What is deep?

“If observations indicate that a mine experiences stress-driven failures in a significant proportion of its excavations” Potvin, Hadjigeorgiou, Stacey, Challenges in Deep and High Stress mining.

standard safety factor design calculations – e.g. weight of the wedge versus capacity of the bars – doesn’t cater for all the potential problems…. B.S.

- Deformation driven failure (especially squeezing ground), bursting (dynamic loads), Shearing for bolts designed as pure tensional elements, un-raveling around the bolts…
“Deep” mining is a relative term

Example of fracturing/loosening
Around shallow opening

Open cut exposed old room &
Pillar coal mine

Stress/strength

Mining layouts can create “deep”
Conditions in otherwise decent
Ground

Sill pillars, NPV designs….

Deep in the Ground Control context - ? Stuff that accelerates hair loss

Don’t want updated photo
10/26/2000
Ground Support Design

- need some calcs/rational behind the support design
- reality is numerous assumptions go into the calcs

<table>
<thead>
<tr>
<th>Support element</th>
<th>Static (kN)</th>
<th>Dynamic (kN/m²)</th>
<th>Characteristic deformation limit (kJ/m²)</th>
<th>Source of information</th>
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<tbody>
<tr>
<td>Boltliner</td>
<td>20</td>
<td>5.0</td>
<td>187</td>
<td>Canadian Rockburst Support Handbook 1996</td>
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<td>#6 gauge mesh</td>
<td>26</td>
<td>7.5</td>
<td>212</td>
<td>Canadian Rockburst Support Handbook 1996</td>
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<td>69</td>
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<td>7.5</td>
<td>80</td>
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<tr>
<td>Fibrocrete</td>
<td>25</td>
<td>2.5</td>
<td>40</td>
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<tr>
<td>Rebar 20mm</td>
<td>160</td>
<td>9.5</td>
<td>31</td>
<td>CANMET average split tube and plate hit for dynamic</td>
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<tr>
<td>Rebar 22mm</td>
<td>235</td>
<td>12.2</td>
<td>31</td>
<td>Estimated by rationing up 20mm results</td>
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<td>Soft yielding bolt</td>
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<td>695</td>
<td>CANMET</td>
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<td>Inflatable type 1</td>
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<td>10.0</td>
<td>125</td>
<td>Canadian Rockburst Support Handbook 1996</td>
</tr>
</tbody>
</table>

Sample factor of safety calculations for support systems – component capacities
- have to decide whether you use averages, lower limits, take it to max displacement…

Numbers used to be very hard to find – CANMET, WASM dynamic testing programs
Going a long way to fill in the blanks, as well as earlier work by Ortlepp/Stacey Kaiser/Tannant etc.…
Sample calculations – numbers all open to debate

Safety factor – load/capacity

Load is educated guess – in this example 4.5 t/m² dead weight
20 kJ/m² dynamic load

Roughly 5x5 opening with fracture zone ~1/3 span (dead weight)
Whack that at 3m/s

Lots of issues with safety factor
Approach, especially for dynamic Support
- Soft retention (mesh, TSL…)
- Relatively stiff bolts
- Can’t act in perfect unison
  - so how do you add up the capacities?
- component testing can’t address this in isolation
- System testing very expensive
  And difficult, how do you account for load/transfer energy loss?
- Blasting always tough to get right
  (ACG Heal et al probably came closest)
- In situ – shearing, local strain energy, deformation sucks up system capacity, QA/QC, corrosion……

Excellent work but can’t get clean kJ/m²
Some of the assumptions / issues buried in the safety factor approach

Zone of influence around each bolt
So there is a practical bolt spacing to ensure liner doesn’t get over loaded

1 giga J bolt can satisfy the math…. But one bolt won’t work
Load/deformation characteristics of retaining elements (screen) and holding Elements (bolts) very different – reality is mesh will balloon out
Well beyond the bolts, especially chainlink

Stiffness contrast between bolt and surface support can be problematic
- Case for yielding tendons

Thanks rick
Some safety factor erosion factors

- Installation quality
- Corrosion

Heavily wrapped post pillar with remote scoop inadvertently scraping off support
Speed wobbles in three different bursts, three different mines, three distinctly different rockmasses

Shearing in the stress induced fracture zone pre-dynamic loading can cause bar lock up – for example many yielding bolts use toe anchor plowing mechanism which is verified by 90° tensile testing.

Never a perfect world underground.

Hand model = rick

In the “deep” mine context, more than just gravity loading; also have to cater for on going deformation, in situ stresses plus the influence of mining...
Rockmass bulking
Slowly uses up
Deformation capacity
Of support systems

Shotcrete and rebar
Good at resisting
Bulking, limit
dilation
However S/C notoriously Limited under high deformation or bursting

Fibres only go so far, material is fundamentally brittle
Mesh can handle a fair amount of Bulking

However – the problem is a fundamental change in how the ground support interacts

Most bolts are friction bolts, dilated material puts low confinement on the tendon… so you end up with glorified rockbolts, anchor to solid, hold at the plate....

For more extreme Ground movement
150x150mm plates
And fibrecrete not Enough retainmnet
Clearly the use of better load spreaders such as mesh plates, straps, butterfly plates can make a huge improvement.
Rebar and cables are still essentially friction bolts, shaking loose rock around them. Without excellent retention system, results in more naked tendons than broken tendons.

Use of mixed mode ground support

- Stiff support to limit dilation / bulking
  - keep laminated beam
  - confinement around the bolts
- yielding support to handle bursting / squeezing

-S/C is expensive, limited in deformation capacity
  - but 100% coverage and very effective at resisting dilation, blast damage, equipment damage...

