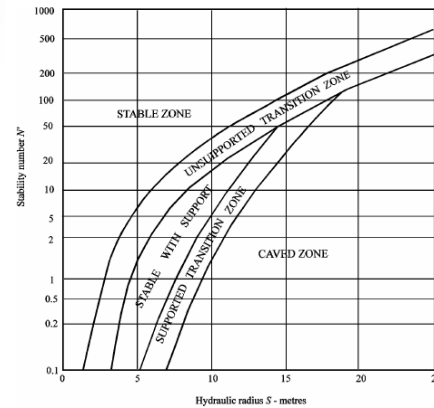
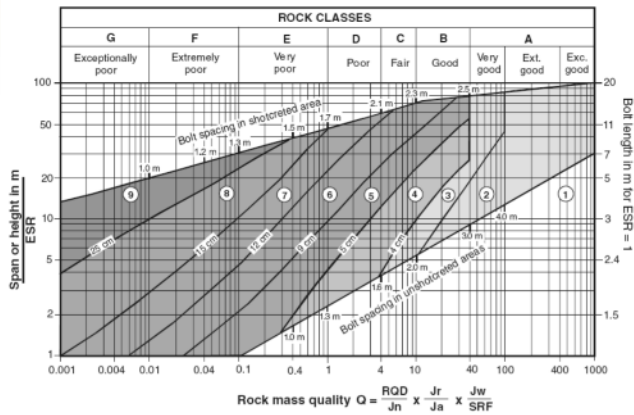
$\sigma_3$  (MPa)  
 (compression negative)



# Geomechanical Design for Underground Mines

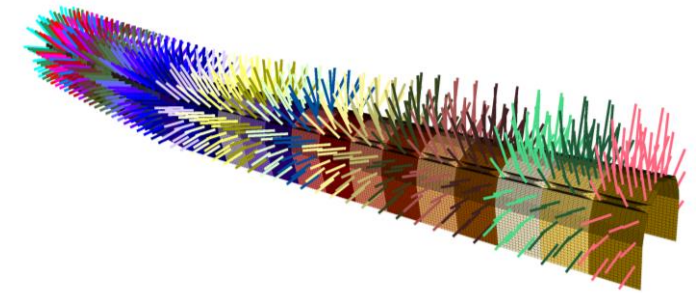
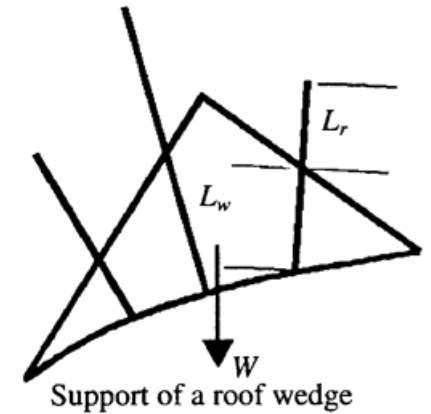
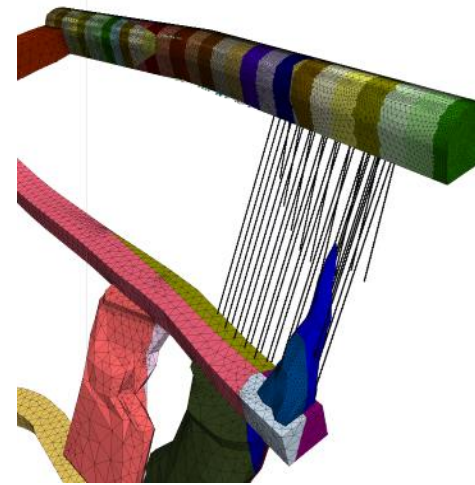
## Susceptibility Design: Susceptibility to a particular ground reaction.

- Achieves qualitative or semi-qualitative expectation of ground or system reaction
- Global scale numerical modelling
- Empirical tools



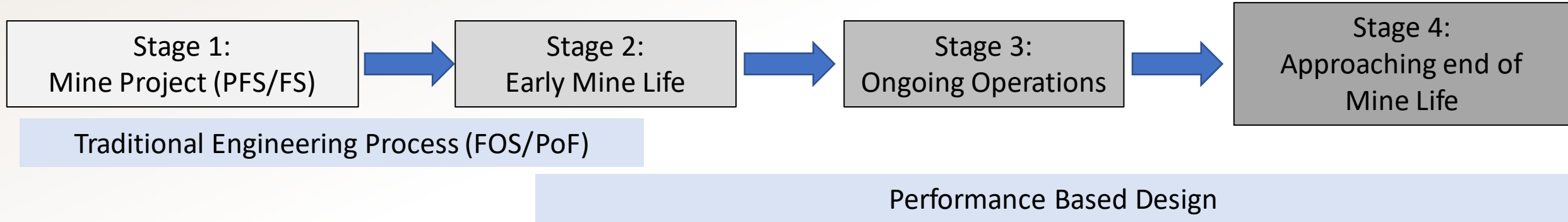
## Mechanistic Design: Understanding of fundamental mechanics

- Achieves quantitative expectation of ground or system reaction
- Local scale numerical modelling
- Analytical tools



# Best Practice

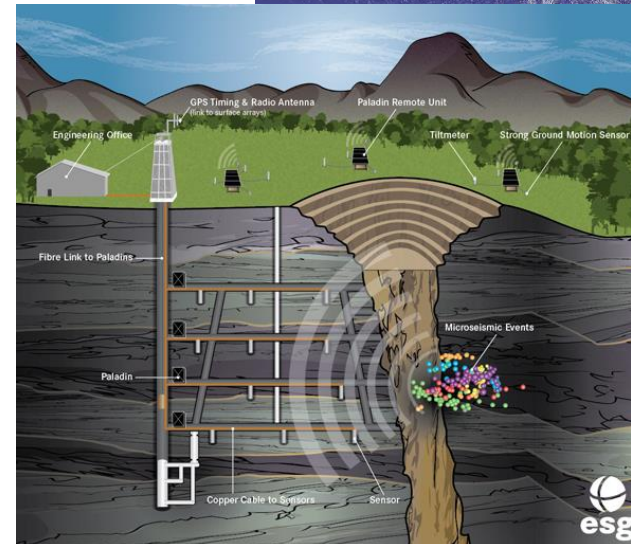
## Performance Based Design for Operations



- Traditional engineering procedures rely on factor of safety and probability of failure as metrics for design adequacy.
- Performance based design compares observed performance to predicted performance.
  - There is no link between factor of safety and excavation performance (excavations must be safe and perform adequately – there is no universal factor of safety threshold that guarantees this – Hoek, 1991)
  - Factor of safety is not necessarily applicable to mine-scale design problems
  - Performance based design must be incorporated as best practice in underground mine operations (fundamental to safety and optimization)

# Geotechnical Monitoring in Mines

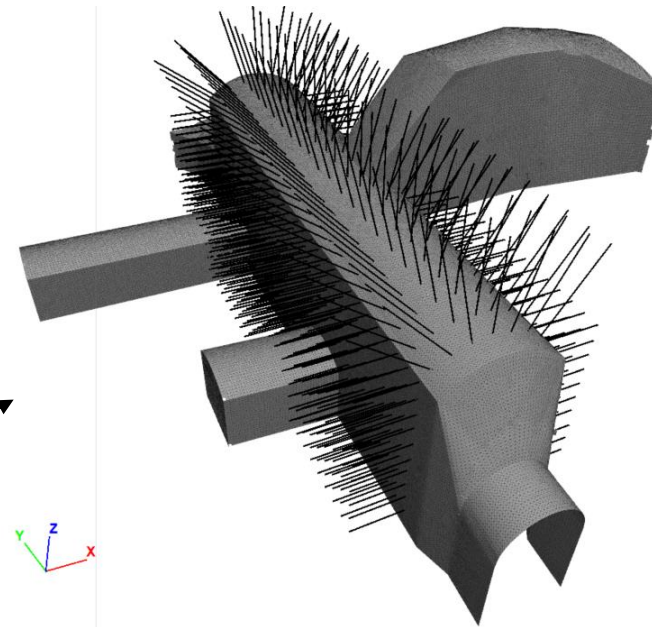
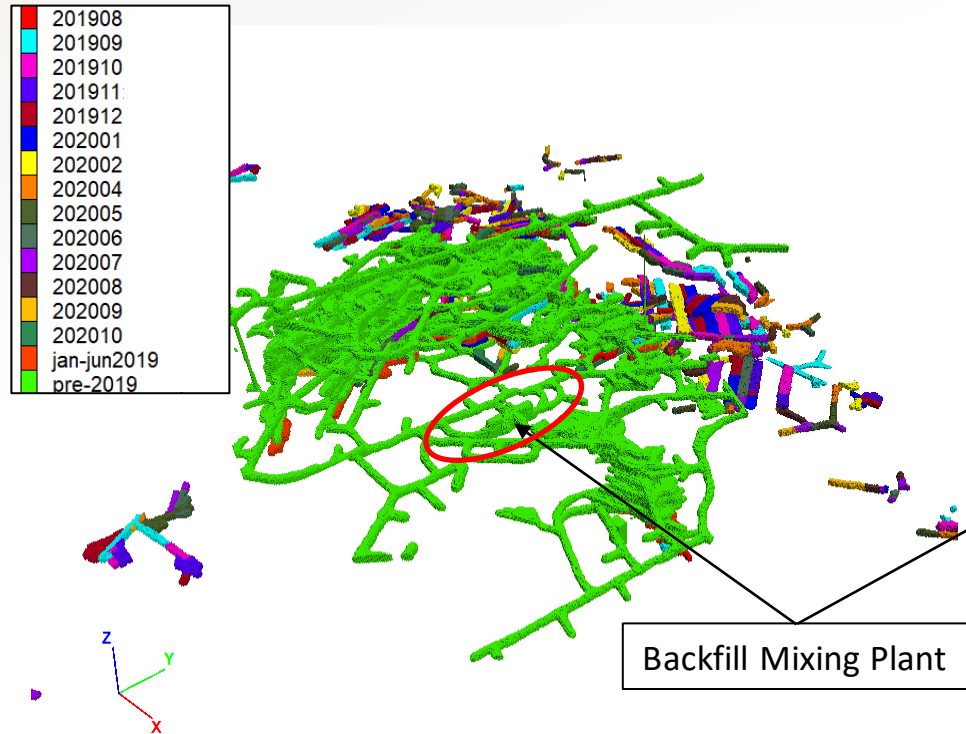
- The objectives are:
  - Safety
  - Design calibration / verification / optimization
  - Interpretation and understanding of ground reaction mechanisms
  - Inform stakeholders
  - Reduce litigation
  - Advance state-of-knowledge
- For monitoring to be successful, conditions need to be changing
  - Ground must be failing
  - Rock must be deforming



# Performance Based Design

## Case Example 1: Infrastructure Maintenance

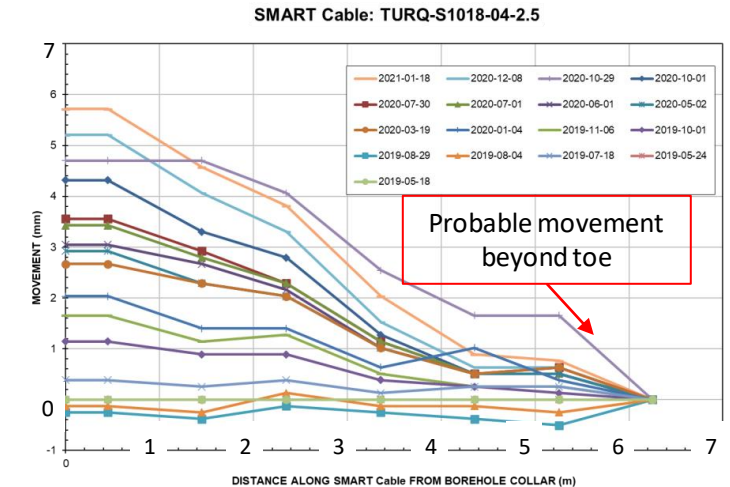
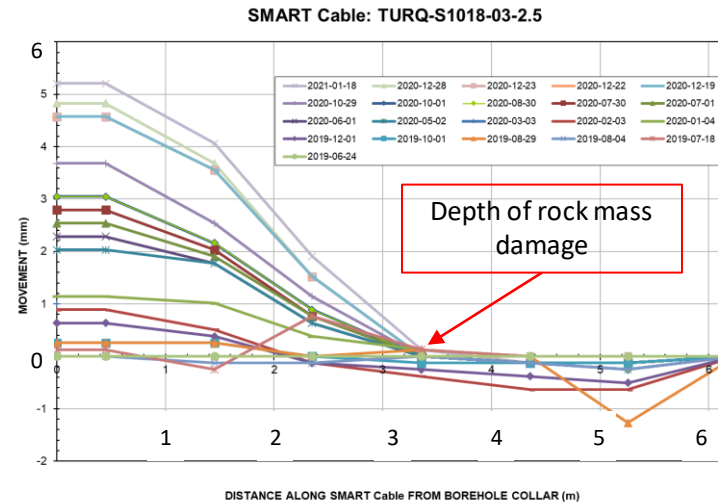
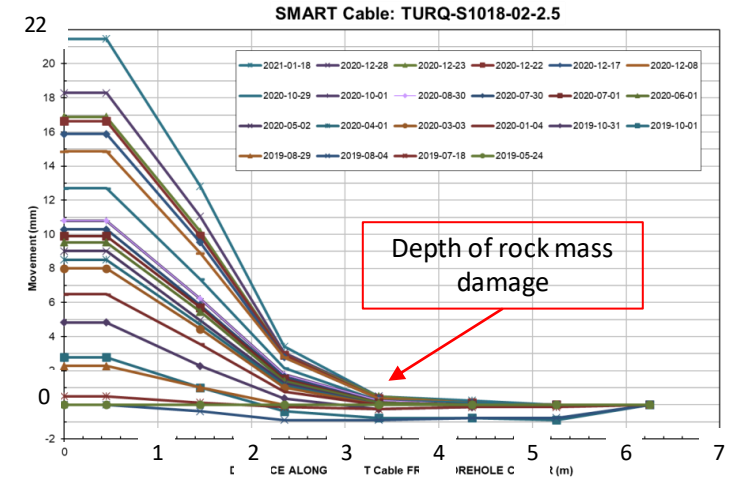
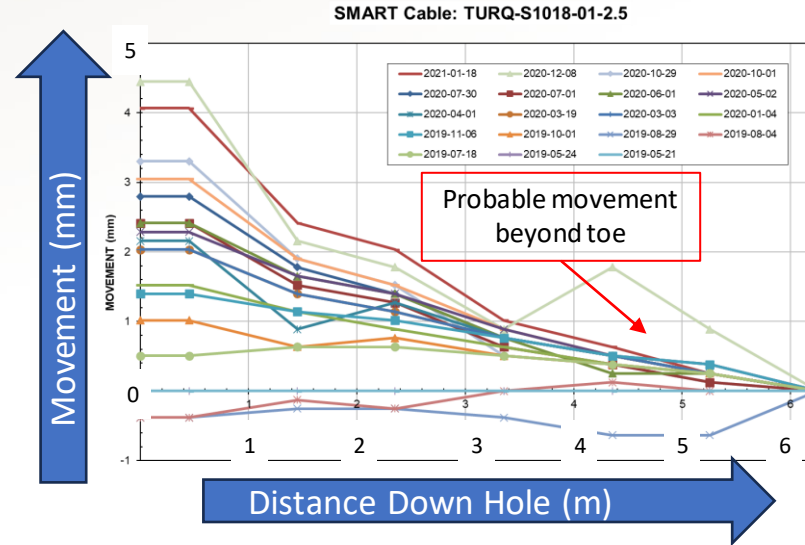
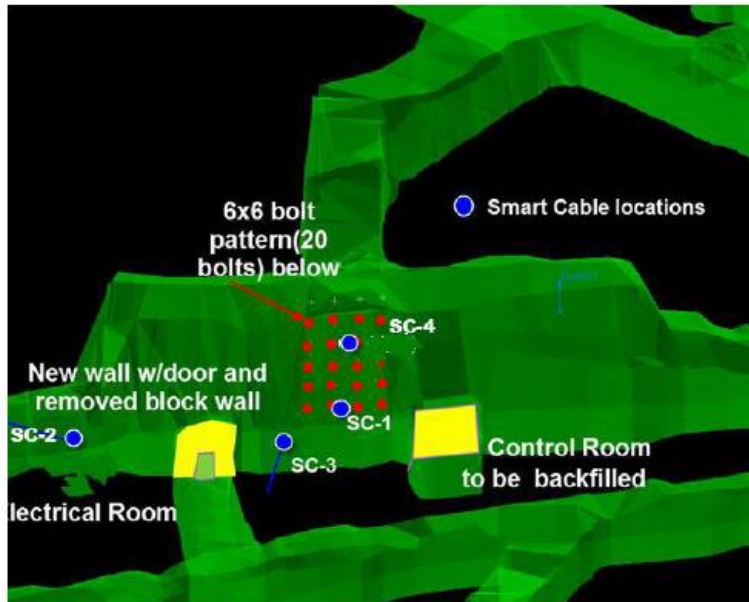
**Case Study:** Planning suitable rehabilitation and ground support design for critical backfill mixing infrastructure in squeezing ground



Squeezing ground has induced damage in heavily reinforced excavation (24 tonne bolts with 75 mm of shotcrete). Support rehabilitation is required.

# Performance Based Design Case Example 1: Infrastructure Maintenance

- Instrumented ground support elements “Smart Cables” provide valuable insight of loading imposed on support elements and depth of damage in the rock mass.



