Calibration of Large-Scale Three-Dimensional Non-Linear Numerical Models of Underground Mines Using Microseismic Data

Patrick Andrieux, Marty Hudyma, Chris O'Connor, Hao Li, Luigi Cotesta & Richard Brummer

Itasca Consulting Canada, Sudbury, Ontario, Canada

First International *FLAC*/DEM Symposium

25-27 August 2008, Minneapolis, MN, USA

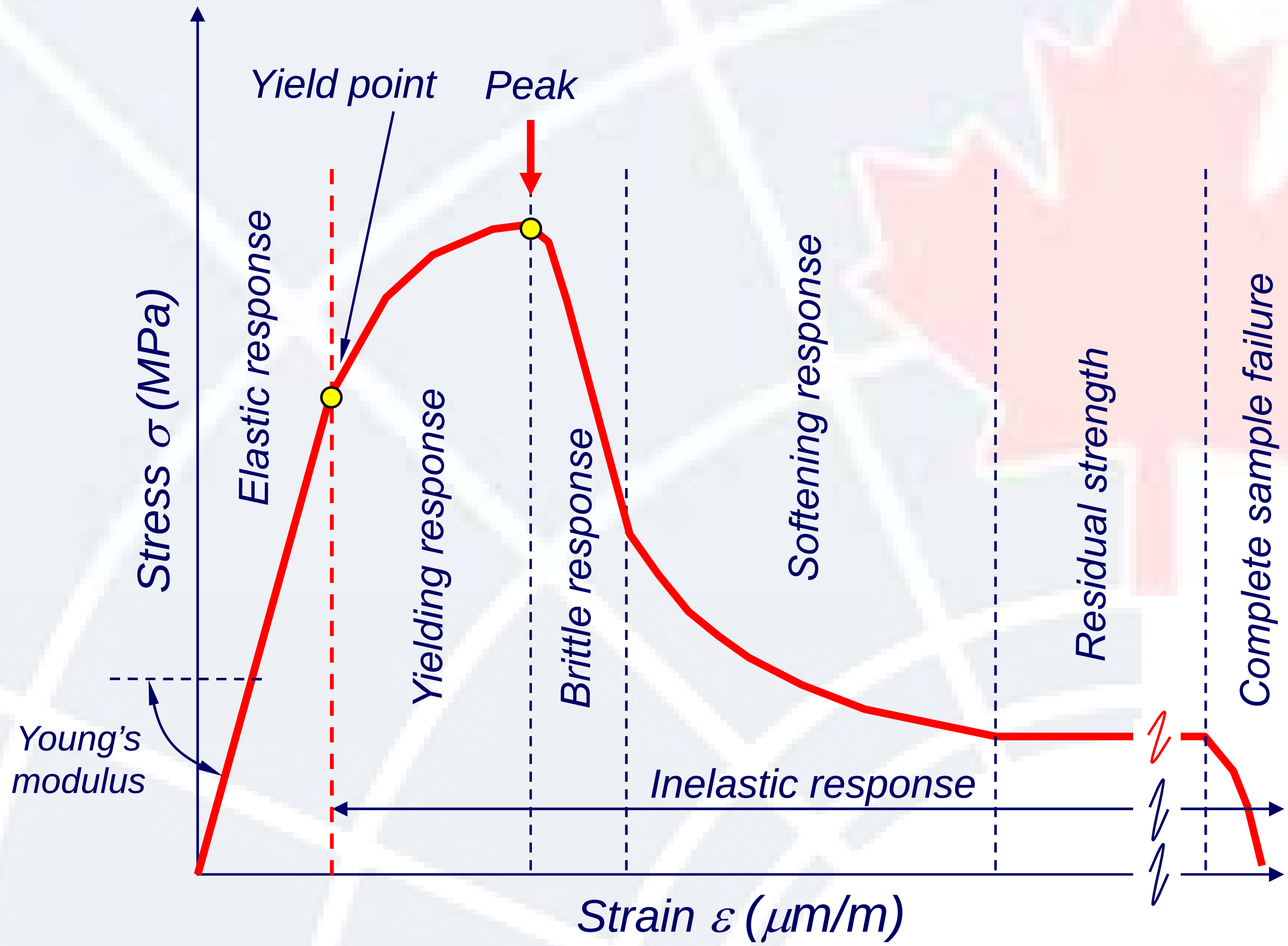
ITASCA Consulting Canada Inc.

