Stresses in the Australian Continental Tectonic Plate
- Variability and Likely Controls

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Why am I in Ballarat?

Spying - looking over the fence!!

We “miners” have ground control / stability issues associated with seismic events, particularly in deep “highly stresses’ underground mines.

While we have a range of procedures and techniques for “predicting” and “managing” these events, they do not always work ....

So ...... what can I find out about your approach to earthquake engineering? ...... and are there equivalent applications to stability issues in mines

Exchange information

What can I tell you “earth-quakers” about rock stresses, which we “miners” think we know something about, and which should be of fundamental interest to you quakes?
Earthquakes

Definition:
SIGNIFICANT SUDDEN PACKAGES OF NATURALLY RELEASED ENERGY – THAT ARE OF SOCIAL AND (CIVIL) ENGINEERING INTEREST

Characteristics:
• Location (longitude, latitude and depth)
• Duration (tens of seconds?)
• Magnitude / Moments
• Frequency
• Focal mechanism
• Associated with shearing on specific and regional geologic features

Seismic Events

Definition:
SUDDEN PACKAGES OF NATURAL + MINING-INDUCED STRAIN ENERGY – THAT ARE OF SOCIAL AND (MINING + CIVIL) ENGINEERING INTEREST

Characteristics:
• Location (northing, easting, RL)
• Duration (a few seconds – similar to large stope blasts)
• Magnitude / Moments
• Frequency (high to low)
• Focal mechanism (shear, explosive, implosive)
• Associated with specific structures, failure through intact rock and collapse
Surface Damage - also possible

Seismic Events – Monitoring and Hazard Prediction

Analysis in 3D - then Hazard Prediction
Seismic Events – Relationship to Stoping and Structures

Seismic Events – Relationship to Rock Stresses
Seismic Event - Prediction

The following would be nice!

- **Timing**: Tuesday 16 at 13.34hrs
- **Location**: 25m below 18 Level @ 5285N, 3456E
- **Magnitude**: 3.5 Mₚ
- **Frequency**: 20 Hz
- **Duration**: 0.3 secs
- **Mechanism**: Shearing on Fault X (dip 75, dip direction 125); maximum of 15mm shear displacement over an area 150m x 50m (strike / dip)
- **Load Redistribution**: To areas X, Y and Z
- **Are more events possible > 1.0 Mₚ?** - No

Seismic Events – Prediction
(Mobilised Shear Stress vs Structures)

Some faults that have a high in situ potential to shear:
- Oval, Lords etc
- Lilac Hill etc
- Steep south dippers

**Strength:**
- \( c = 3 \text{MPa} \)
- \( \phi = 18^\circ \)
Seismic Events – Prevention / Standards

GROUND SUPPORT LAYOUT

UNFOLDED VIEW OF MESH AND BOLT PATTERN

- The last ring of fully installed 2.4m long bolts is considered supported ground.
- Front row of 1.5m split set bolts must be installed prior to installing resin bolts.

Typical

- 2.4m resin grouted Secura bolts
- 2.4m Split Set bolts
- 50mm P-beams

Seismic Events – Prevention / Implementation
Company Policy – The Driver

No Harm

Everybody goes home safely – every day

Nobody is allowed to work beneath unsupported ground – no exceptions
  • Screen +
  • Bolts

Company Policy – Acceptance of Risk
Ongoing Seismicity Investigations

- Monitor events - time, location, magnitude etc etc etc
- Record mining context and performance of openings
- Accumulate associated data (structures, rock stresses, rock properties)
- Analyse (plot, graph, scratch and drink lotsa coffee!!)
- Fund R&D …. and “look over the fence”

R&D

- Lots of discussion / papers with Peter Mikula and (lately) Stephen Fraser
- R&D undertaken by the Australian Centre for Geomechanics (ACG)
- The odd chats with Gary Gibson
- Seminars (2) on Earthquake Building Codes
- 2008, Ballarat - rock stresses

- Future?
  Special Eastern Australian Ground Control Ground (EAGCG) meeting?
Background - Max

Qualifications - Geology (BSc Hons) + Civil Engineering (MSc)

Profession - Geotechnical Engineer (34 yrs; Mt Isa Mine, CSIRO, AMC)

Interests:

• Geology
• Structural Geology
• Ground Behaviour
• Rock Stresses
• Rock Properties
• Tectonics

Rock Stresses

• Old Engineering Theory

• Indicators

• Measurements
Old Theory

Just due to the weight of overburden rocks??

• Vertical component = $\sigma_V = \text{major principal stress} = \rho \ g \ \text{Depth}$

• Horizontal components = $\sigma_H$ and $\sigma_h = [\nu / (1 - \nu)] \rho \ g \ \text{Depth}$

Indicators

• Geological – grains, folding and faulting

• Boreholes - breakout and drilling induced fractures

• Underground Openings - high stress spalling

• Mining-induced Seismicity – shearing (new and pre-existing structures)
Geological – Grain Size

Geological - Folding

Many many years ago!
Geological - New Fault (rare)

Normal Faulting

Thrust Faulting

Strike-slip Faulting

SV > SH > Sh

SH > Sh > SV

Geological – Shearing on Pre-existing Structure (common)

Normal Faulting

Thrust Faulting

Strike-slip Faulting

SV > SH > Sh

SH > SV > Sh

THE DIRECTION OF THE SHEAR DISPLACEMENT – EG DURING AN EARTHQUAKE - DOES NOT HAVE TO BE PARALLEL TO THE LOCAL MAJOR PRINCIPAL STRESS!!
Boreholes - Breakout

$\sigma_{\text{max}}$

Boreholes - Breakout + Drilling Included Fracturing

$\sigma_{\text{min}}$

induced fracture

induced fracture

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Borehole – core discing

Underground Openings - High Stress Spalling
Underground Openings - High Stress Spalling

$
\sigma_{\text{max}}$

Mining-induced Seismicity – Sudden Shearing

Local Magnitude 2.9

15mm

15mm

Dilation = 2mm
Mining-induced Seismicity – Sudden Shearing / Bursting

Insitu Rock Stress Measurements - Australia

- 40+ years

- 1000+ in situ measurement sites (hydraulic fracturing, overcoring etc) – mostly at mines and civil engineering projects

- Depths up to 1.6km – cf = 35Km thick continental crust (SHALLOW!!)