# Performance Based Design

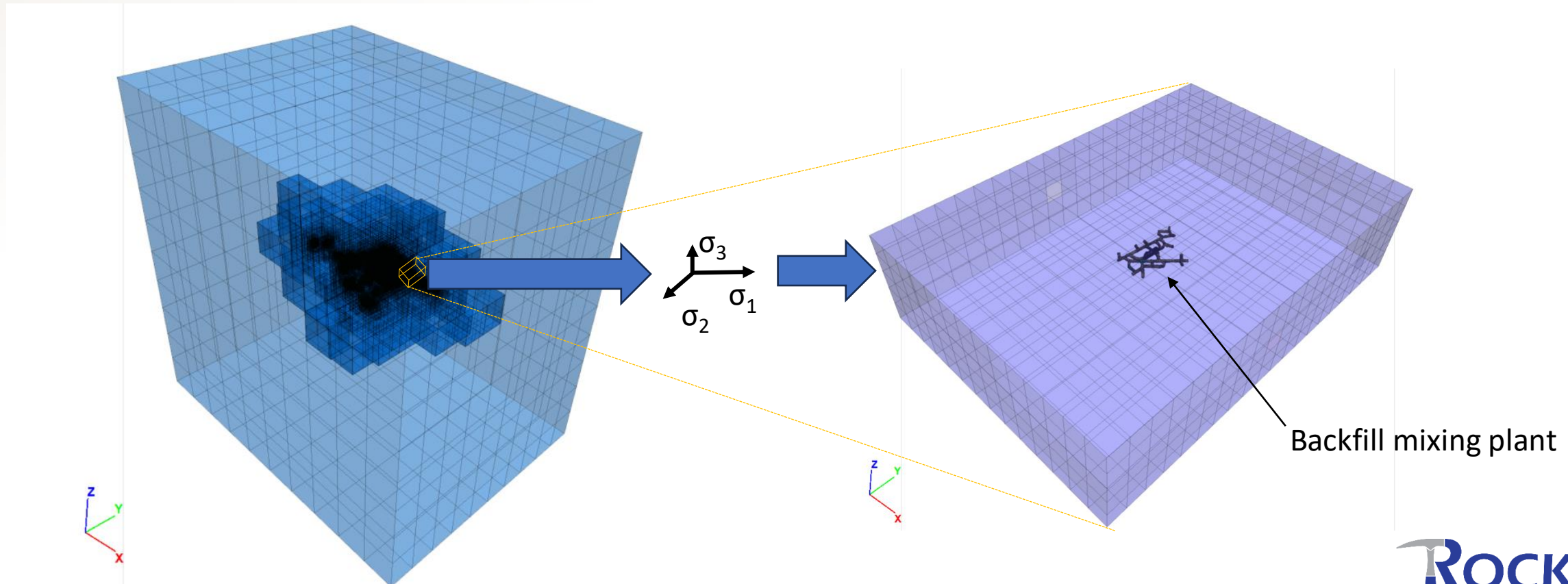
## Case Example 1: Infrastructure Maintenance

### Global Model:

- Simulates the mining history for the entire underground operation
- Induced stress conditions at the backfill plant location are sampled for import to the local model

### Local Model:

- In situ stress conditions are varied according to the Global model predictions of imposed load
- Provides detailed simulation of the backfill plant geometry and explicit representation of the ground support elements



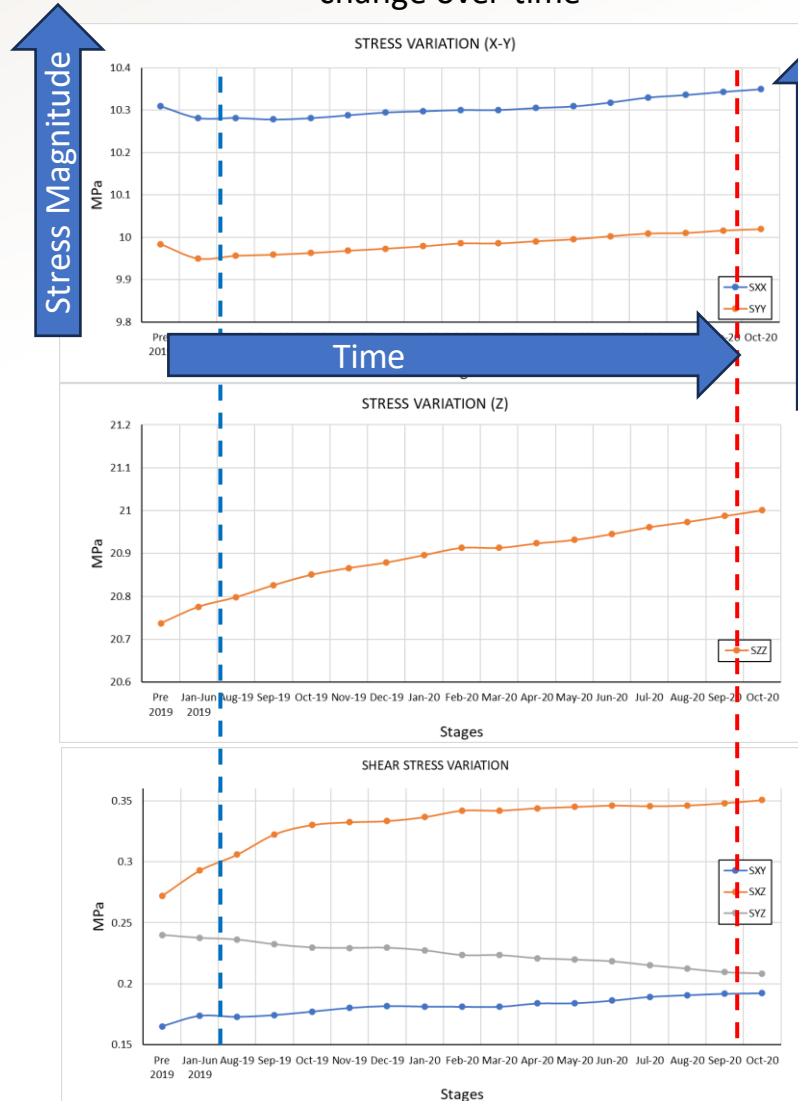


# Performance Based Design

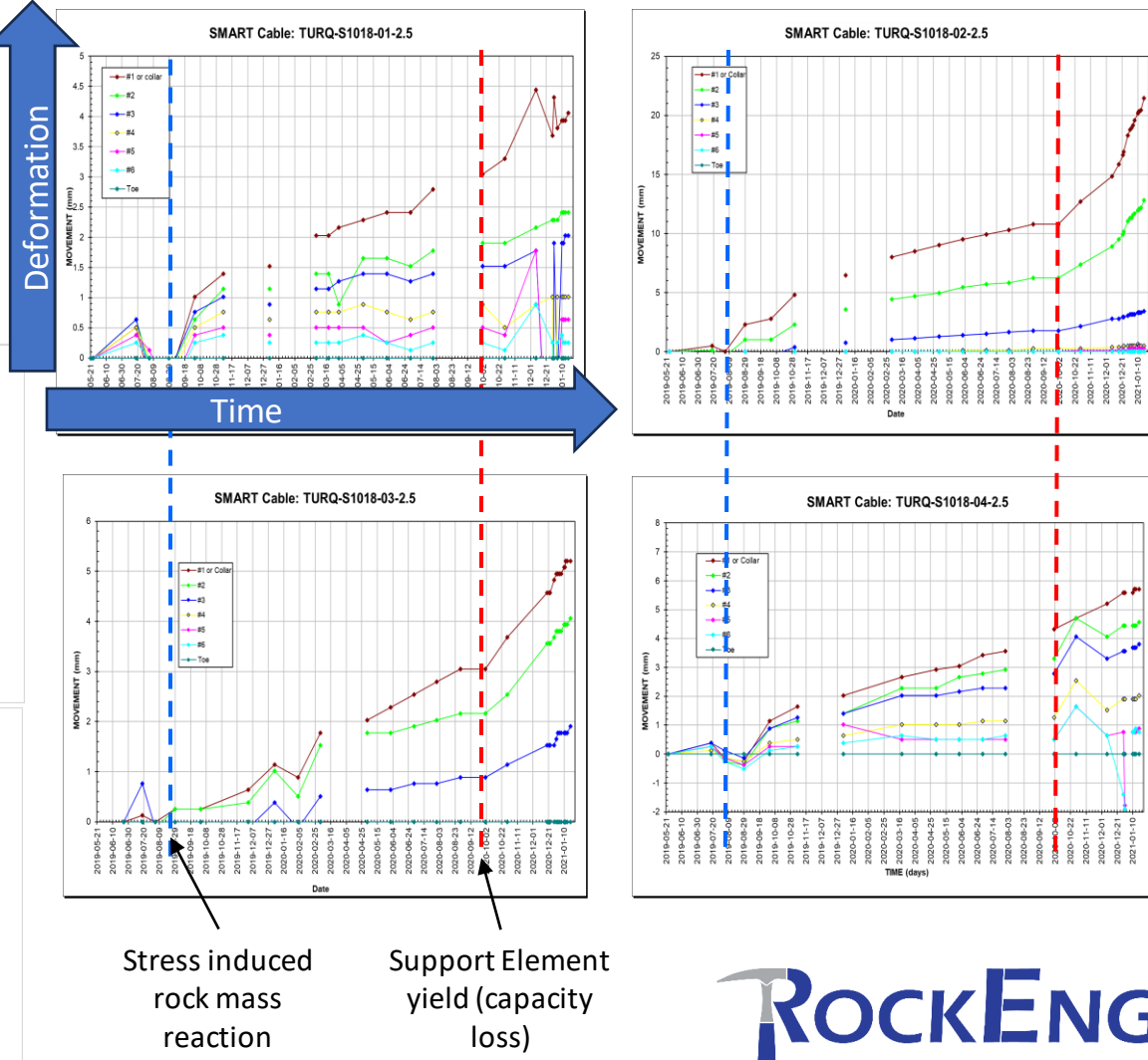
## Case Example 1: Infrastructure Maintenance

- Global model predictions of stress change imposed on the area of interest are critical to capturing loading conditions contributing to accelerated at specific points in time.

Global model prediction of stress state change over time



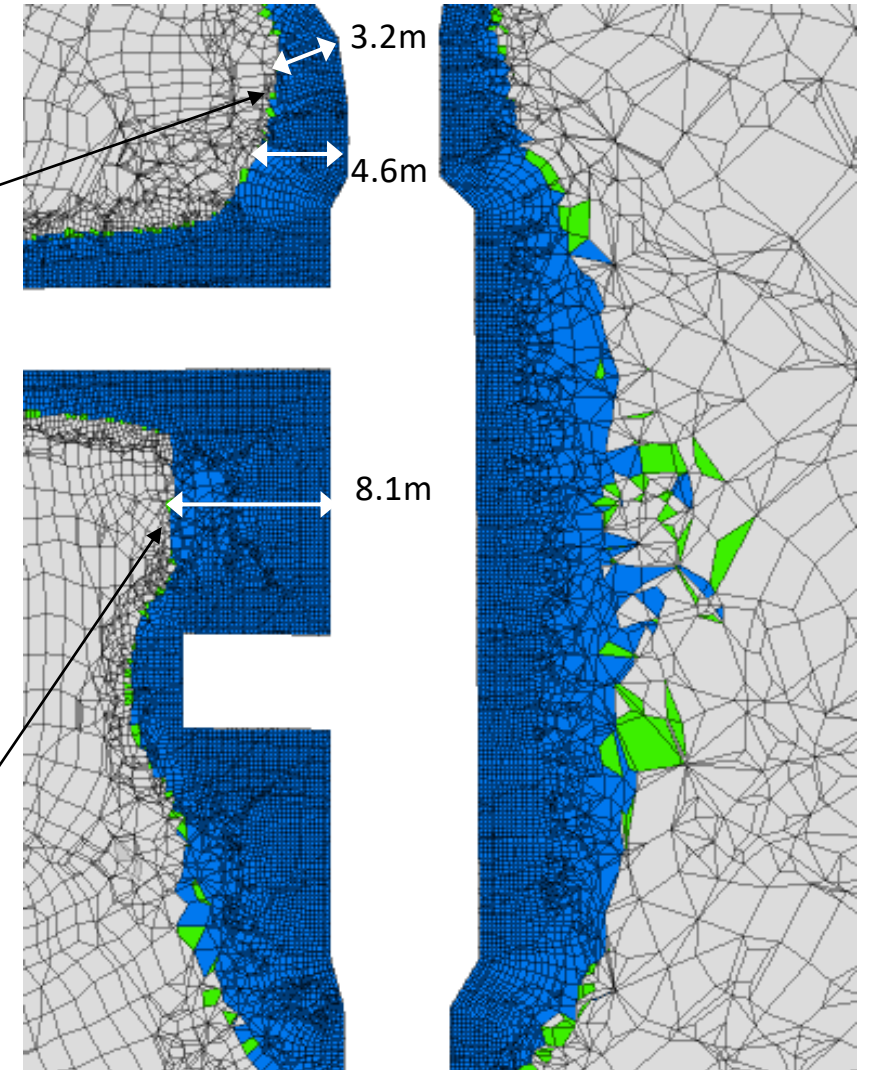
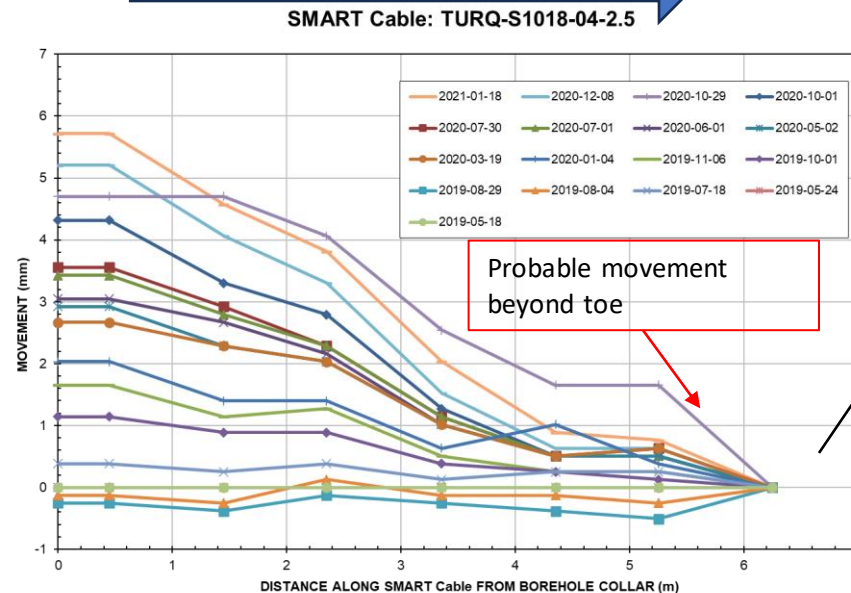
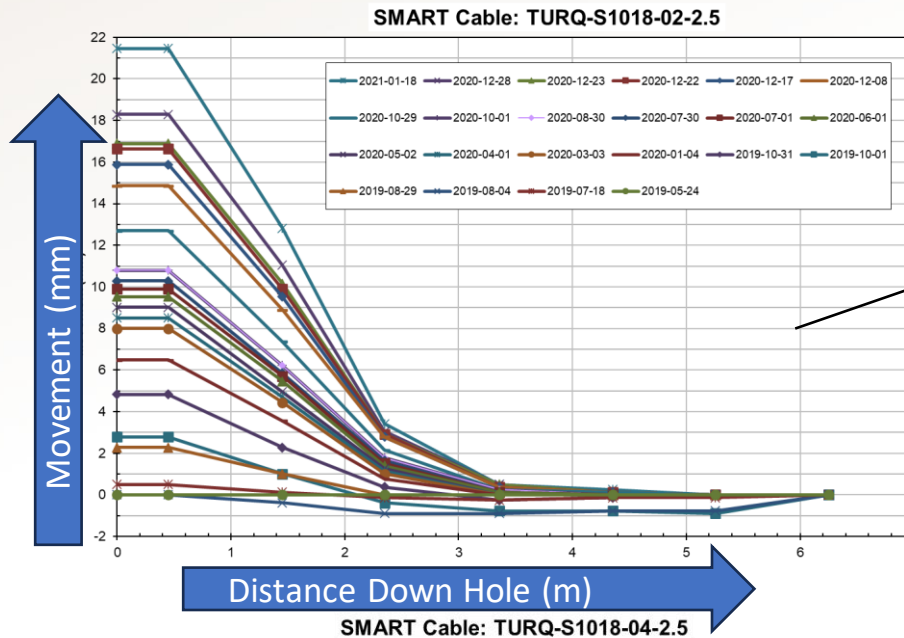
Monitoring data demonstrating periods with accelerated deformation of ground support elements



# Performance Based Design

## Case Example 1: Infrastructure Maintenance

- Local model explicitly simulates ground support elements and instrumentation data

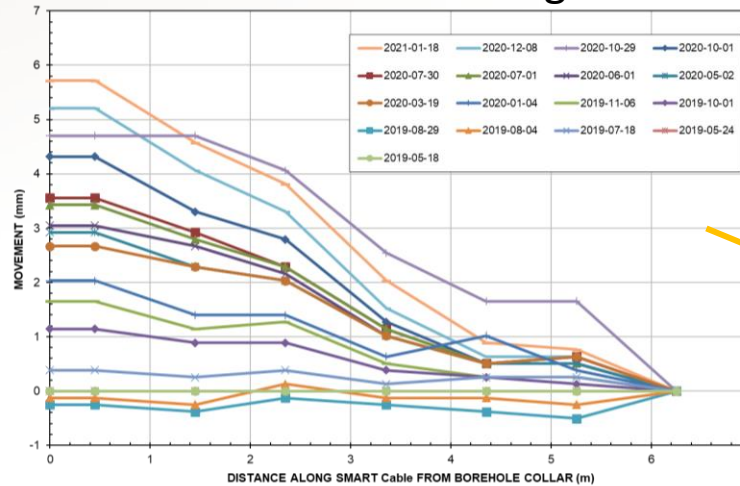


# Performance Based Design

## Case Example 1: Infrastructure Maintenance

- Local model explicitly simulates ground support elements and instrumentation data

Field monitoring



Modelled instrumentation

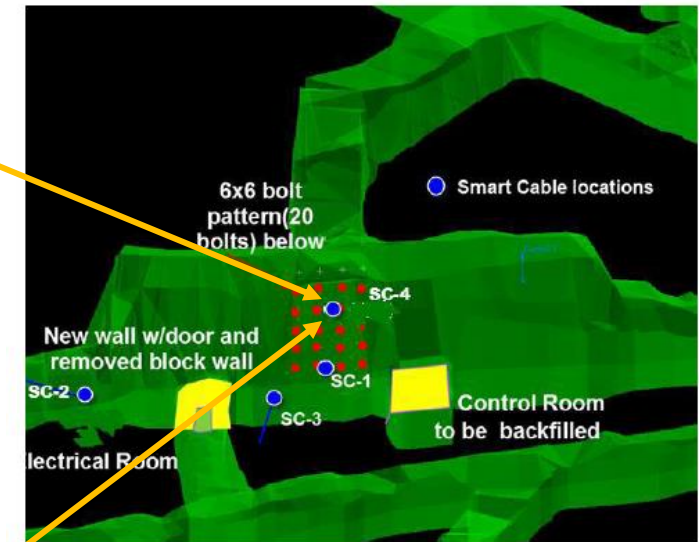
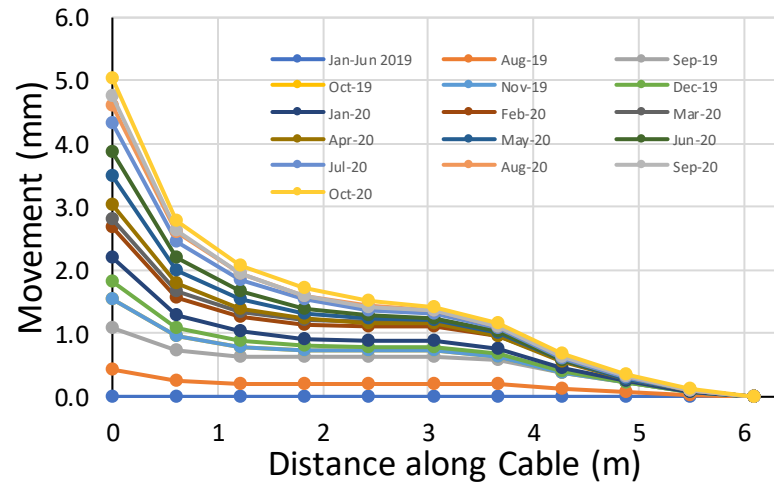