HC ITASCA An Company

Introduction

- In mining applications, numerical modelling is generally concerned with the simulation of the stress, deformation and failure profiles that develop in and around an ore body as it is extracted
- In the case of deep and/or highly stressed underground excavations in moderately jointed hard rock masses, extensive failure usually occurs around the excavations, necessitating the usage of a non-linear numerical approach
- The proper calibration of such non-linear numerical models is one of the most crucial (and difficult) aspects of this type of analyses

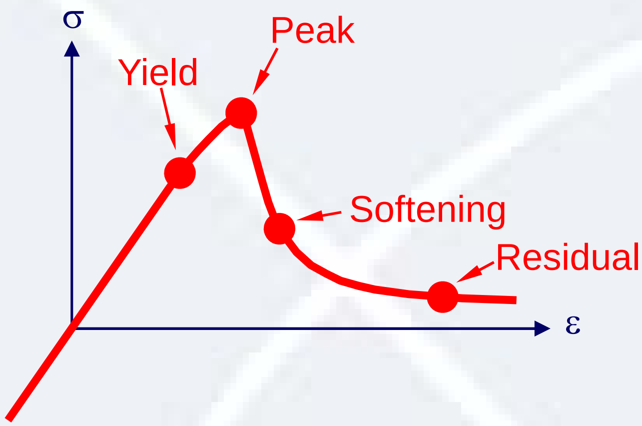
General Axial Stress-Strain Relationship



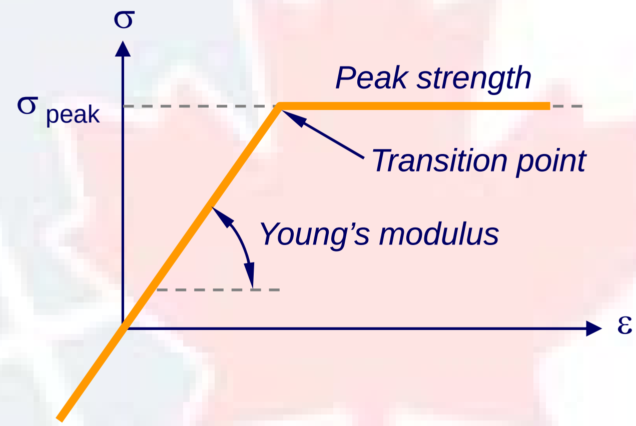
Typical stress-strain curve for a strain-softening material at a given level of confinement

ITASCA
Consulting Canada Inc.