“What’s does the data tell us?”
Insitu Rock Stress Measurement
Drilling, Installation, Overcoring and Biaxial Testing

Rock Stress Measurement
Overcoring using CSIRO HI Cells
Measurement Specification: CSIRO HI Cells

Elastic isotropic rock

Holes oriented to avoid undesirable high stress effects - borehole breakout, discing, tensile stresses, excessive strains etc

Overcore at least 1.5 “diameters” away from opening

Various overcore sizes: 6 inch (142mm) and 74mm

To collect sufficient data, typically 3 successfully overcores per site

Measure strains to within 1° of ambient rock temperature, or correct - 1° ≈ 1MPa

Good rock property data is just as important as good overcore strain data

Analyse data in a consistent manner - after Worotnicki (1993)

Fully document results

Qualitatively rate the confidence that can be placed in each overcore and site result

Expect variability - after all it’s rock!!

Overcoring not an appropriate measurement technique for some situations

Rock Stress Measurement - Oz Distribution

- Accepted methods (overcore and hydraulic fracturing)
- 3D
- Rating ≥ Fair
- 258 site measurements
- 145 deeper than 500m
- No coal, no civil
- Scattered
- Representative sample stresses in the Australian continental plate?
All Rock Stress Measurements are NOT Equal

Qualitative Rating depends on;

- Technique; Stress Relief (CSIRO HI cell, ANZI cell, CSIR cell, USBM cell, Door-stoppers, Borre cell, Borehole slotter, Flat Jacks etc), Hydraulic Fracturing, Acoustic Emission, Displacement Rate Analysis etc
- Experimental difficulties / procedures; poor rock, electrical, mechanical, thermal etc
- Amount of data collected; strains and rock properties ($\sigma = E \varepsilon$)
- Assumptions; rock is NOT always a perfectly homogeneous, isotropic and linearly elastic material!!
- Data analysis; assumptions of result per cell, result per site

Mess ??

No simple depth vs stress relationship
Principal Stress Magnitudes vs Depth

- Magnitude (MPa)
- Depth Below Surface (m)
- Major
- Intermediate
- Minor
- SVert for ρ = 2.65 t/m³

Australia Anomalously High

- Excellent
- Good
- Fair
- Poor
- Very Poor
- No Rating

North America

Principal Stress Orientations vs Depth

- σ3 mostly, but not always sub-vertical
- No preferred σ1 direction
- More scatter stresses < 500m
Maximum Horizontal Stresses vs Tectonic Zones Orientations and Magnitudes @ 1000m

Plate Stresses vs Plate Motion

- NOT related to plate motion
- FUNCTION of interactions with other tectonic plates
  - Shearing - thrusting (subduction) and strike slip
  - Normal Load – rifting (normal faulting?) and tractions
- FUNCTION of plate thickness?
Vertical Component – Measured > Theoretical in Yilgarn

Principal Stress vs 1st Invariant
Principal Stress vs 1st Invariant – rock is rock is rock!!

Same world wide

\[ \sigma_{1}/\sigma_{3} = 2.3 \]
\[ \sigma_{1}/\sigma_{2} = 1.5 \]
\[ \sigma_{2}/\sigma_{3} = 1.5 \]

Rock Mass Strength (\(\sigma_{1} vs \sigma_{3}\))

Back analysed insitu shear strengths of typical Yilgarn structures (for high normal loads):

- Graphitic: \(C = 2\text{MPa}, \phi = 12^\circ\)
- Talc-rich: \(C = 2\text{MPa}, \phi = 18^\circ\)
- Chloritic: \(C = 2\text{MPa}, \phi = 23^\circ\)
Similar Rock Mass = Similar Structure Characteristics

Same Shear Strength
C = 2MPa, \( \phi = 23^\circ \)

Pre-mining + Mining Induced + Stress Change Monitoring

Residual: c = 2MPa, \( \phi = 23^\circ \)
Peak: c = 8MPa, \( \phi = 23^\circ \)
Conclusion

- At any location - a few local structures (orientation and shear strength) dictate the local rock stresses (principal stress orientations and ratios)

- The mobilised shear stress on these "stress-controlling-structures" is - typically - on / near their (large scale) shear strength

- Stress changes (eg reductions in normal load – nearby mining) = shearing (eg plastic - creep; brittle - seismicity / earthquakes)

- A detailed knowledge of structures + stresses should lead to forward earthquake “prediction”

There’s more!!

Stress change monitoring cells
Periodic Stress Decreases – horizontal NE-SW

Australian Plate Motion vs Time

- Cretaceous - End of the dinosaurs
- Devonian - Au in Ballarat
- Don’t expect plate stresses to be constant!!
- Expect on-going shearing on pre-existing structures
Shear, Load Re-distribution, Stress Change -
Shear, Load Re-distribution, Stress Change -

etc etc etc