Figure 1: Smart Cable Locations

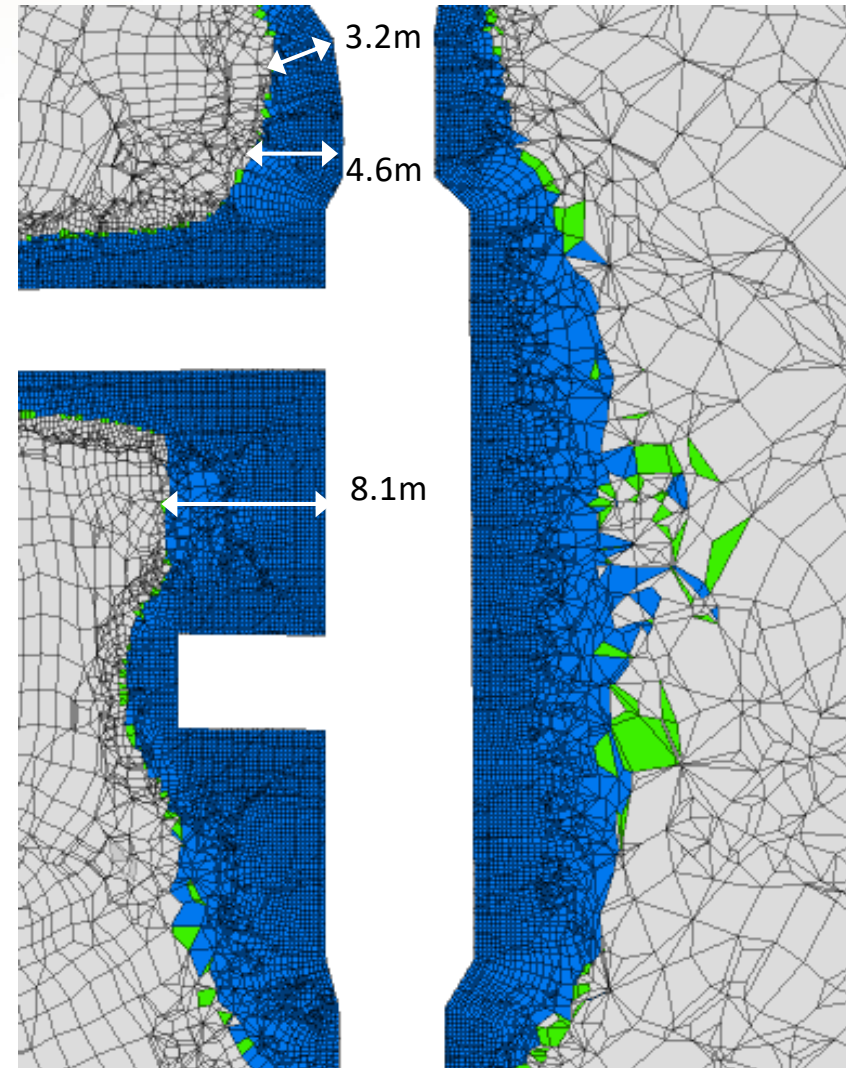
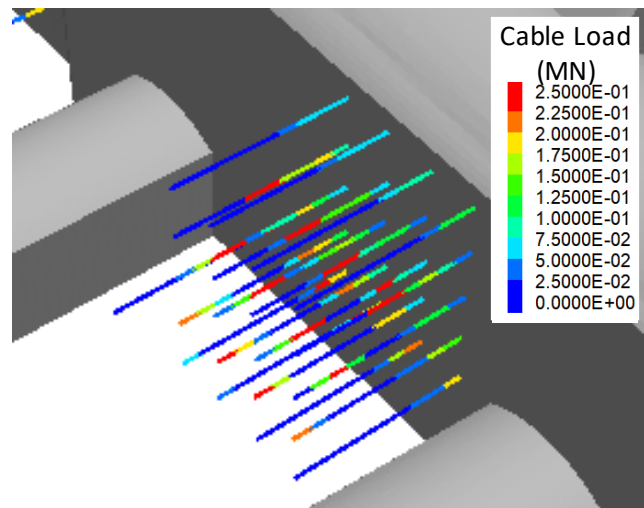
# Performance Based Design

## Case Example 1: Infrastructure Maintenance

### Design Outcome:

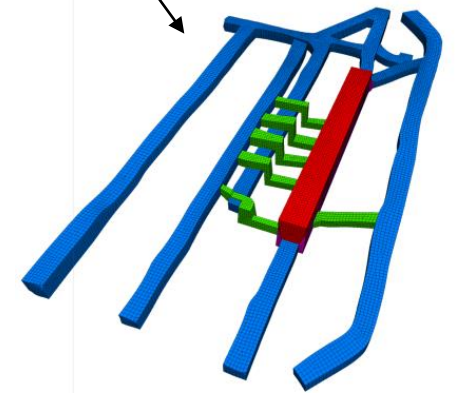
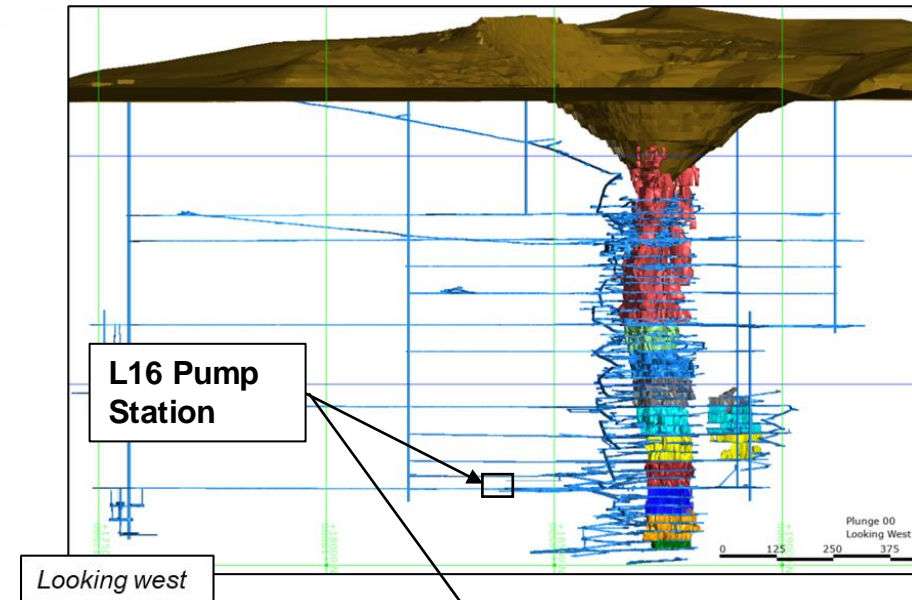
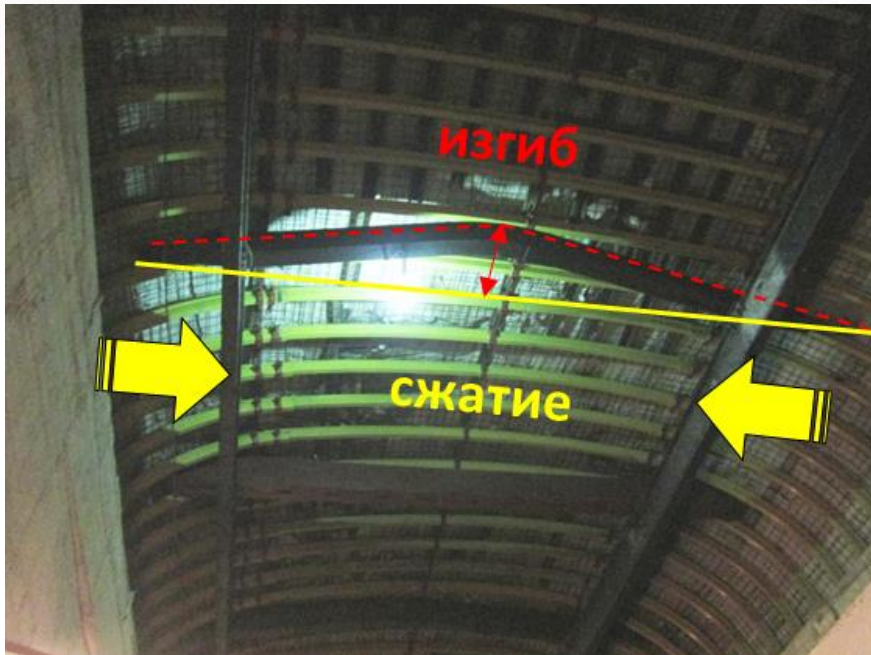
With a calibrated and verified numerical model, informed quantitative design decisions can be achieved.

1. Length of support elements according to damage depths
2. Support system capacities according to simulated loads.



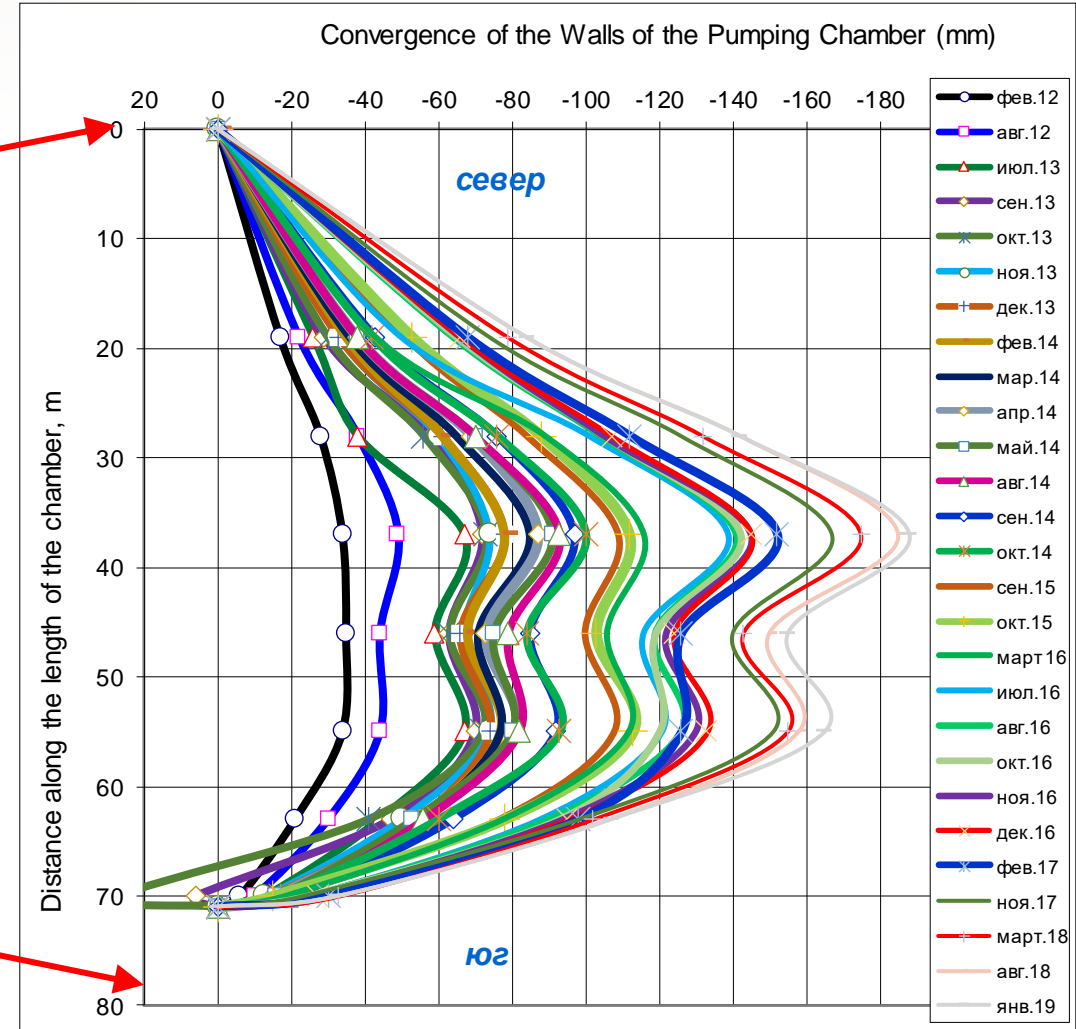
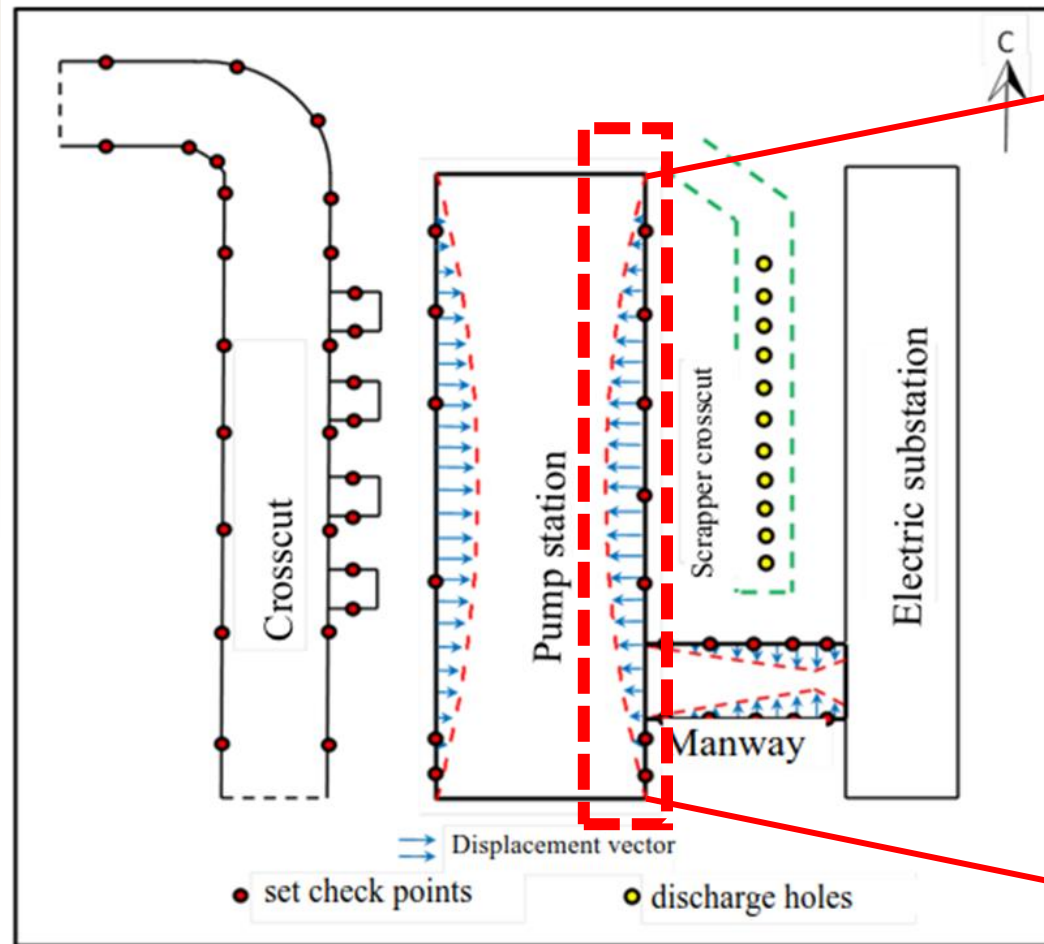
# Performance Based Design Case Example 2: Infrastructure Maintenance

**Case Study:** Understanding the ground reaction and failure mechanism to predict future ground reaction in a critical Pump Station (informing decisions to maintain or replace)



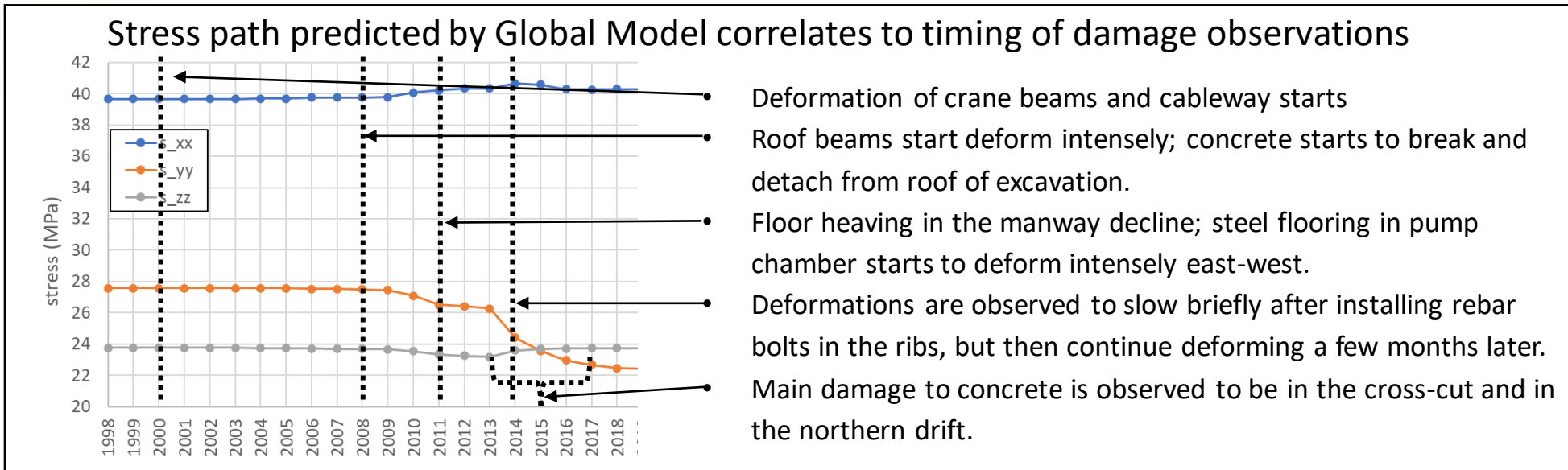
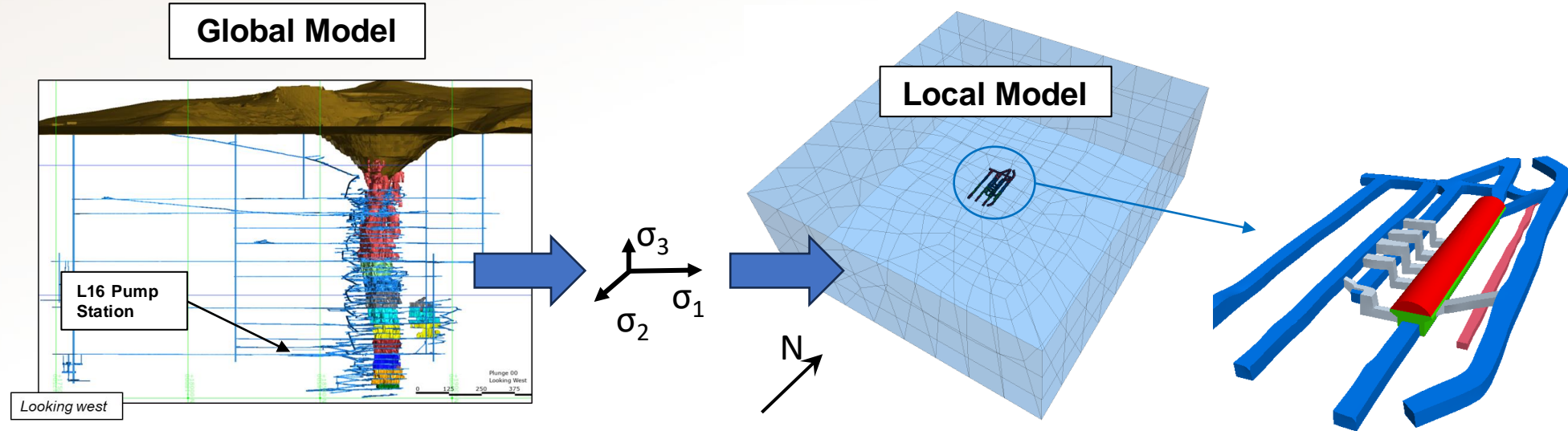
# Performance Based Design