Common Representations

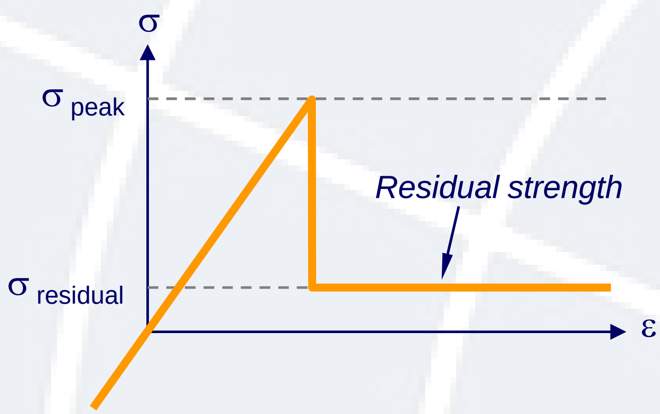


“Actual” inelastic behaviour

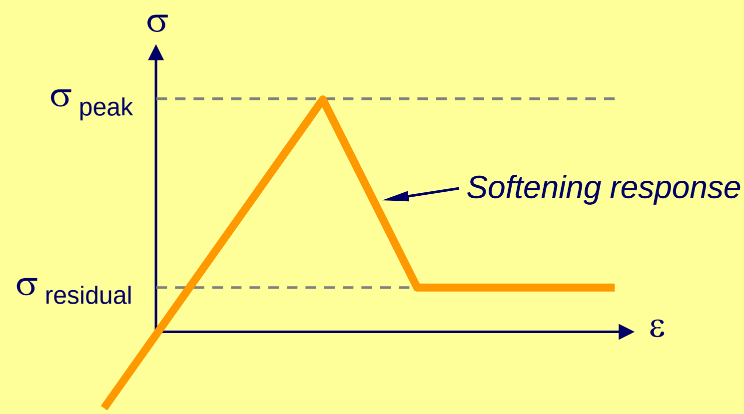


Elastic-perfectly plastic behaviour

Often the most representative of moderately jointed hard rock masses



Brittle behaviour



Strain-softening behaviour

ITASCA
Consulting Canada Inc.

Post-Peak Properties

- Besides the proper adjustment of the elastic and strength properties, a particularly important aspect of non-linear modelling is the accurate adjustment of the post-peak properties of the rock mass

Post-peak properties
↓
Residual strength of the rock mass
↓
Stress redistribution that follows failure
↓
Risk associated with the mining method examined (location of the stress fronts *vs*. mining activity, type of failure anticipated, concentration severity)

ITASCA Consulting Canada Inc.

Strain-Softening Behaviour

- When using a strain-softening behaviour, the need arises to also determine the range of plastic strain over which the strain-softening response occurs at the scale of the rock mass
- This controls *how* failure will occur and, importan-tly, indicates under which conditions, e.g., suddenly (seismically) *vs*. progressively (aseismically)
- A few approaches can be considered...

ITASCA
Consulting Canada Inc.

Possible Approaches

- Laboratory analyses with a stiff servo-controlled press, followed by an extrapolation method to the rock mass scale
  - Empirical scaling (weak…)
  - Synthetic scaling, e.g., synthetic rock mass models with *PFC*^{3D}
- Empirical back-analyses, based on past records, such as:
  - Circumstancial observations of failures (need many…)
  - Measured failures (e.g., long-term stress cycles)
  - Measured deformations (need to be at the right place…)
  - *Reliable long-term seismic records*

Basic Concept

- Back-analyses are conducted, whereby reliable long-term microseismic records (with thousands of events) are compared to modelling results
- The objective is to match regions of rock mass failure determined by the model at various mining steps, with the corresponding recorded seismicity
- This is done iteratively with a visualisation platform (Gocad) that brings together results from the seismic analyses (from MS-RAP, or similar software), the numerical results, and other spatial data, such as geology and mining excavations

Basic Concept

Zone 1 – elastic phase

- Theoretically, no permanent damage
- In practice, some low level of microseismic activity is possible, due to the loading of heterogeneities and flaws in the rock mass
- Unlikely to be detected by a mine-wide seismic monitoring system

Basic Concept

Zone 2 – yielding phase

- Onset of permanent dama-ge in the rock mass
- Some microseismicity can occur, with low amplitude and high frequency
- Acceleration of the micro-seismic event rate following mine blasts
- Possibly recorded by a very sensitive mine-wide seismic monitoring system

ITASCA
Consulting Canada Inc.