- more work to do to quantify the cost/benefits of different approaches
  - tight bolting? Mix of soft + stiff bolts, different surface support....
Mesh reinforced S/C one step up
Example of blow out where the screen
Reinforcement stopped

Some deep mines are going to screen
Over shotcrete – S/C to keep ground
Tight, mesh to take over if bursting or
High deformation takes place
Old school safety nets = chainlink or expanded metal mesh combined with lacing, empirically works well but expensive because difficult to automate.

Upper right – ACG newer version (easier to mechanize)

Dynamic loading is more complex – more guess work in SF calculation required.

Potentially over looked phenomenon

Stored strain energy local to the drive
  • damage is often not closest opening to the event
  • often can’t explain observed ejection velocity versus ppv predicted from magnitude / distance relationships
  • coiled spring that gets released by far field seismic wave

Wave amplification around fracture zone interface & free surface
  • observe the effects, but may not have good enough understanding to quantify
  • likely some earthquake engineering literature to delve into…
A recognized omission from the 1996 Canadian Rockburst Support Handbook is the influence of strain energy around the excavation (coiled spring).

Coil spring (strain energy released by seismic event)
Examples......

Sub level cave
Eventually gets deep enough
Where high stresses hit
Main haulages

Upper left/lower right Corner of strike drives High stress
Large bump caused damage over Long section of strike drive (coiled spring triggered by fault slip event)

Hard to see but Floor heave in Lower right corner

Eventually get enough vertical Load in draw point pillars as Overall extraction progresses

Can be ticking time bomb

Sill elevations in horizontal Stress field, steep deposit

Pillar burst mechanism Is about stored strain Energy, bump sometimes Is just trigger

Pillar burst mechanism is about stored strain. Energy, a bump sometimes is just a trigger.

Sill elevations in horizontal stress field, steep deposit.

Eventually get enough vertical load in draw point pillars as overall extraction progresses.

Can be ticking a time bomb.
Mn 2.0 32m away, had to be significant strain energy stored locally, bump released coiled spring

Seismic Wave amplification

Google search yields loads of references in earthquake engineering

"frequency-dependent amplification of seismic waves by near surface low velocity layers is a well known phenomenon"

Mn 2.4 30m Away

Often seems like fracture zone gets spit out

PPV’s estimated from magnitude & distance usually low versus observed ejection velocity

E.g. Hedley formula yields 0.33m/s, but rock blew off the wall (a few m/s)
Lots of examples of seismic waves hitting underground openings (see “Rock Fracture and Rockbursts – an illustrative study” Dave Ortlepp) – but S/C posts provide some of the clearer visuals because they are stiff and connected to floor and back

Contradictions

- Good to keep rubble in place to dampen the blow of a rockburst
  - in some cases better not to de-bag the screen and scrape to solid
  - rubble zone doesn’t store local strain energy
  - but bolts become glorified mechanical bolts hanging the loose to toe anchor

- How do the surface waves interact with both the fracture zone (low velocity layer) and the free surface (Raleigh & love waves…)
  - how much amplification do we really get?

Ideally keeping the fracture zone tight (laminated beam) is best
- Still fractured rock so won’t store local strain energy
- reduces naked tendon potential
- Help rock support itself
Conclusion 1

Standard safety factor calculations for support design in deep mining

- ball park estimates
- Snapshots in time
- deformation eats up capacity
  - dynamic and static

Light at the end of the tunnel – empirical experience
Empirical experience has some success stories (Kidd, Brunswick, Sudbury, others...). In this case floor heaved +60cm, destroyed 1.8m diameter shotcrete posts, major cracks. Mn 3.3 ground motion hitting High stress area, but dynamic bolts, straps, chain-link over original rebar + shotcrete system survived.

STRAPS ON SEAMS

1.6 Mn

Stiff bolts with heavy retainment (rebar, straps, mesh plates, small aperture mesh)
Late 90’s
• really wasn’t off the shelf yielding bolts in Canada
  • debonded cables probably closest thing

• Now a lot to choose from!

• database of dynamic testing building
  • CANMET
  • WASM

Emerging technology
Numerical modeling tools
Getting sophisticated enough to give realistic load/displacement Histories of tendons in areas where significant mining induced stress change occurs
- Use to estimate strain energy store around openings?
- Can simulate dynamic waves

3D laser scans and/or photographic methods getting accurate enough to do real Convergence monitoring – logistically a bit awkward but mm accuracy possible
Wireless technology is now working underground to remotely measure ground control instruments (smart cables, extensometers, instrumented bolts....).

Bulls eye for equipment Damage

- Manual readings, slow
  - can miss critical changes between readings
  - improving logistics = easier to read more instruments

Enabling technology to estimate loss of support capacity with time/mining

High resolution seismic monitoring – MS-RAP type analysis to understand failing Zones, failed zones (seismic dead zones), strain energy storing, sensitive structures....
Passive tomography utilizing recorded seismicity to track damage zones, high stress Areas (for example Westman – Virginia Tech, also Golders Montreal)

Currently some resolution problems – particularly with constant velocity model for Seismic location

Top left example – ray path goes through a significant fault (not shown) causing Slower effective velocity than constant velocity assumption, and location offsets

Top right example – blasts offset from actual drive due to ray path going around stopes And fractured ground causing slower velocity than assumed in location algorithm, also fringe Of array

Ray tracing algorithms (ESG, IMS), and variable velocity models are emerging, but not Routinely applied to every event
Thanks for your attention
Any questions?

102 t sulphides
12 t fibrecrete