## Case Example 2: Infrastructure Maintenance



# Performance Based Design Case Example 2: Infrastructure Maintenance

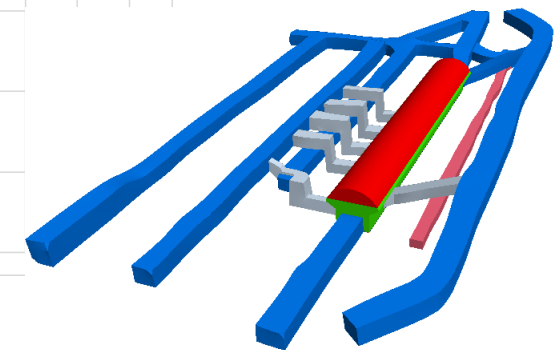
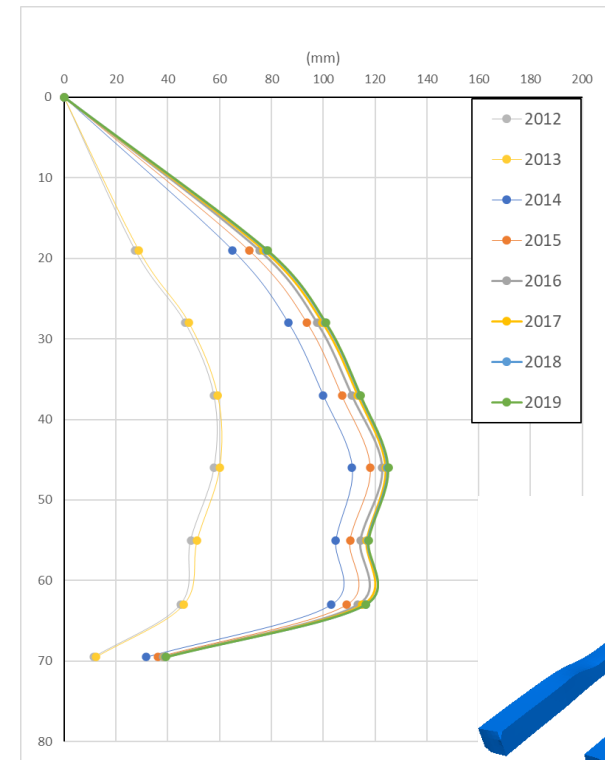
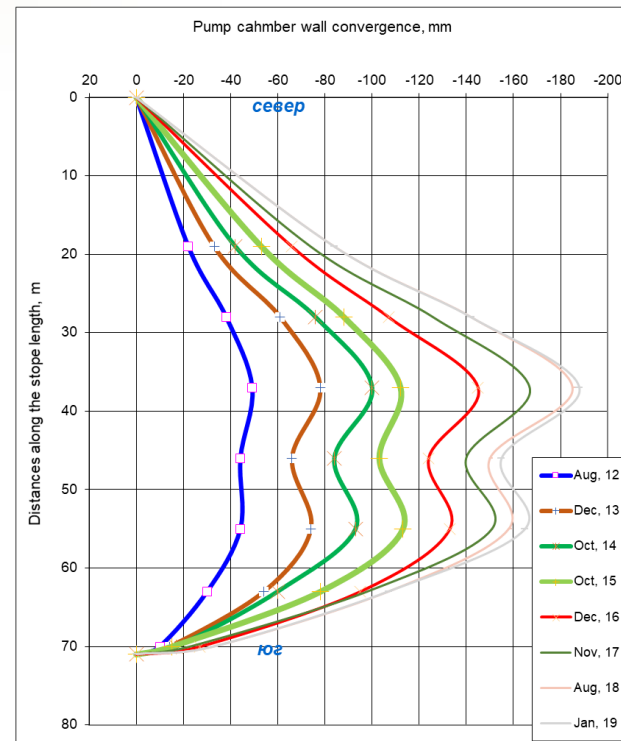
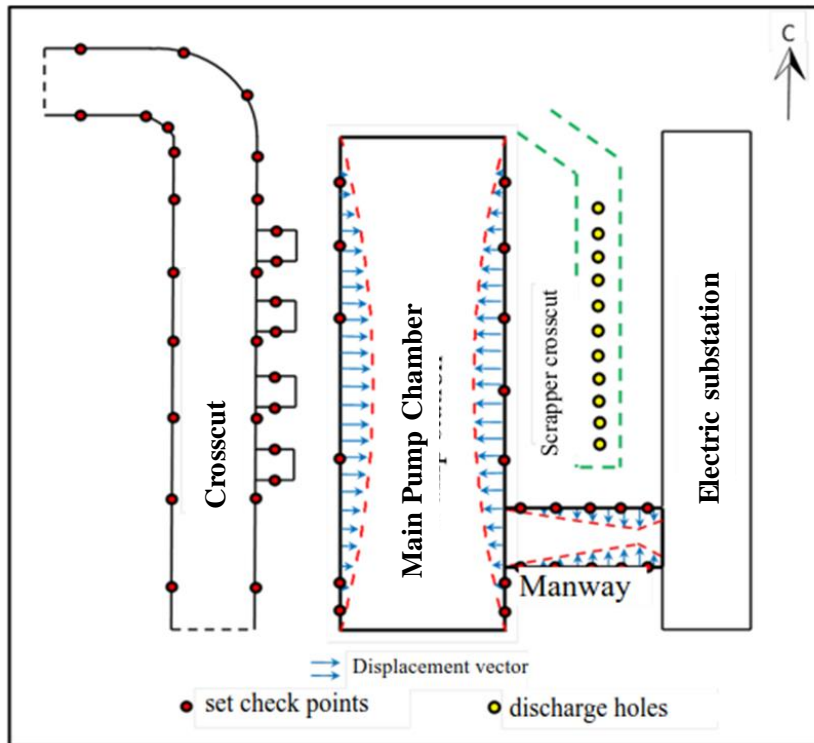
- Reliance on multi-scaling modelling to capture stress path conditions (global scale) and ground reaction / support system interaction (local scale)



# Performance Based Design

## Case Example 2: Infrastructure Maintenance

- Numerical simulations are calibrated to achieve simulated displacements which are compatible with observed displacements.

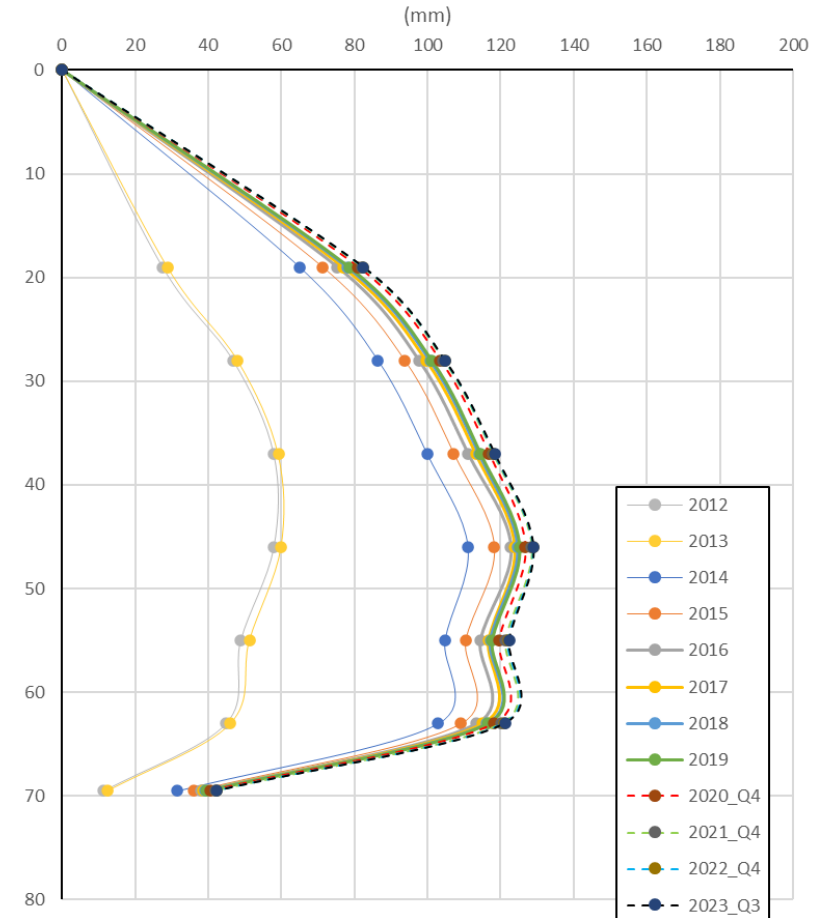
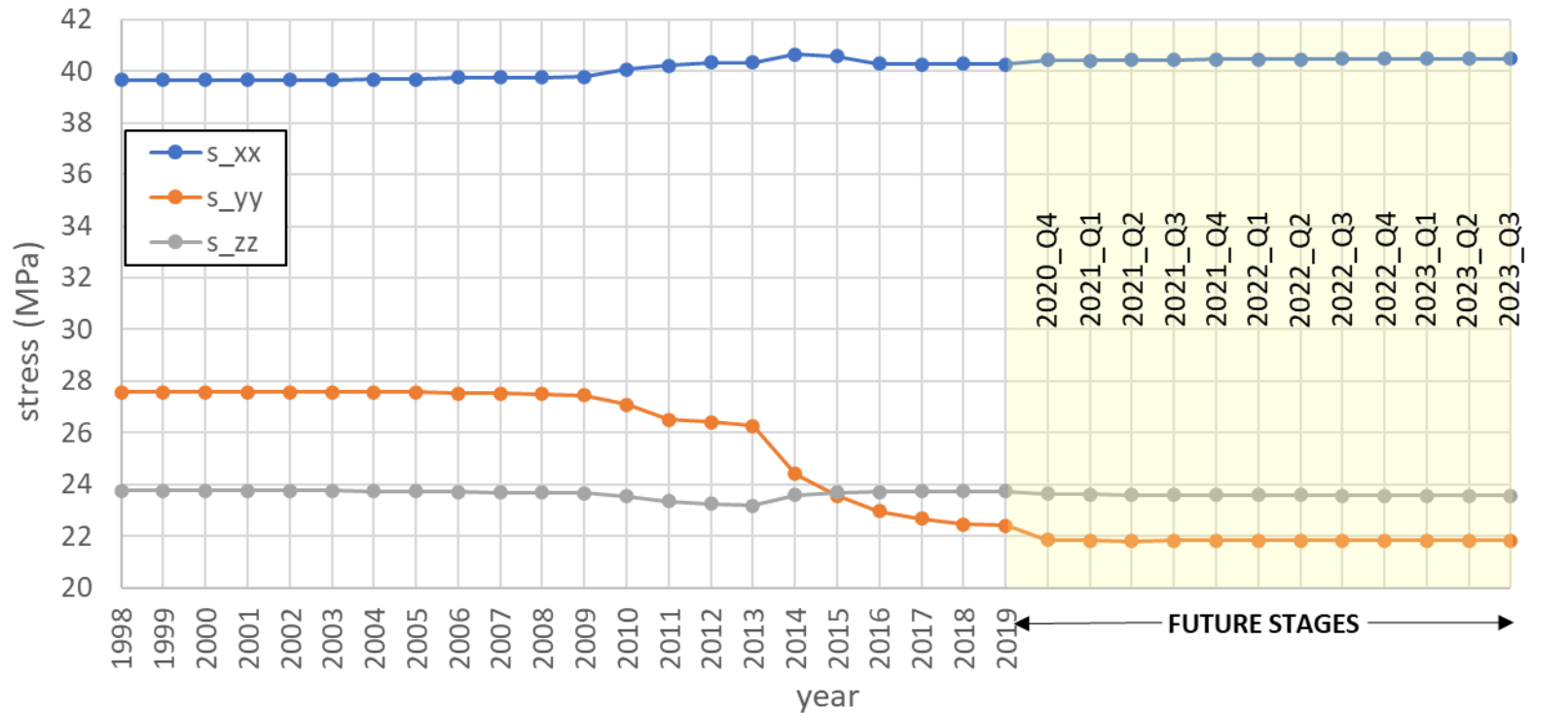




# Performance Based Design

## Case Example 2: Infrastructure Maintenance

Stress Path Predicted by Global Model



**Design Outcome:** Informed decision making for infrastructure maintenance vs. replacement. Forward simulations indicated no significant changes in induced stress (from global model) are observed for future stages.

Deformations drastically decelerate during future stages

# Performance Based Design: Stress and Seismic Hazard Management

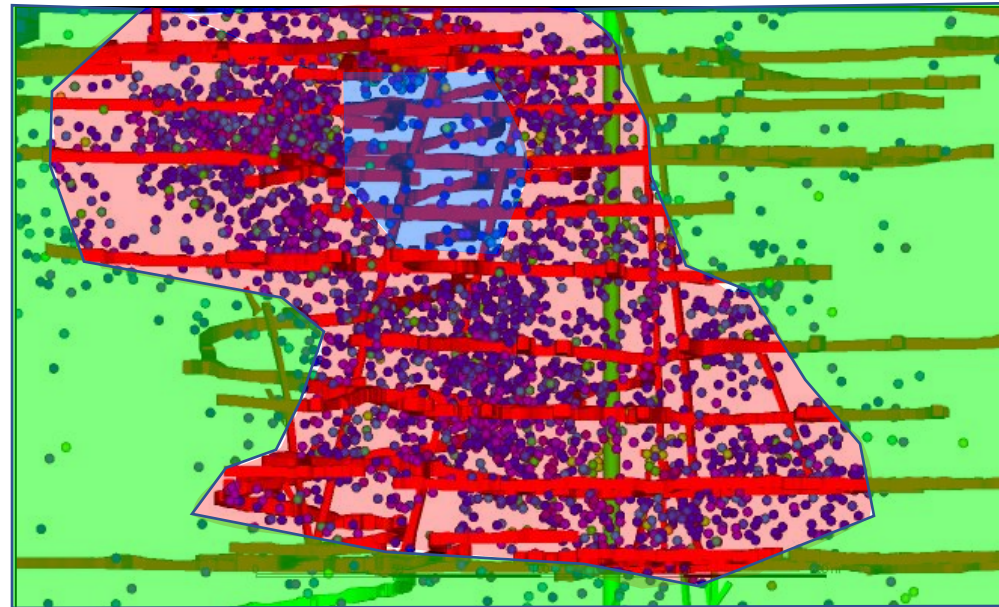
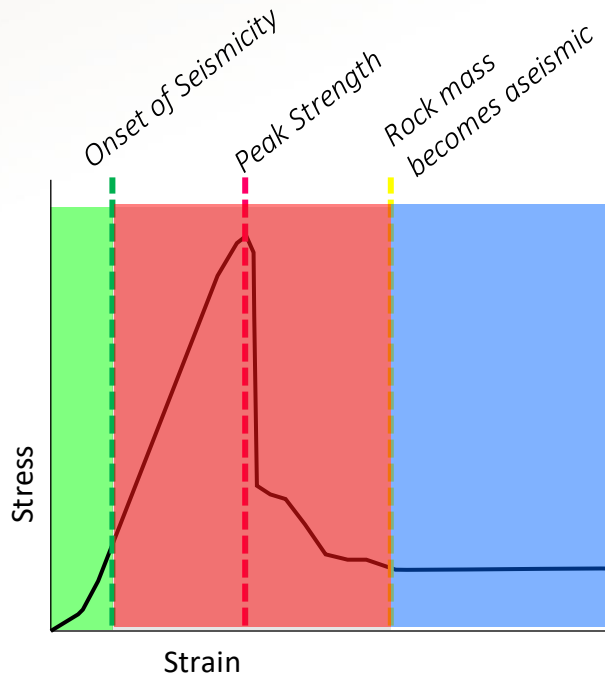
## Design Objective:

- Excavation damage introduced by seismic events (rockbursts) can impact:
  - Worker safety (injuries / fatalities)
  - Production (equipment damage / rehabilitation / loss of access)
  - Project economic (resource recovery)
- It is critical that conditions with elevated seismic hazard be identified
  - Mining in deeper and / or high-stress regimes
  - Brittle, hard rock conditions
- An understanding of seismic hazard allows for informed decision making with respect to establishing strategic and tactical controls.



# Performance Based Design: Stress and Seismic Hazard Management

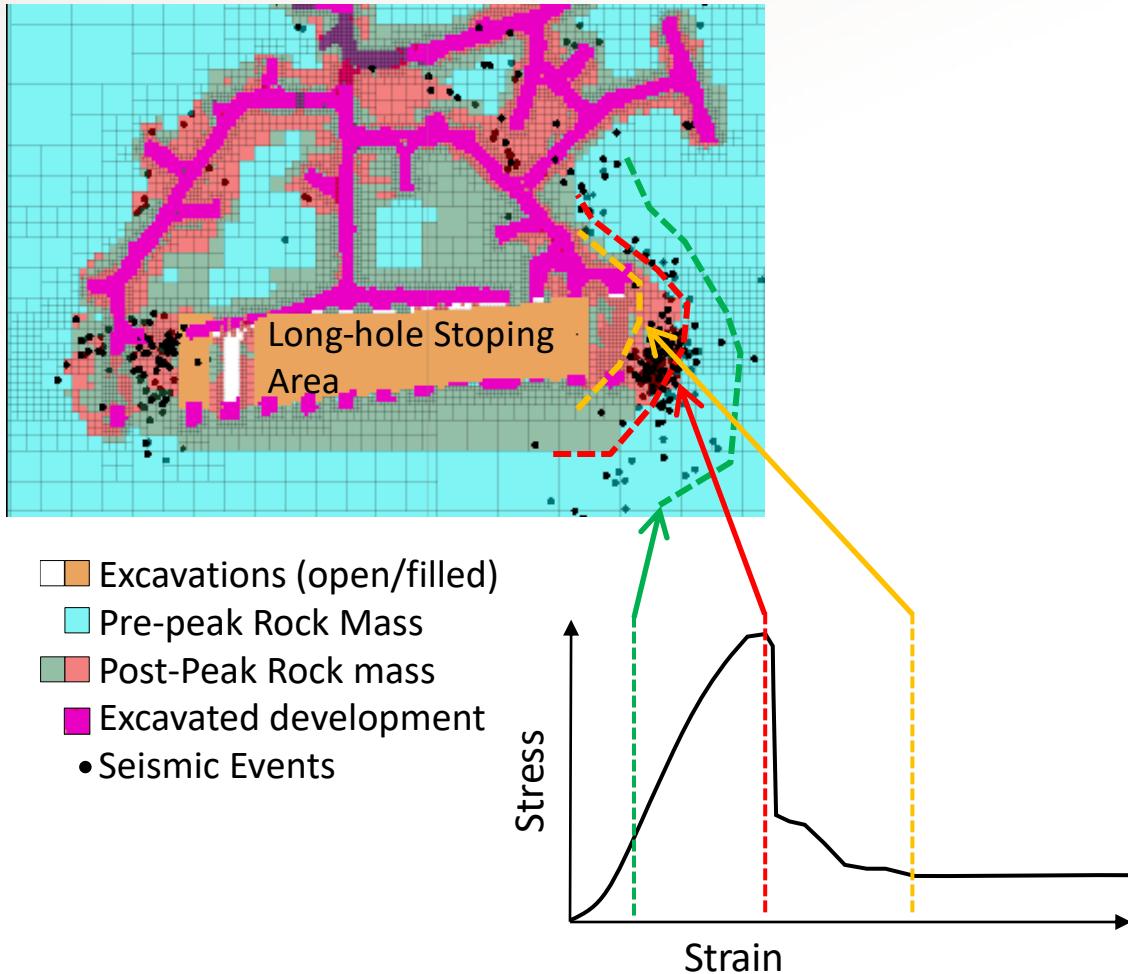
- Micro-seismic data can provide the fully 3-dimensional volumetric extent of where a rock mass is transitioning through the yielding process, and characterize the energy released during fracturing and deformation.