Basic Concept

Zone 3 – brittle phase

- Often associated with the largest seismic energy release in moderately jointed hard rock masses
- Events typically of high energy and relatively high moment
- Easily recorded by a well-designed mine-wide seismic monitoring system

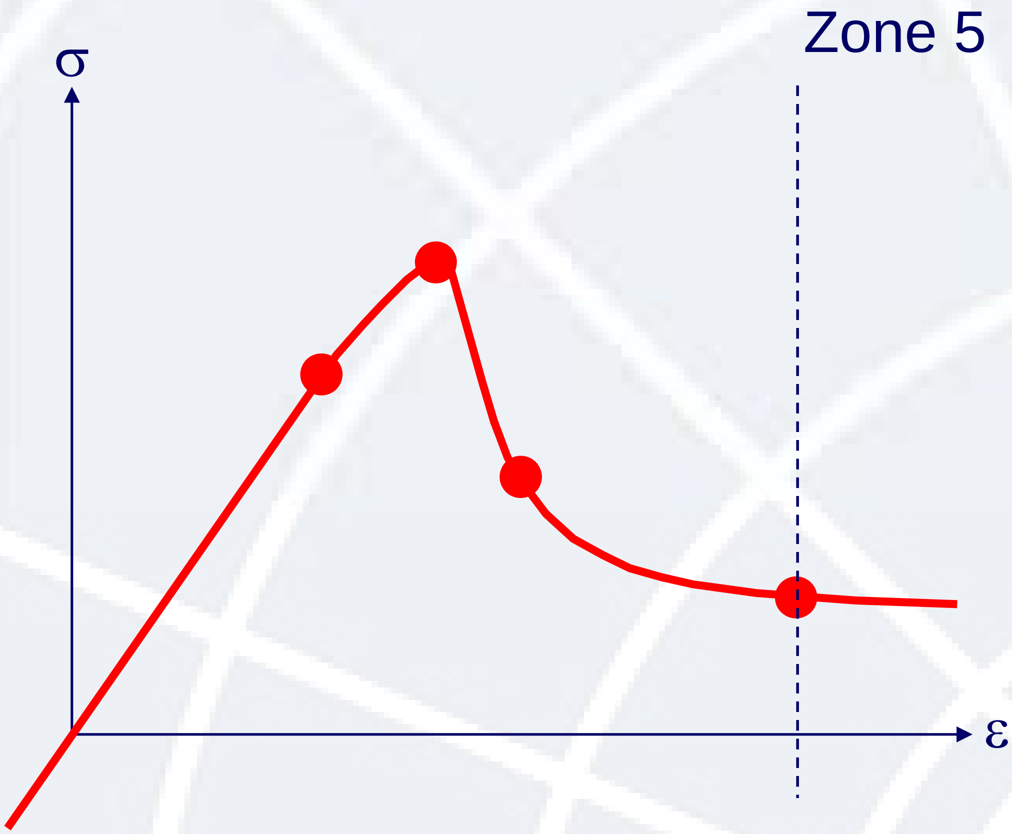
ITASCA
Consulting Canada Inc.

Basic Concept

Zone 4 – softening phase

- Can be associated with large seismic events in moderately jointed hard rock masses
- Events typically of lower energy, but of larger moment than during the brittle response
- Easily recorded by a well-designed mine-wide seismic monitoring system