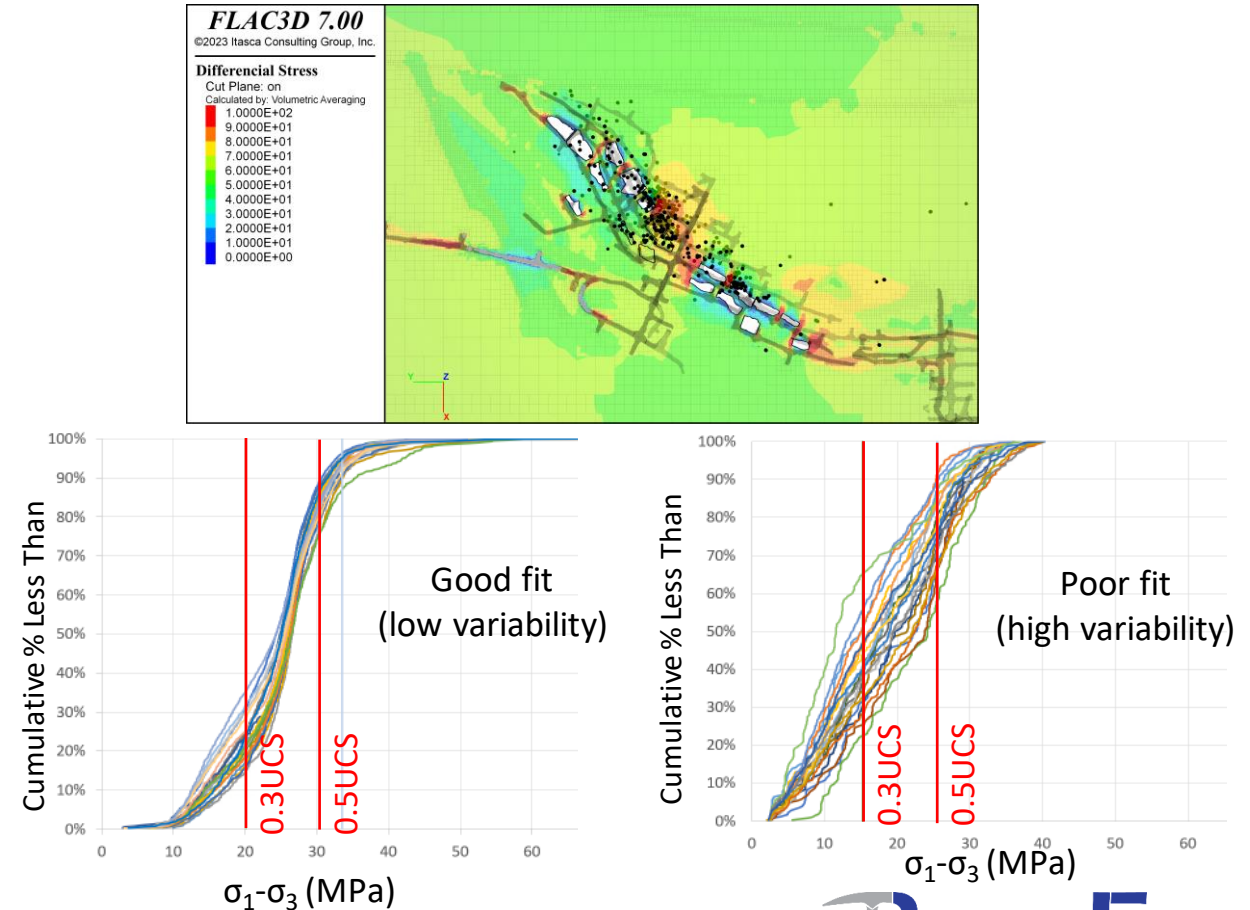
# Performance Based Design: Stress and Seismic Hazard Management

- Performance based design in stress and seismic hazard management requires numerical stress modelling

Qualitative

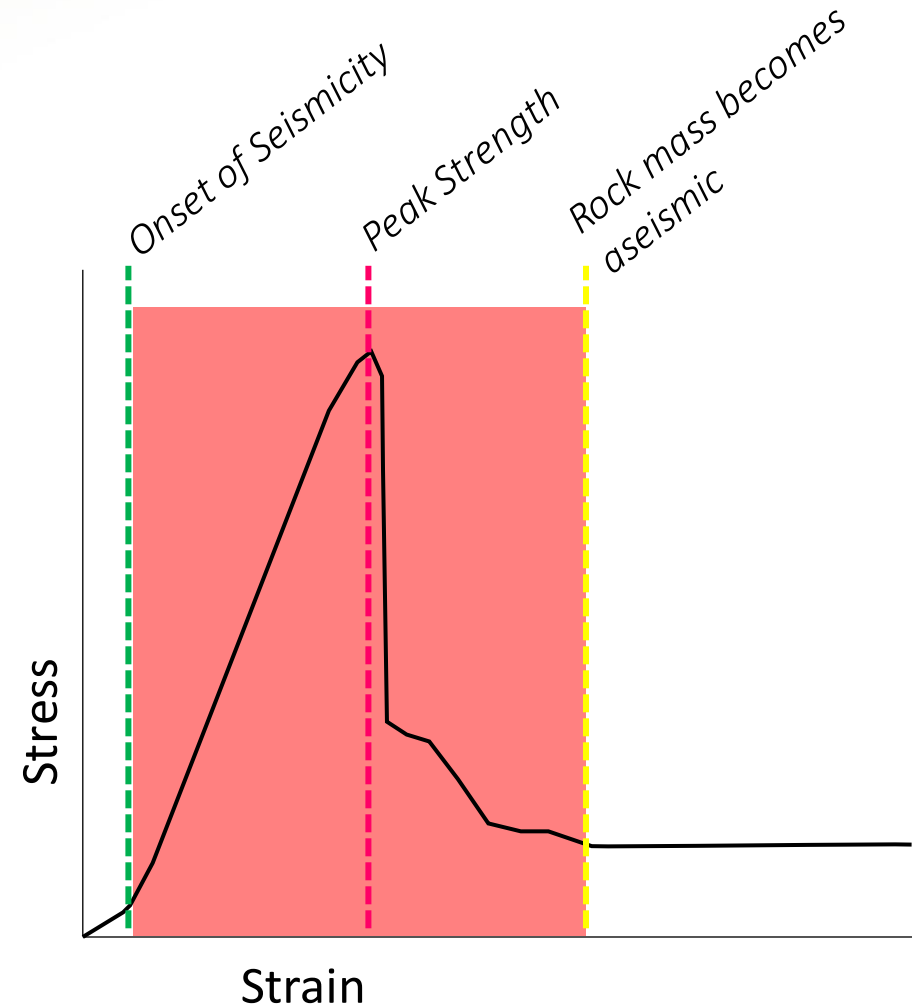


Quantitative



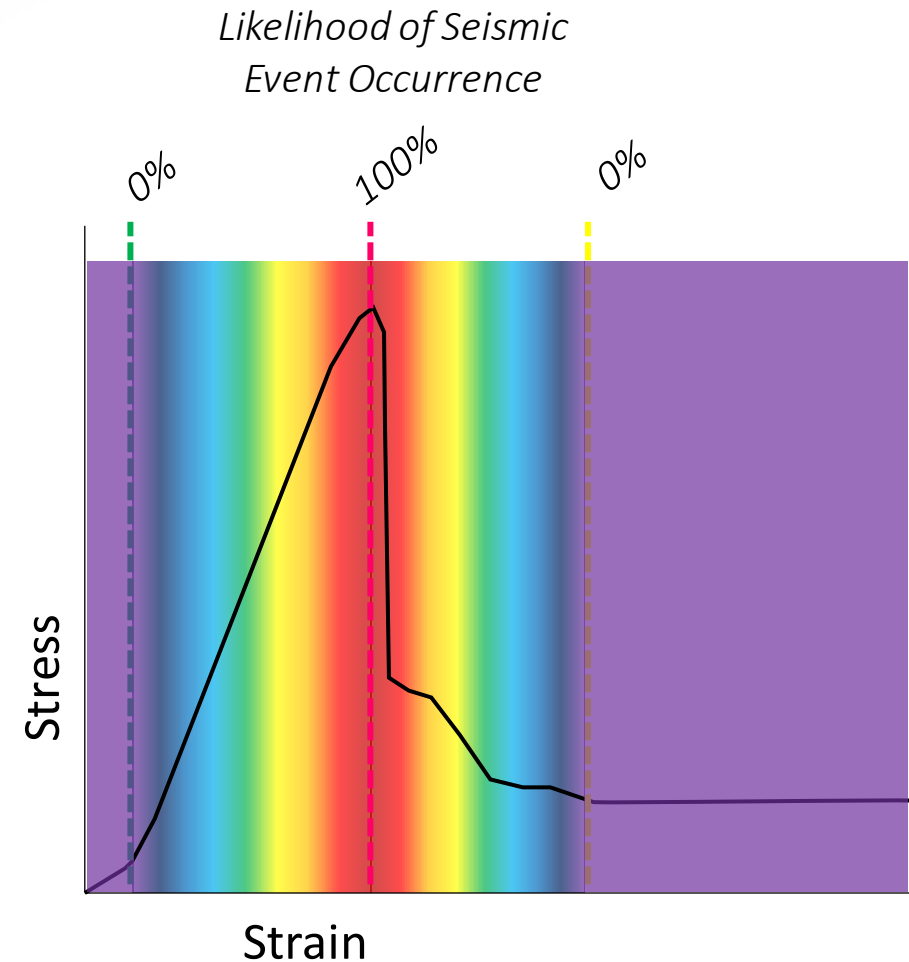
# Performance Based Design: Stress and Seismic Hazard Management

- Numerical models are calibrated to resolve a set of numerical inputs that reproduce observed behavior.
- Forward predictions of seismic potential can be made based on stress, strain and yield state conditions.



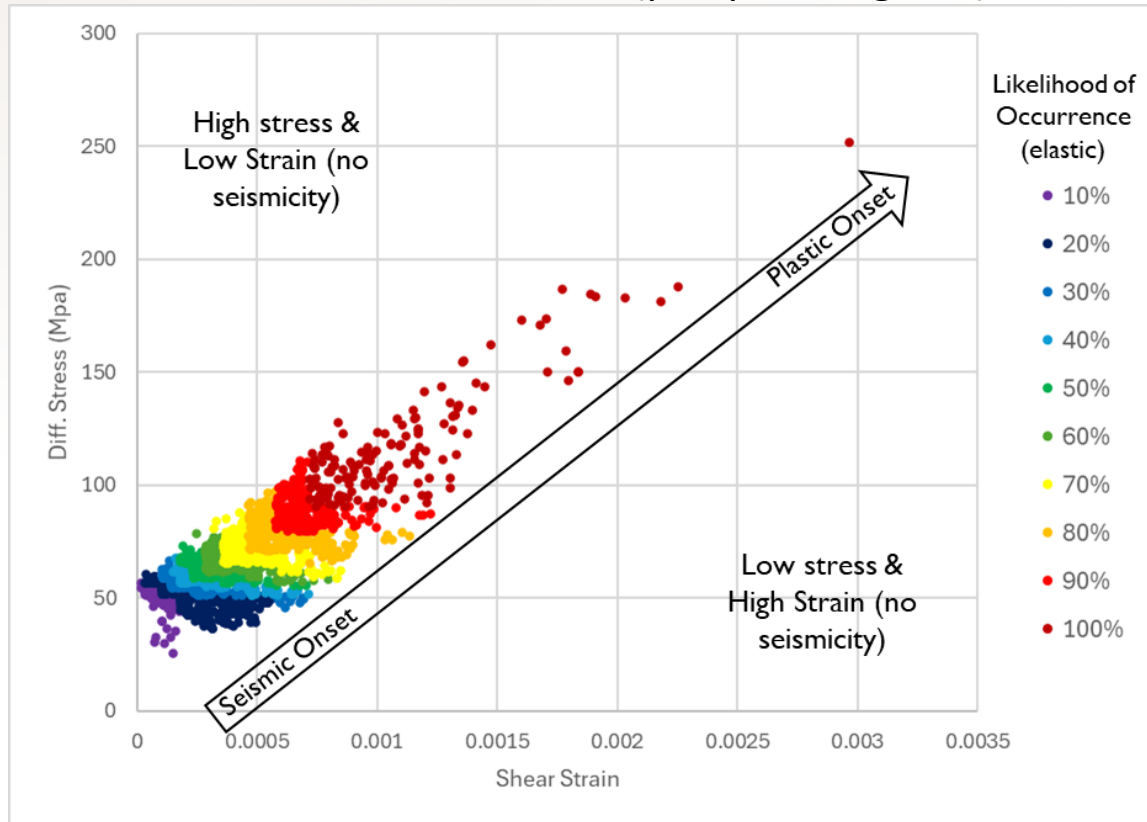
# Performance Based Design: Stress and Seismic Hazard Management

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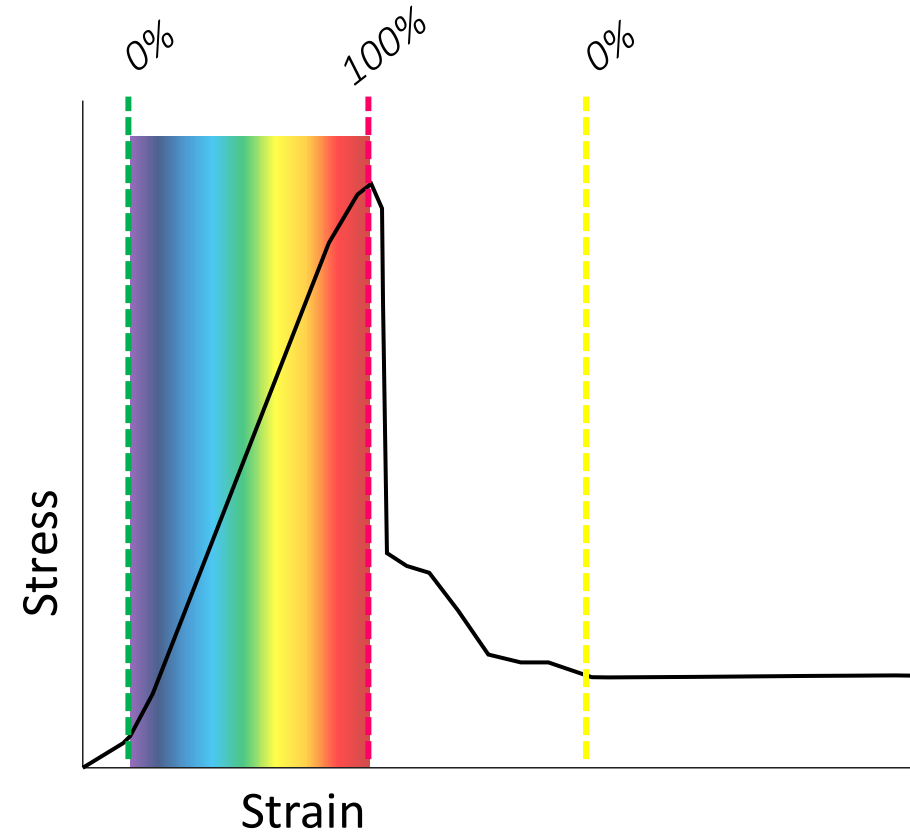


# Performance Based Design: Stress and Seismic Hazard Management

Stress and strain states sampled in numerical model at seismic event locations (pre-peak regions)

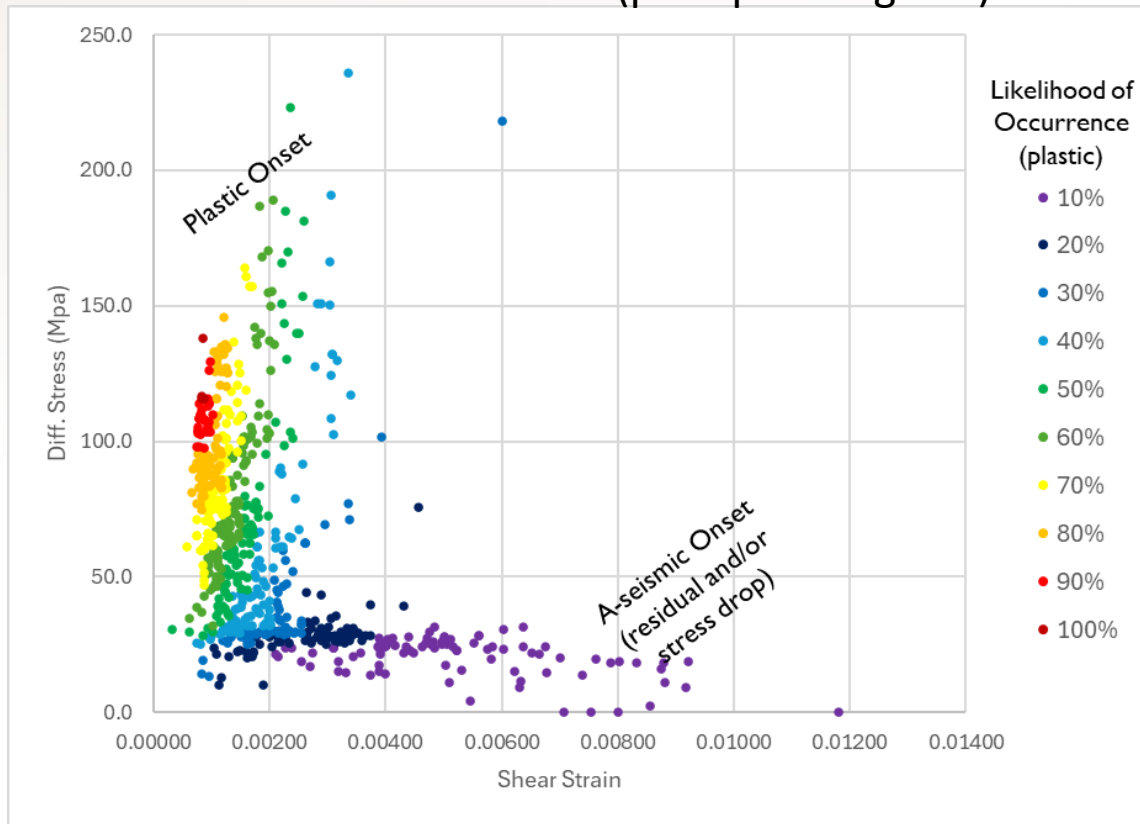


Likelihood of Seismic Event Occurrence

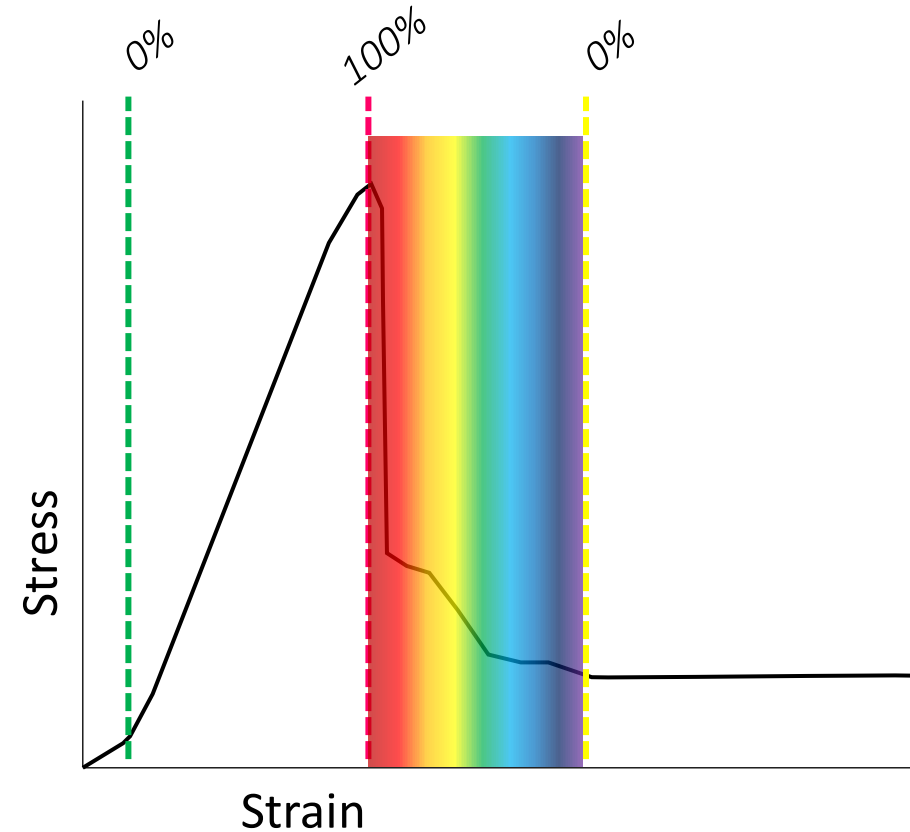


# Performance Based Design: Stress and Seismic Hazard Management

Stress and strain states sampled in numerical model at seismic event locations (post-peak regions)



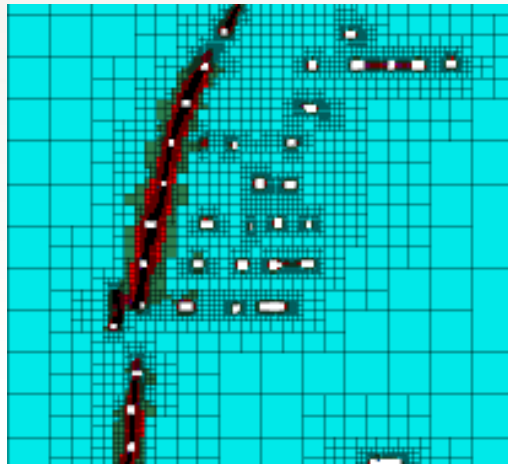
Likelihood of Seismic Event Occurrence





# Performance Based Design: Stress and Seismic Hazard Management

Yield State



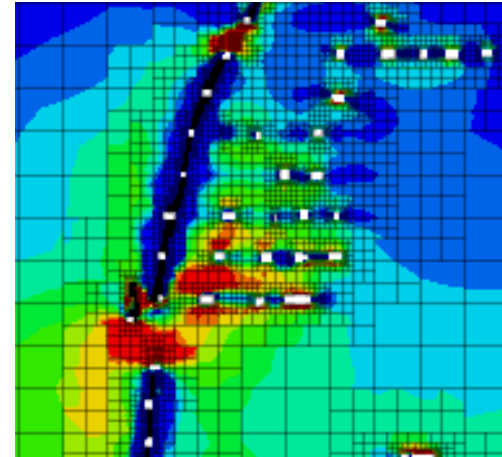
+

Strain State



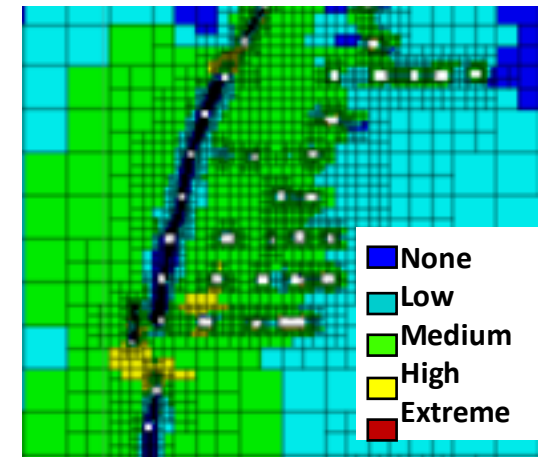
+

Stress State



=

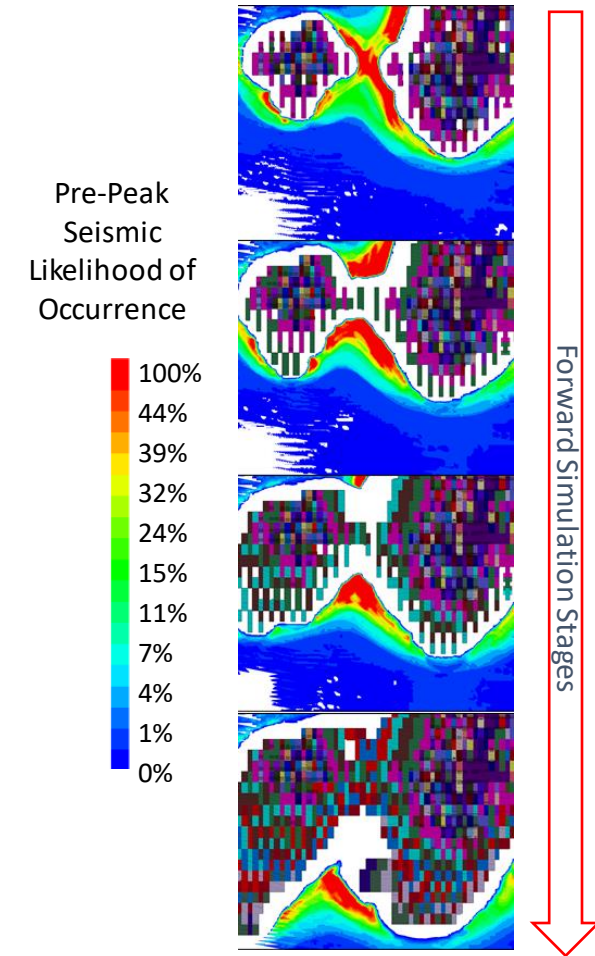
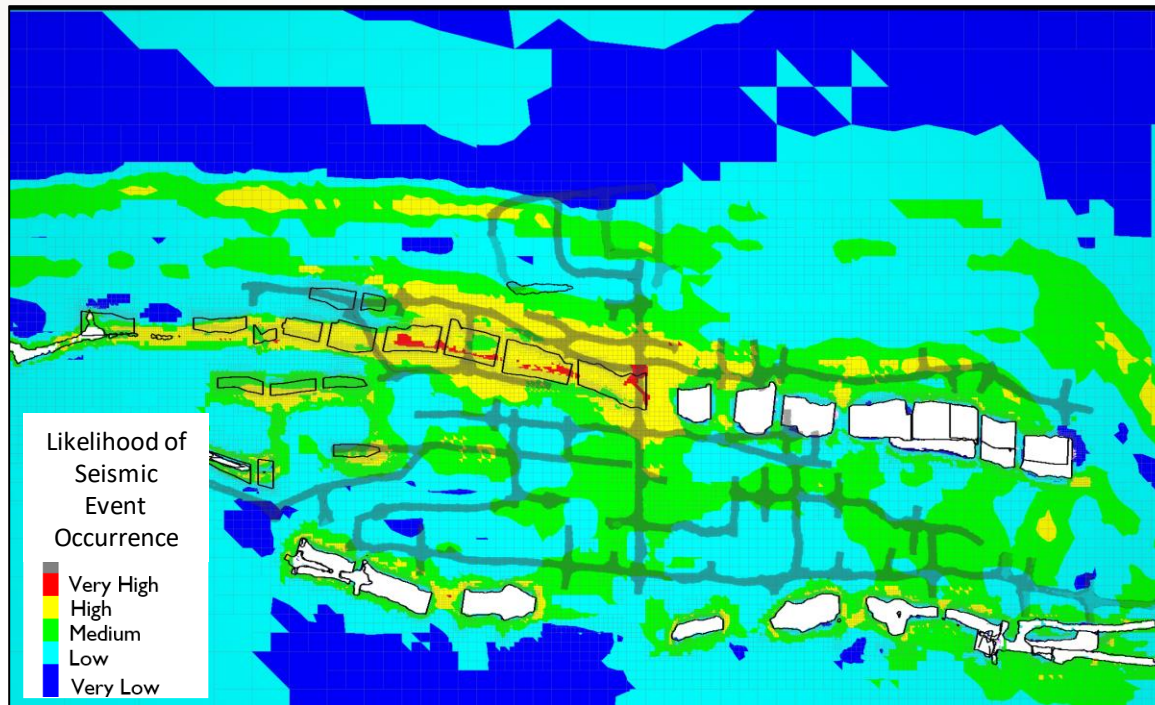
Hazard Prediction



- None
- Low
- Medium
- High
- Extreme

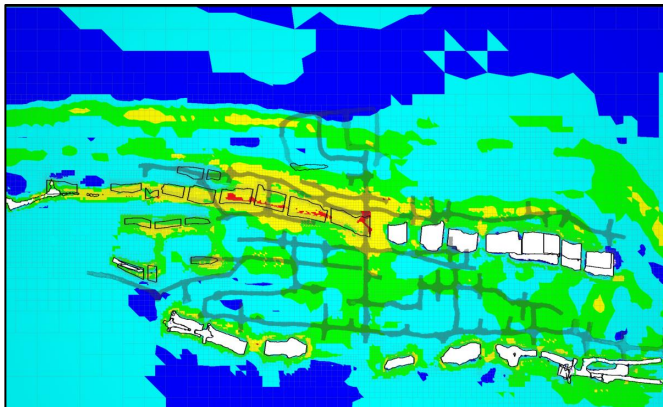
# Performance Based Design: Stress and Seismic Hazard Management

**Design Process Outcome:** Calibrated numerical outputs can be statistically resolved to provide predictive capabilities for seismic hazard forecasting (in space, and time over the life of mine)



# Practical Applications of Seismic Hazard Prediction

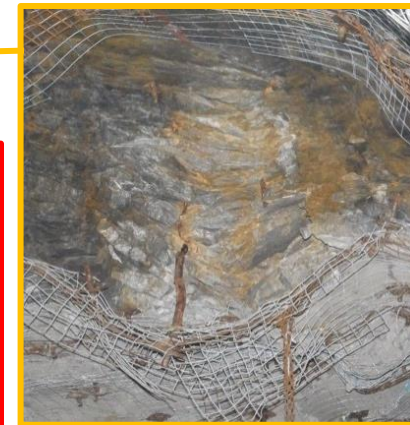
**Design Process Outcome:** When calibrated and verified models are paired with observations of excavation performance, predictive tools provide facilitate planning and design for optimized future risk mitigation



| Description        | Est. Depth of Yield | Risk Management  |
|--------------------|---------------------|--|
| No visible damage  | 0 m                 | No Action  |
| Minor damage       | 0 – 0.2 m           | Observe  |
| Moderate Damage    | 0.2 – 1.0 m         | Minor Rehabilitation, minor operational delays             |
| Significant damage | 1.0 – 2.0 m         | Significant Rehabilitation, significant operational delays |
| Severe damage      | >2 m                | Major Rehabilitation, potential loss of access             |

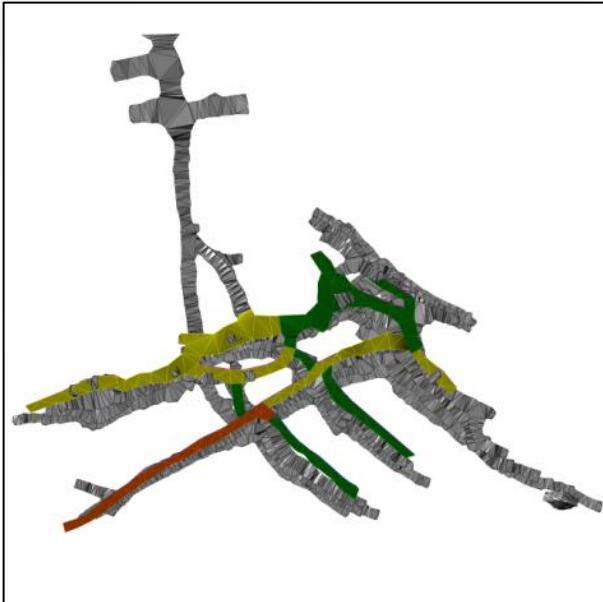
Ground Response

Implication to Design and Operations



# Practical Applications of Seismic Hazard Prediction

**Design Process Outcome:** Forward predictions of hazard related to high stress and seismic ground reaction provides opportunity for optimized and domained application of risk mitigating controls



| Risk Level             | LOW          | MODERATE           | HIGH              |                 |                 | SEVERE      |
|------------------------|--------------|--------------------|-------------------|-----------------|-----------------|-------------|
| Anticipated Seismicity | $M_N < -0.5$ | $-0.5 < M_N < 0.5$ | $0.5 < M_N < 1.5$ |                 |                 | $1.5 < M_N$ |
| Anticipated Damage     | S0 – S1      | S2                 | S3+               |                 |                 | S3+         |
| Ground Reaction        | N/A          | N/A                | Squeezing         | Strain Bursting | Pillar Bursting | Bursting    |

Ground response

Support Standard

Standard Support

Class C

Class B

Class A

Class A

Implication to Design and Operations

Re-entry Time

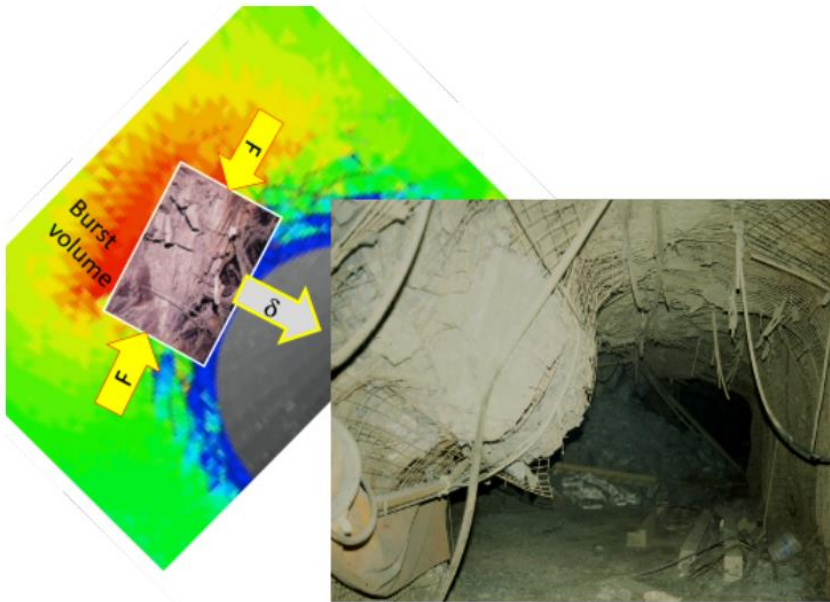
At background

5 hours after background

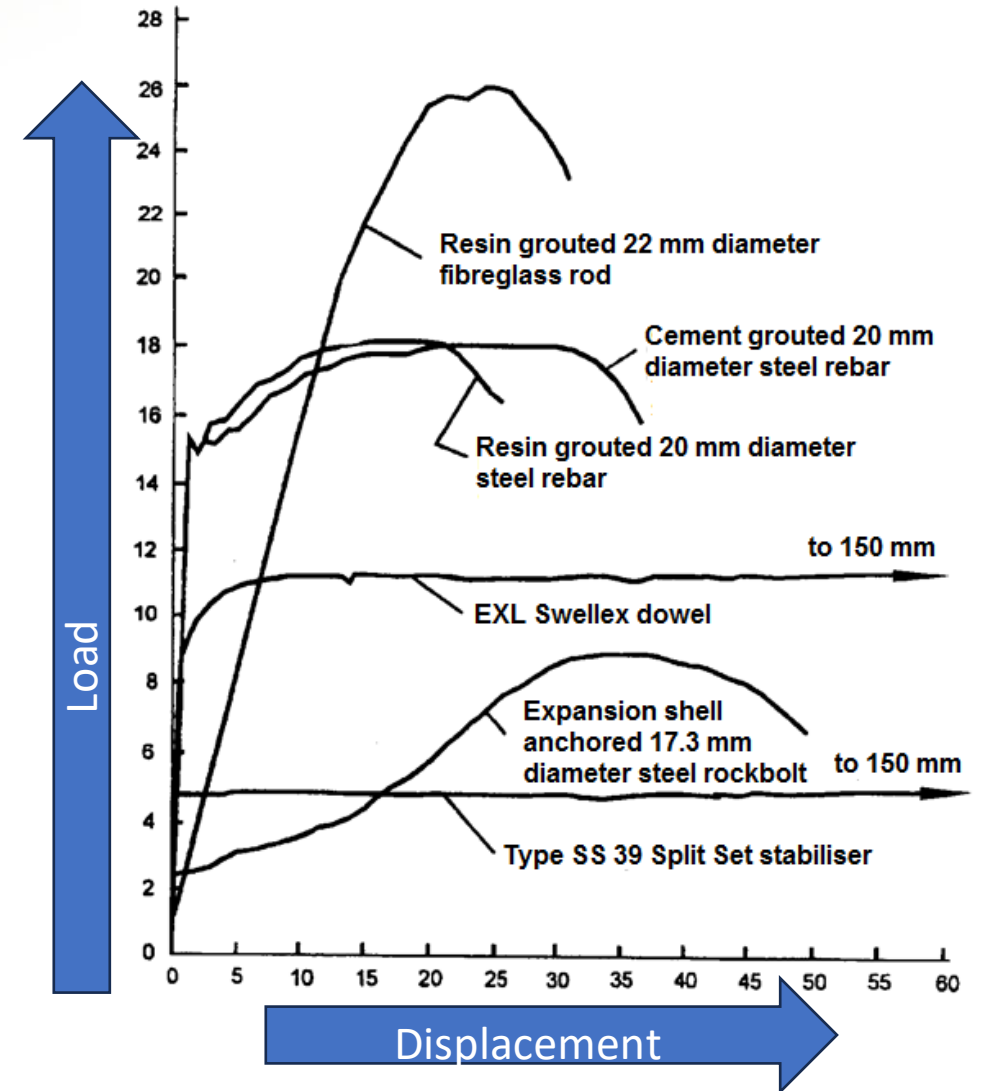
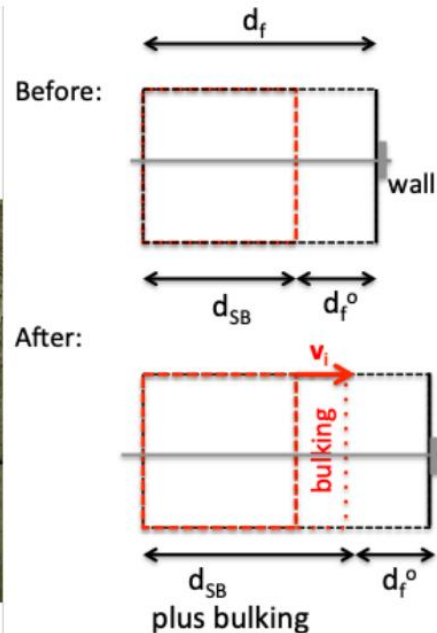
24 hours after the event or 5 hours after background

# Performance Based Design for Ground Support Maintenance and As-built Capacity

- Support displacement capacity is consumed as deformation occurs after support installation.
- Performance based support design must account for remnant capacity, rather than the installed capacity.
- Ground deformation is a critical component of support system design and maintenance.