Basic Concept



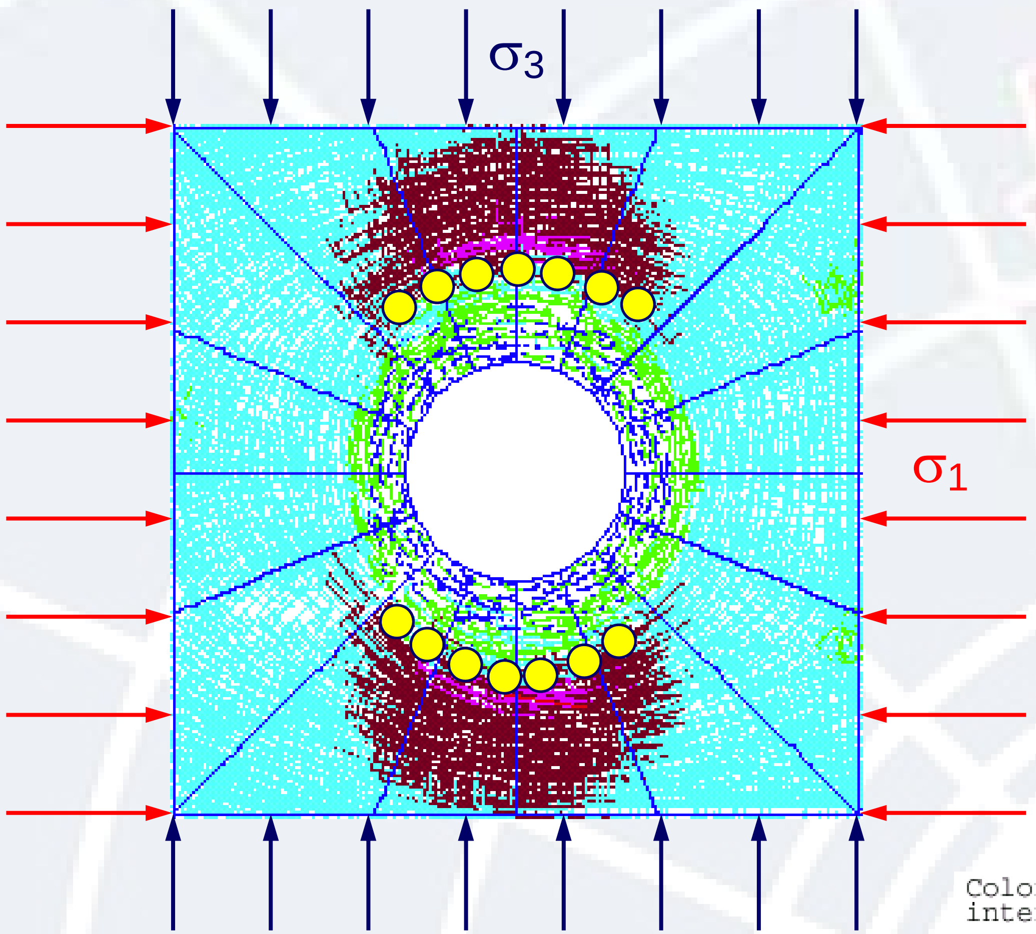
Zone 5 – residual phase

- Some seismicity can still occur, but the rock mass can no longer store sufficient energy to generate large seismic events
- Events typically of low energy and relatively small moment
- Can be recorded by a well-designed mine-wide seismic monitoring system

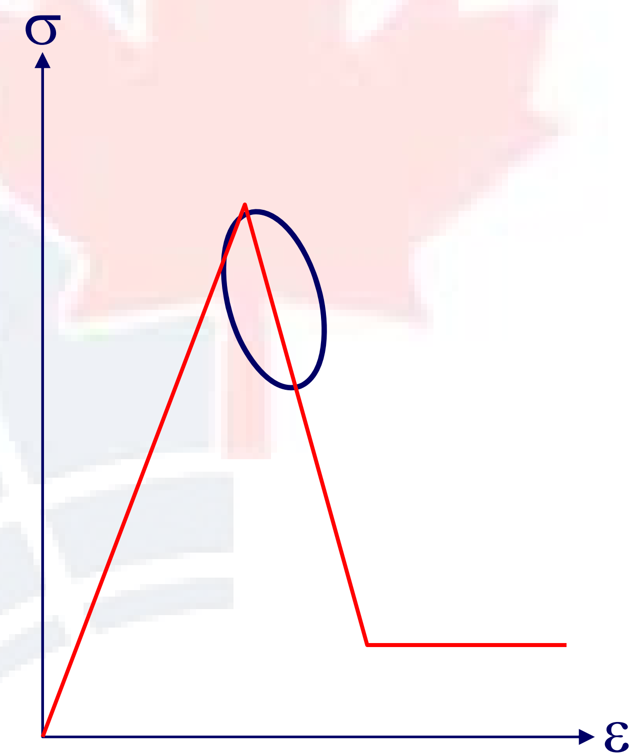
ITASCA Consulting Canada Inc.