Kaiser & Moss (2021)

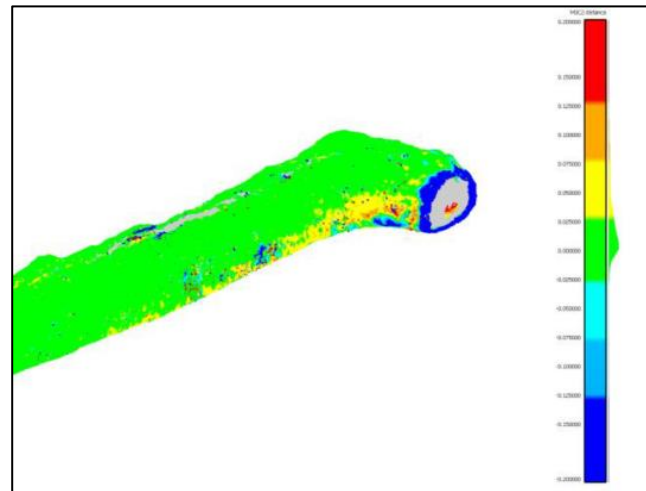
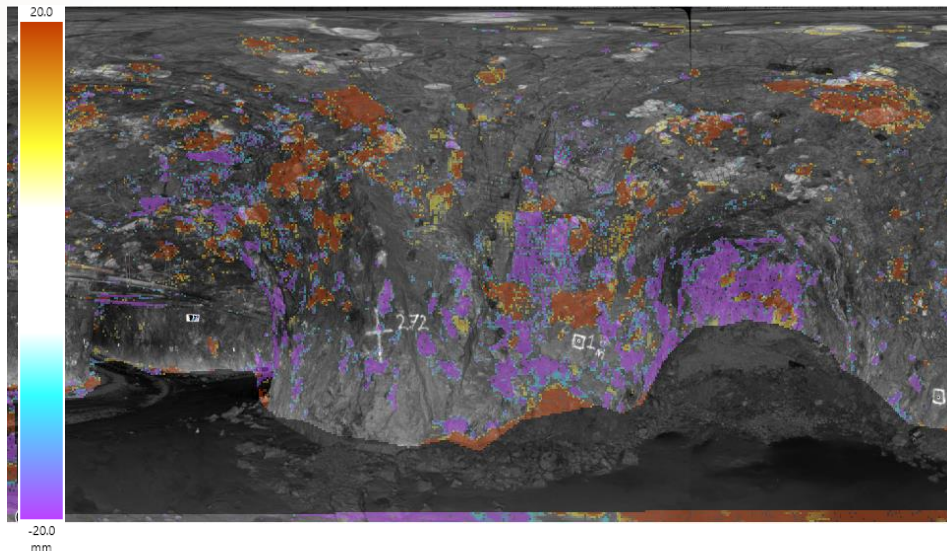


# Performance Based Design for Ground Support Maintenance and As-built Capacity

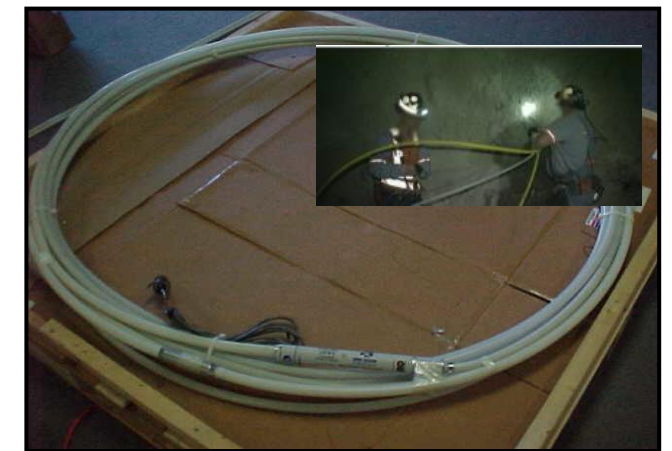
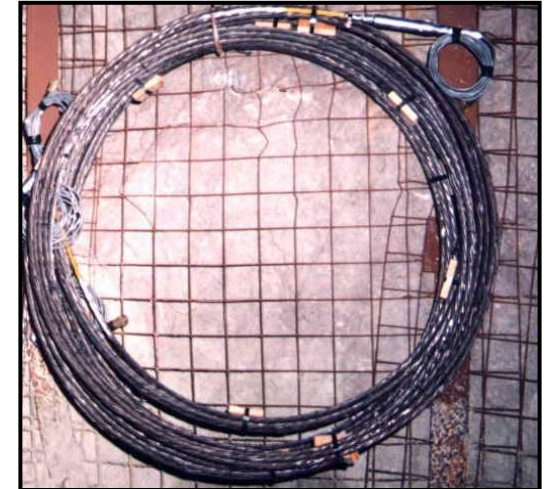
Deformation monitoring can be achieved by a range of tools:

- Laser scanning and sensing technologies
- Borehole instruments (multi-point borehole extensometers)
- Instrumented ground support elements (ex. Smart cables)
- and more

## Surficial Displacements

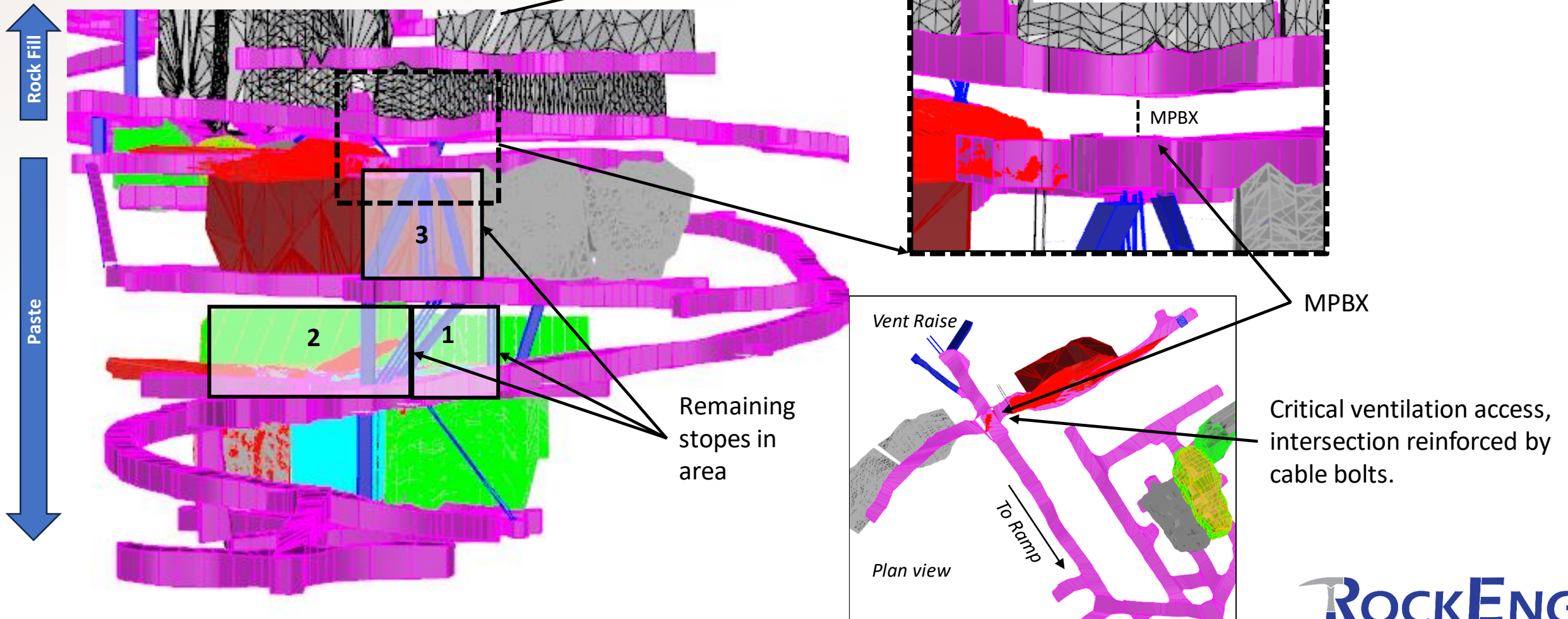


## Down Hole Instruments

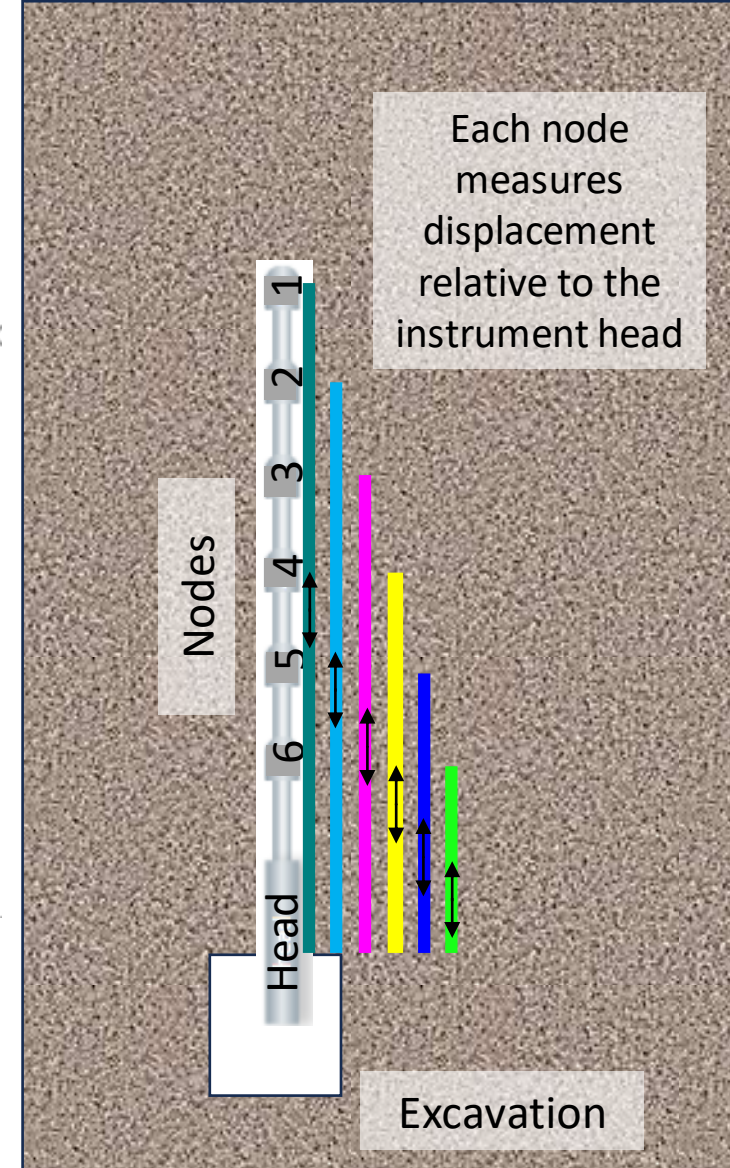
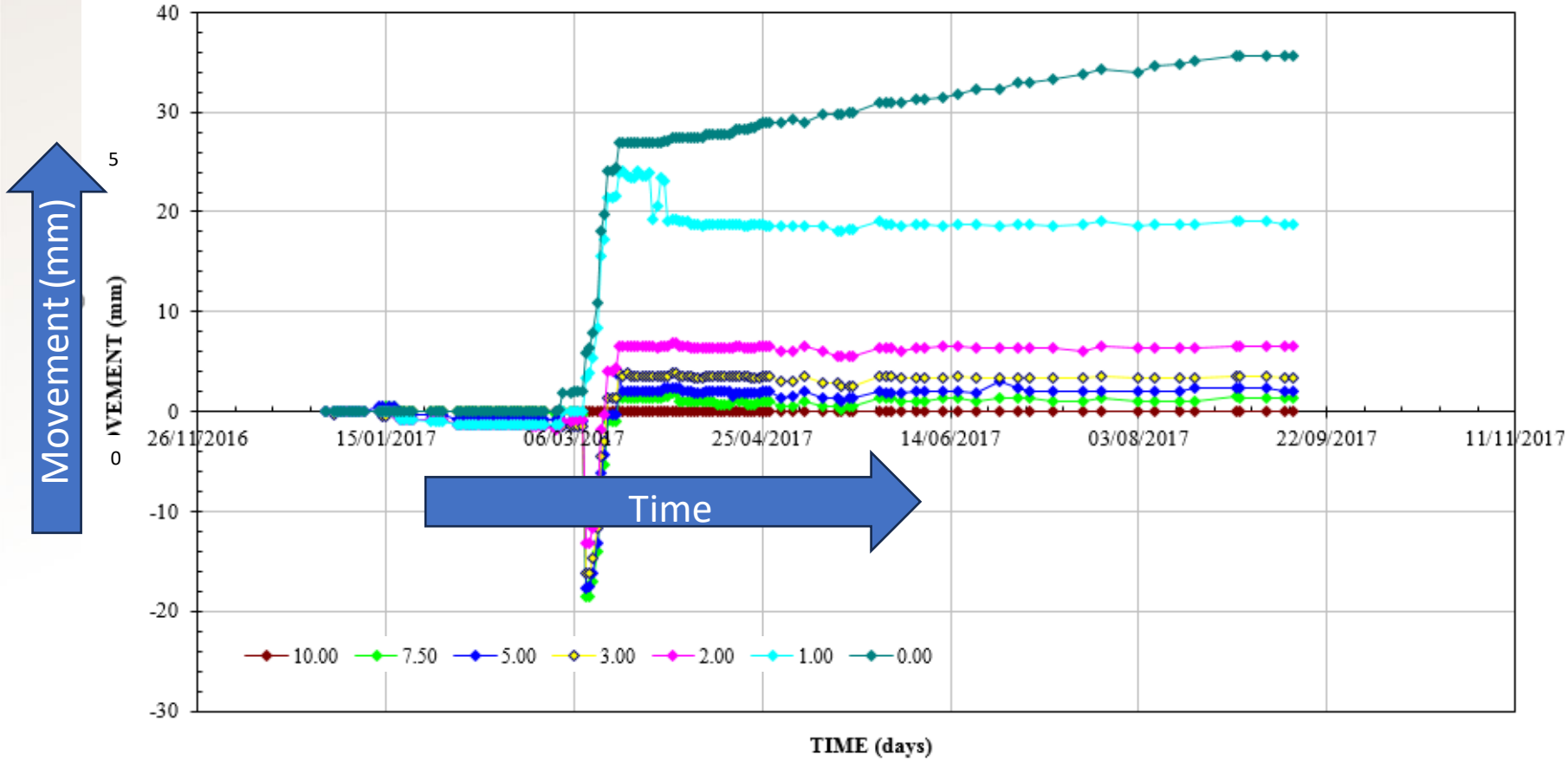