Basic Concept

Conceptual 13m-diameter horizontal tunnel at 2,000 m below surface



Principal stress vectors, colour-coded by σ_1 magnitude



Color by PS1 mag.
interval = 3.000E+01

min	max
-1.800E+02	-1.500E+02
-1.500E+02	-1.200E+02
-1.200E+02	-9.000E+01
-9.000E+01	-6.000E+01
-6.000E+01	-3.000E+01
-3.000E+01	0.000E+00

Below *in situ* levels (failed)

ITASCA Consulting Canada Inc.

Basic Concept

- Adjust strength and softening parameters until this match is obtained
  - Adjust the distance between failure zones and seismic events by varying the peak strength
  - Adjust the thickness of the failure zones by varying the softening characteristics
- A few iterations are usually required, depending on the number of geological horizons and the degree of match required

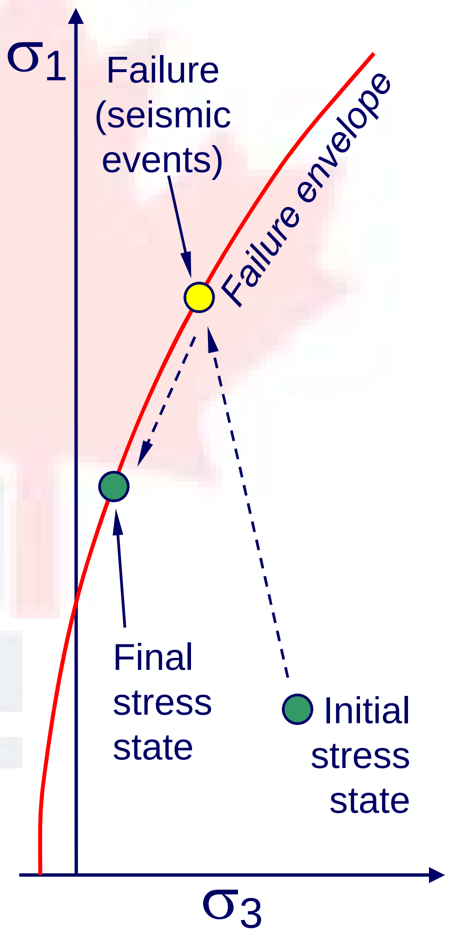
ITASCA
Consulting Canada Inc.

Certain Complications in Practice...

- Different geological horizons
- Different geomechanical domains
- Rock mass anisotropy and heterogeneities
- Large seismic records are over long periods of time, and pertain to many stopes — generally too many stopes than can be modelled individually
  - Need to group stopes in manageable/relevant mining steps
  - Need to consider only the *relevant* events (not all events during a modelled step are related to the stress state at the end of this step). Exclude fault-slip events.
  - Trade-off between considering smaller mining steps (better correlation) and having a manageable number of steps

Certain Complications in Practice...