# Performance Based Design Case Example: Ground Support

**Case Challenge:** Survivability of critical ventilation access within stress loaded pillar

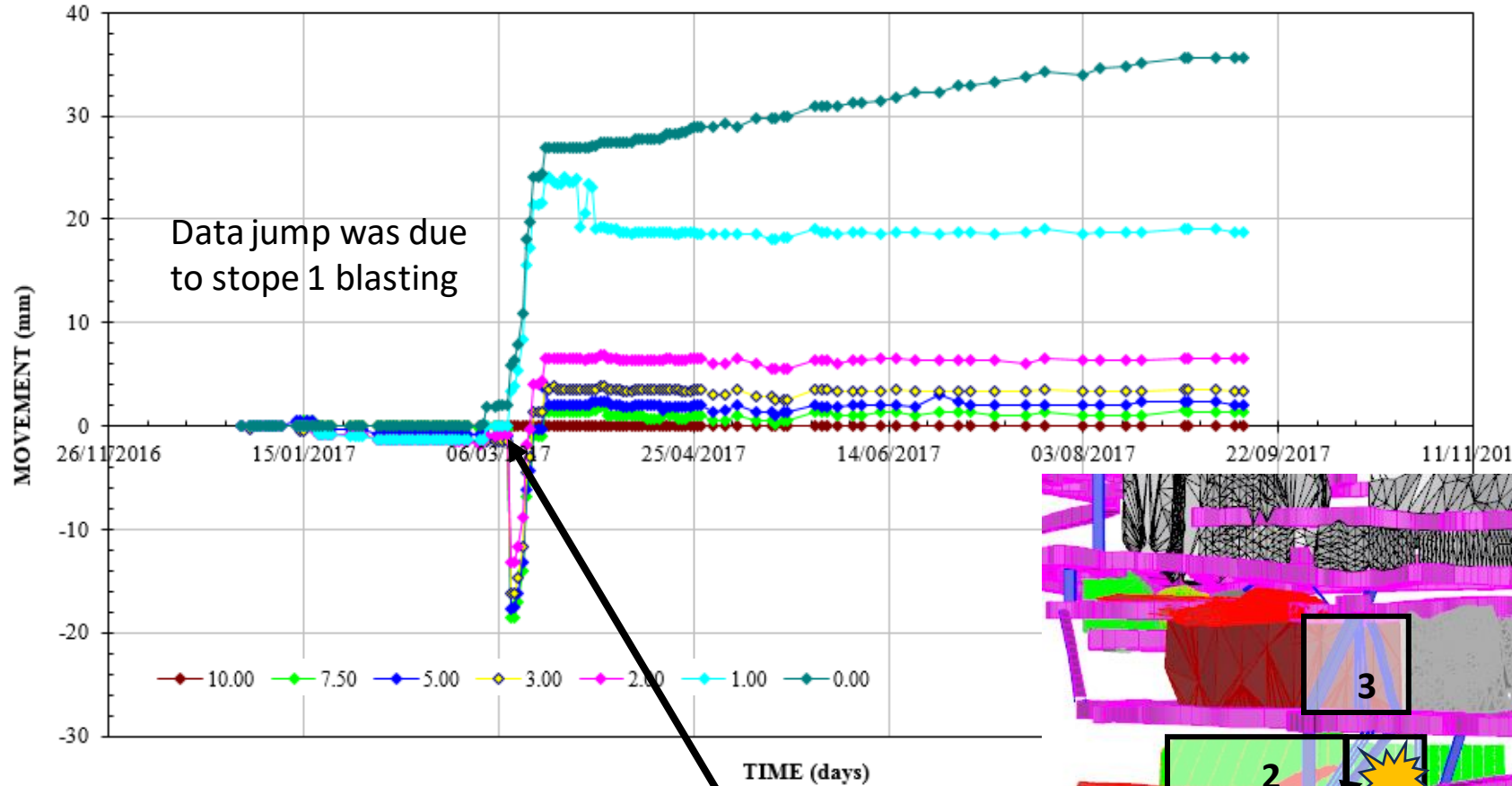


# Performance Based Design Case Example: Ground Support

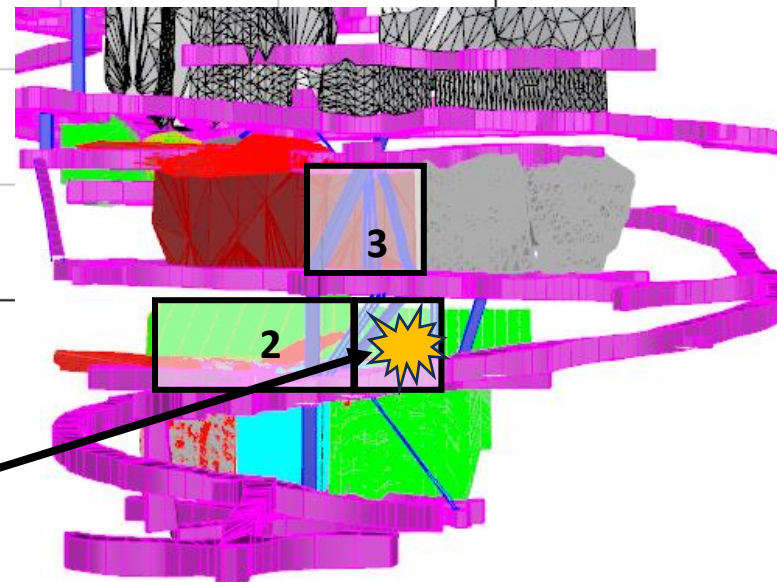




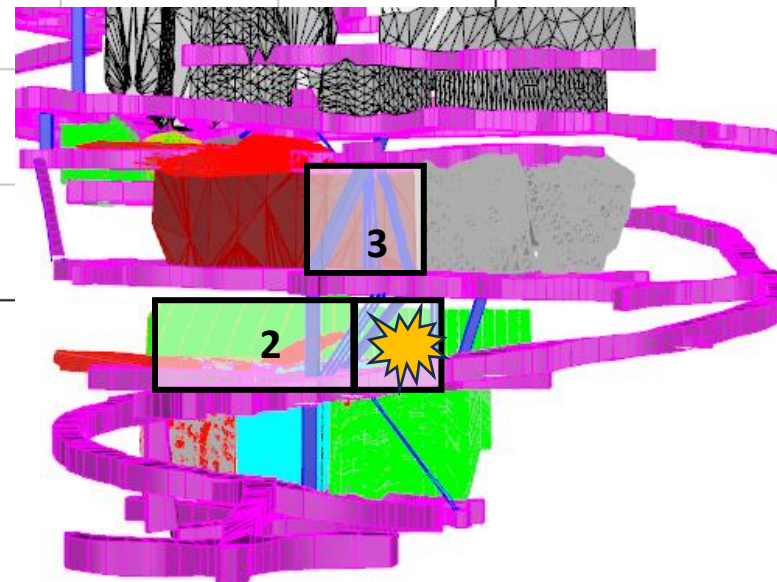
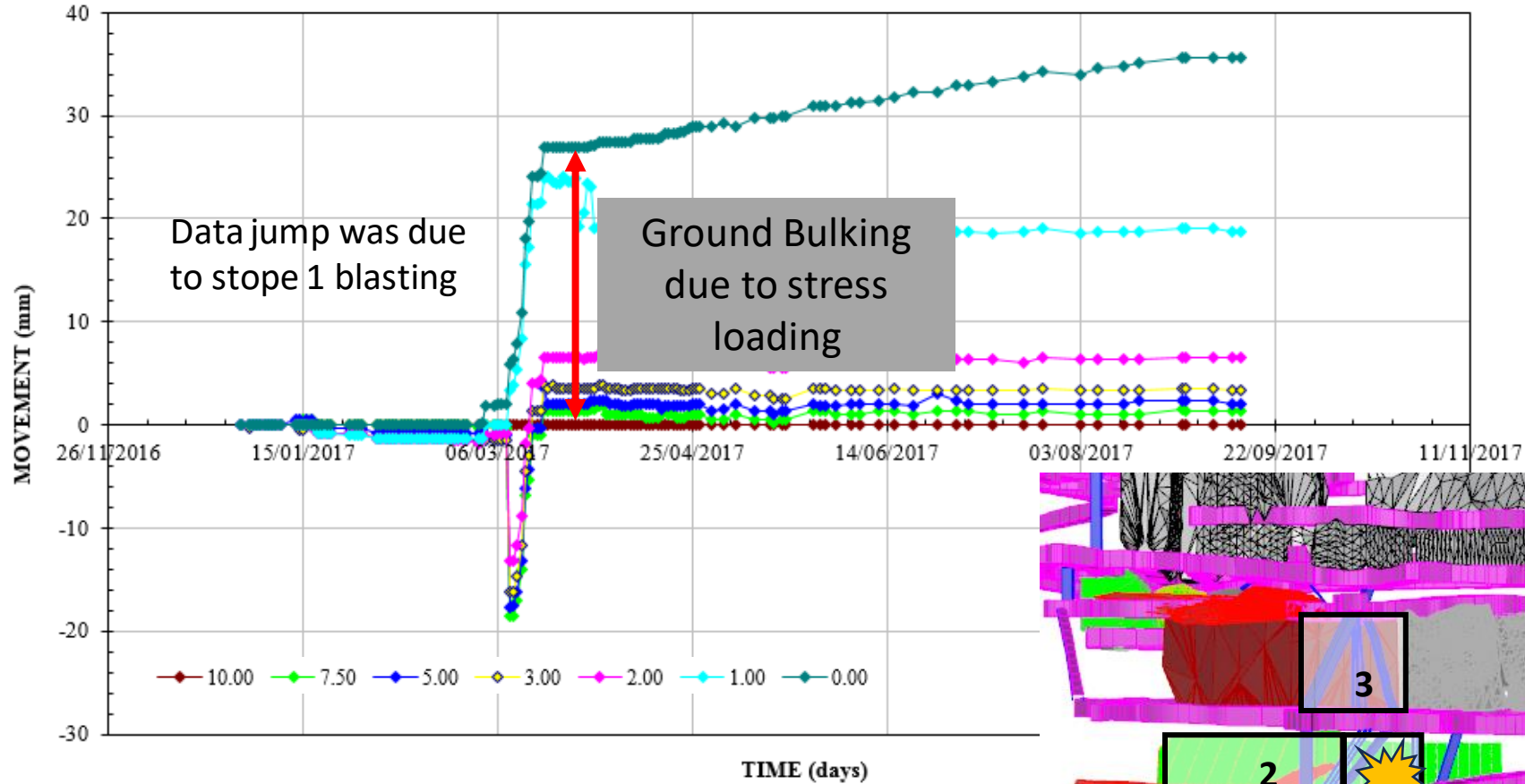
# Performance Based Design Case Example: Ground Support



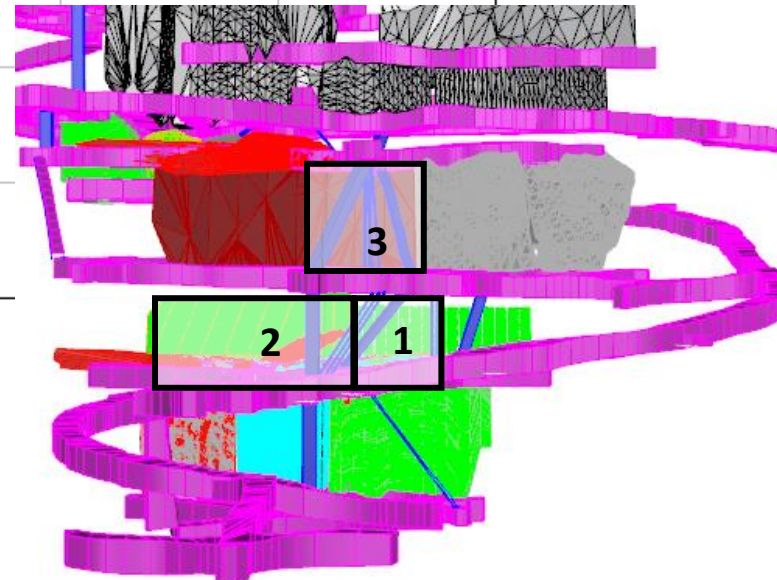
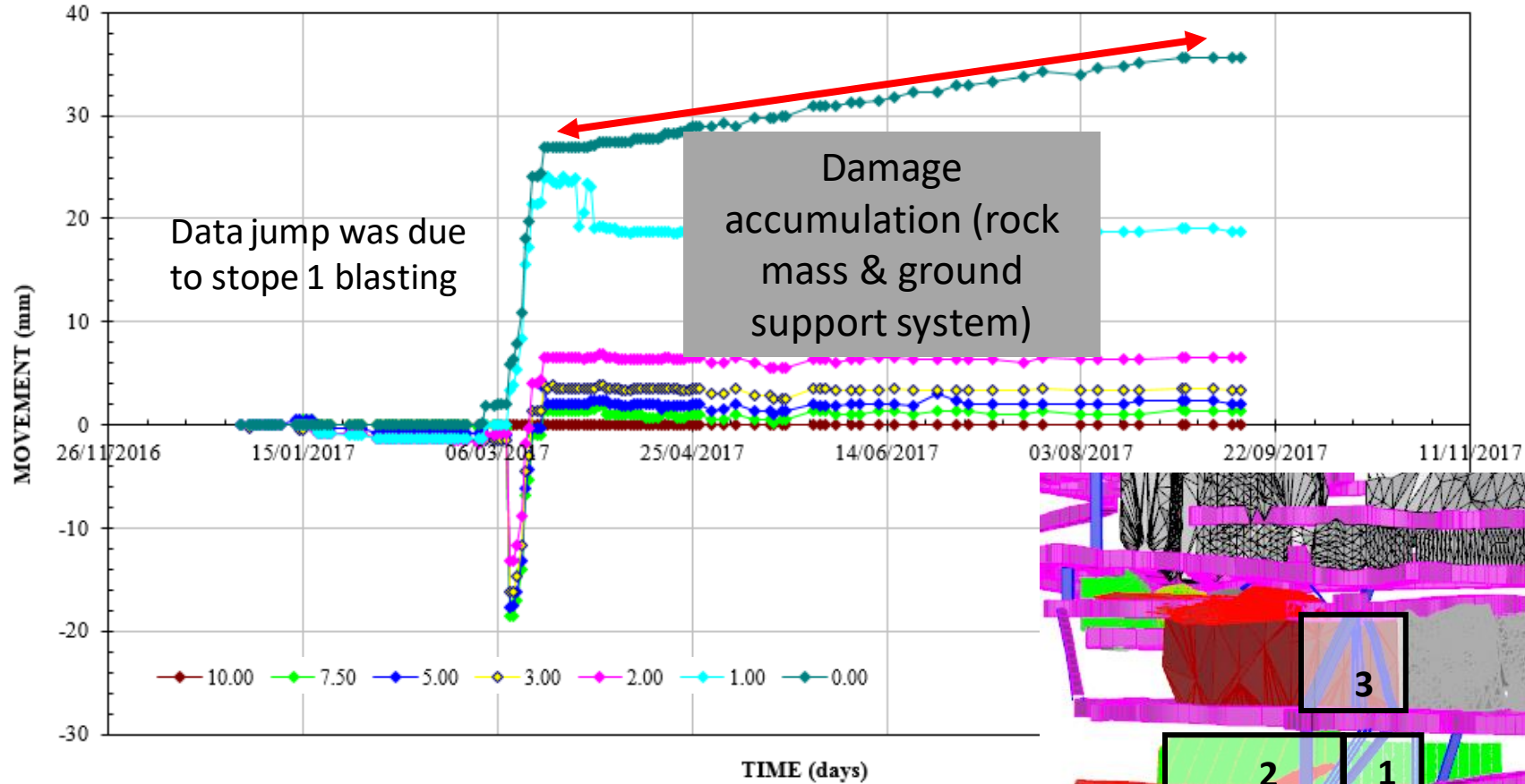
# 1 is blasted



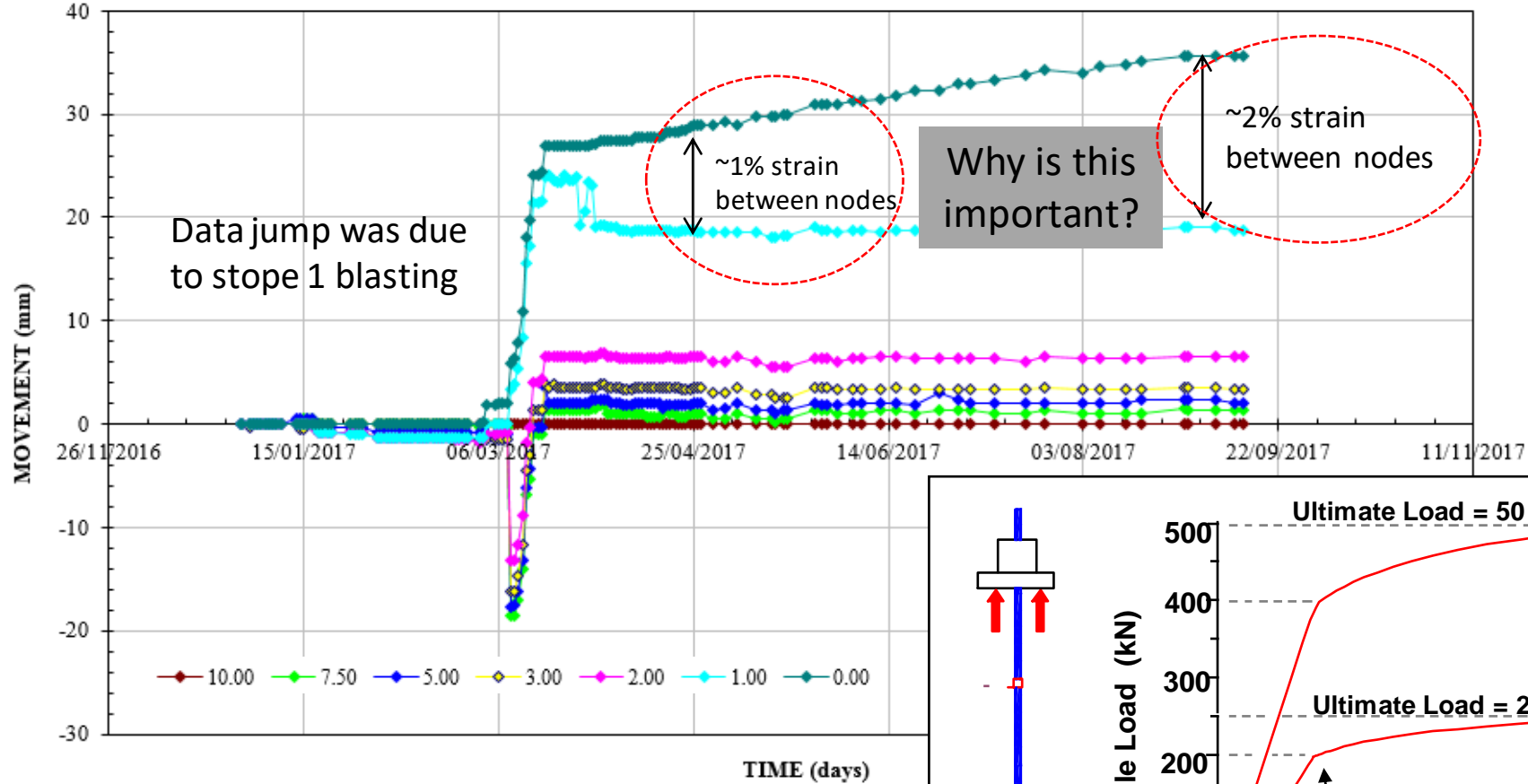
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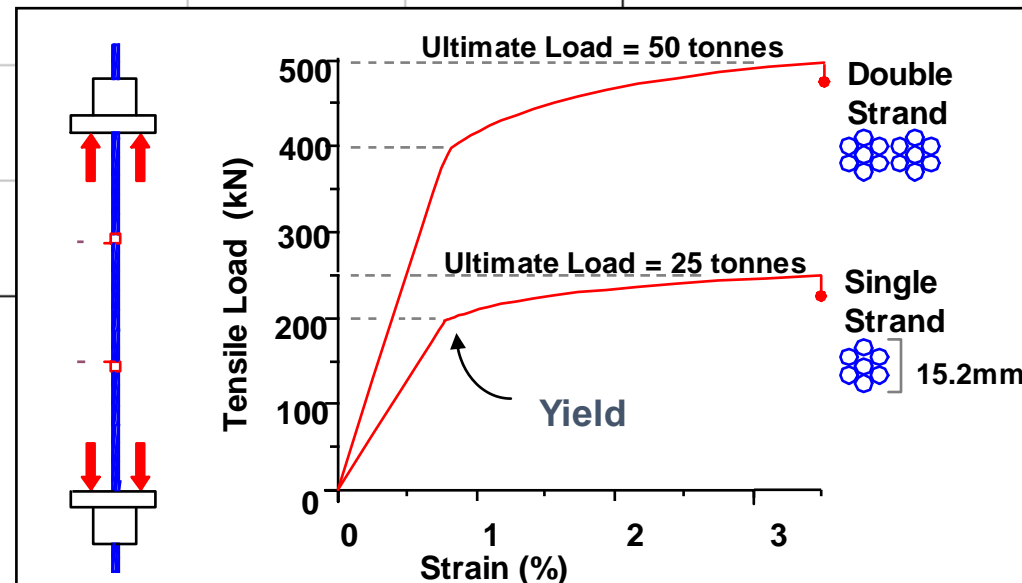
# Performance Based Design Case Example: Ground Support



# Performance Based Design Case Example: Ground Support



**Design Outcome:** Informed decision making regarding support system prehabilitation and excavation maintenance planning (safer working environment with improved planning and cost management).



## Summary of Best Practices - *that must be common practices* -

- Establish technical justification of data collection plans based on anticipated ground conditions and ground reaction foresight. *There is no one-size fits all for geotechnical data collection.*
- Establish and maintain a ground behavior model. *Data is drastically de-valued when it cannot be visualized and interrogated in 3D space.*
- Strain-based initialization of geologically realistic in situ stress states. *In situ stress states are inherently complex and we must not oversimplify the stress state.*
- Performance based design for all aspects of geomechanics and ground control in underground mines. *Traditional reliance on factor of safety and probability of failure are not widely applicable in mining operations due to the scale of our design projects and inherent design input uncertainties.*

# References

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- LeRiche, A., Kalenchuk, K. and Diederichs, M.S. 2017. Estimation of in situ stress from borehole breakout for improved understanding of excavation overbreak in brittle anisotropic rock. In Proceedings of the Eighth International Conference on Deep and High Stress Mining, Perth, Australia.
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- Palleske, C, Kalenchuk, K, Hume, C, Bawden, W, 2017, Strategic use of geotechnical data for maximised value added. Eighth International Conference on Deep and High Stress Mining. Perth, Australia.

Thank-you

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