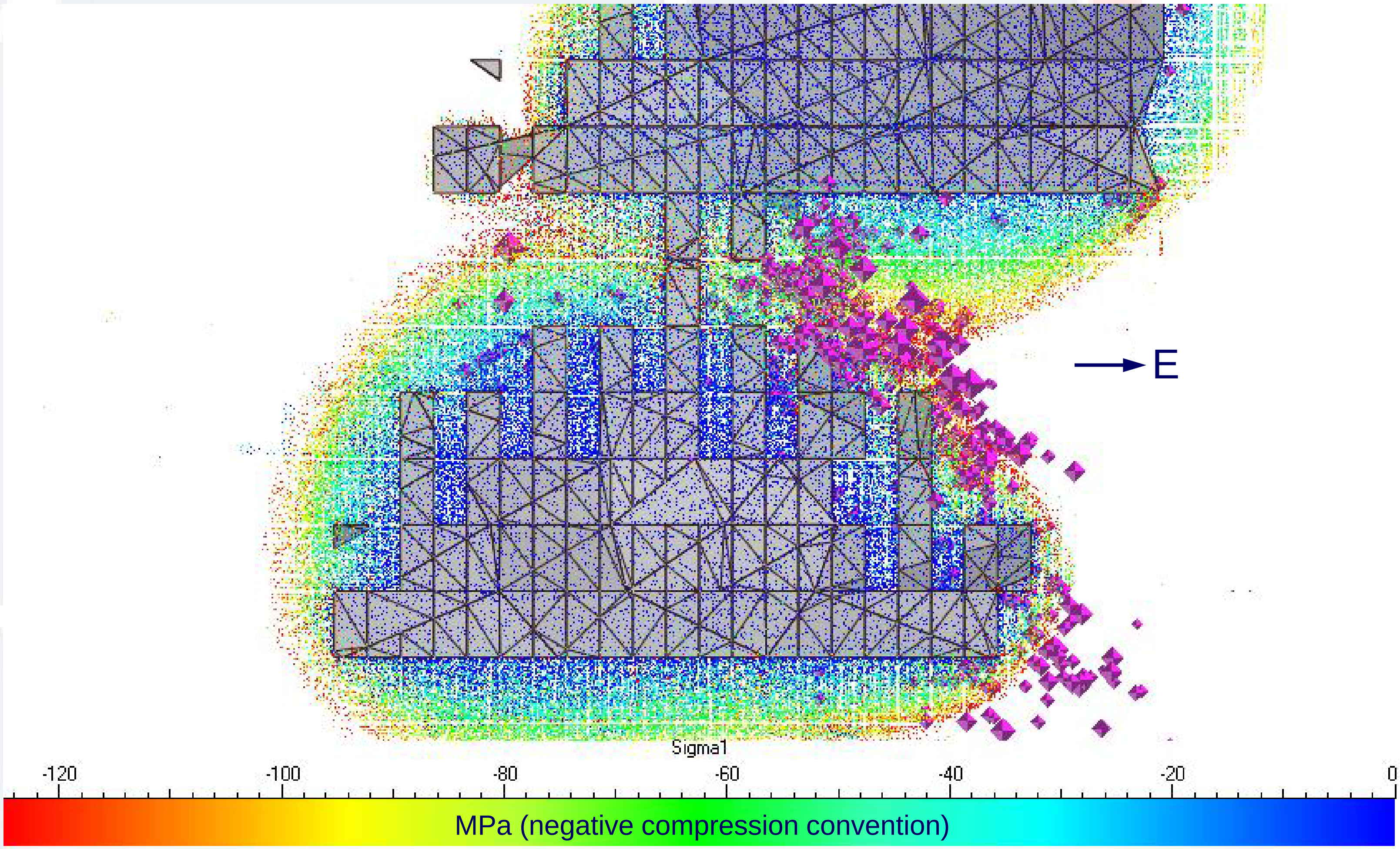
- The "apparent" stress change bet-ween two mining steps (ignoring the stress path between) can be confusing
- Only one failure envelope per rock type – there will in fact be local strength variations
- Failure not occurring at clear-cut stress levels, as per the failure envelope



- Gaps in the seismic record, or poor events accuracy – need high quality data

ITASCA
Consulting Canada Inc.

Practical Example (20,000 Events, 200 Stopes)



Centroid of numerical elements that have encountered the failure envelope during the computation, colour-coded by their σ_1 magnitude (indicating ~ where they stand along the stress-strain curve – red = just failed, blue = long failed)

ITASCA
Consulting Canada Inc.

Conclusions

- Seismicity being an expression of rock mass failure, seismic records are particularly well adapted to adjust the peak strength and softening properties of an inelastic model by ensuring that computed failure and stress-induced seismicity are located in the same regions around the excavations
- One great advantage of seismic events is their non-ambiguity – their location and time of occurrence are precisely known
- Although the methodology has limitations, it remains a powerful tool to calibrate complex numerical models, whereby thousands of recorded seismic events may be used in the process

ITASCA
Consulting Canada Inc.

ITASCA
Consulting Canada Inc.