INTEGRATING LASER SCANNING WITH DISCRETE ELEMENT MODELING FOR IMPROVING SAFETY IN UNDERGROUND STONE MINES

JUAN J. MONSALVE
M.S. MINING ENGINEERING
MINING AND MINERALS ENGINEERING DEPARTMENT
VIRGINIA TECH
1. INTRODUCTION
2. OBJECTIVE
3. CASE STUDY MINE / GEOTECHNICAL CONDITIONS
4. METHODOLOGY
5. RESULTS
6. CONCLUSIONS
7. REFERENCES
1. INTRODUCTION

“The guidelines for pillar and roof span design are empirically based; their validity, therefore, is restricted to rock conditions, mining dimensions, and pillar stresses that are similar to those included in this study. These guidelines should be applicable to the majority of stone mines in the Eastern and Midwestern United States. If pillars need to be designed that are outside the validity of these design guidelines, the advice of rock engineering specialists should be sought.” (NIOSH, 2011)
2. OBJECTIVE

To develop and implement a methodology that integrates laser scanning technology along with Discrete Element Modeling as tools for characterizing, preventing, and managing structurally controlled instability that may affect large-opening underground mines from a risk perspective.
3. CASE STUDY MINE
3. CASE STUDY MINE

- 30° Dipping deposit
- Room & pillar mining method with eventual stoping
- 24 m x 24 m pillars (80 ft x 80 ft)
- Stope height ≈ 30 m (100 ft)
- Drifts 12.8 m x 7.6 m (42 ft x 24 ft)
3. GEOTECHNICAL CONDITIONS

~ 10 ton
3. GEOTECHNICAL CONDITIONS

Description

Jointing pattern where at least four joint sets were well defined

- Observed wide-joint spacing, generally ranging from 0.6 m to 2 m,
- Amount of fallen blocks observed on the floor with cubical and tabular shapes,
- Joint surfaces defined as mostly closed, flat and smooth, with a JRC ranging from 2 to 4, completely dry and fresh,
- Other geological structures, such as faults and contacts, that could generate a rock fall in the absence of the required support

Rock Mass Classification

<table>
<thead>
<tr>
<th></th>
<th>RMR</th>
<th>Q</th>
<th>GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70 - 75</td>
<td>8 - 20</td>
<td>≈ 75</td>
</tr>
<tr>
<td>Classification</td>
<td>Good</td>
<td>Fair</td>
<td></td>
</tr>
</tbody>
</table>
3. GEOTECHNICAL CONDITIONS

\[ \sigma_v = \gamma h = 2.7 \frac{\text{ton}}{\text{m}^3} \times 9.81 \frac{\text{m}}{\text{s}^2} \times 700 \text{m} \quad \sigma_v = 18.5 \text{ MPa} \]

**Stress Condition**

Max. Principal Stress = Horizontal Stress \((1.2 \sigma_v)\)

**Lithology**

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Density (ton/m³)</th>
<th>UCS (MPa)</th>
<th>Brazilian Tensile Strength (MPa)</th>
<th>Young’s Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Hanging Wall</td>
<td>2.69</td>
<td>0.01</td>
<td>163.74</td>
<td>37.84</td>
</tr>
<tr>
<td>Ore Body</td>
<td>2.69</td>
<td>0.01</td>
<td>159.20</td>
<td>21.25</td>
</tr>
<tr>
<td>Footwall</td>
<td>2.72</td>
<td>0.01</td>
<td>217.29</td>
<td>36.12</td>
</tr>
</tbody>
</table>

\[ \sigma_v \approx 75 \]

**Risk/Hazard Assessment**

- **Weak & Soft Rocks**: Brittle & Hard Rocks
  - GSI < 30
    - Stress-induced brittle spalling
    - Usually found in blocky and massive rock masses
  - GSI > 40
    - Gravity-induced structurally controlled block movement
  - GSI \approx 75

(Martin, Kaiser & Christiansson, 2003)
4. METHODOLOGY

1. Laser Scanning

2. Virtual Discontinuity Mapping

3. DFN Generation

4. Preliminary 3DEC Models

5. Stochastic 3DEC Modeling
5. RESULTS
5.1. LASER SCANNING - EQUIPMENT

<table>
<thead>
<tr>
<th><strong>FARO Focus 3D</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Resolution 710.7 Million of points / scan</td>
</tr>
<tr>
<td>Purchased in 2011</td>
</tr>
<tr>
<td>Maximum Measurement Speed 976,000 pts/s</td>
</tr>
<tr>
<td>Ranging error ± 2mm @ 10 m</td>
</tr>
<tr>
<td>Internal Compass</td>
</tr>
<tr>
<td>No integrated GPS</td>
</tr>
</tbody>
</table>
5.1. LASER SCANNING – STATIONS LOCATION

13 m Between stations

6.5 m Between stations and reference objects
5.2. VIRTUAL DISCONTINUITY MAPPING
5.2. VIRTUAL DISCONTINUITY MAPPING - RESULTS

Trace Length

Set 1
Set 2
Set 3
Set 4

Log-normal
μ=0.33373
σ=0.65988
Log-normal
μ=0.31829
σ=0.77215
Log-normal
μ=0.019
σ=0.74999
Log-normal
μ=0.77886
σ=0.93466

Fracture Density $P_{10}$

Set 1
Set 2
Set 3
Set 4

Normal
μ=0.111
σ=0.451
Max=0.376
Q0=1.180
Min=0.447
Max=1.847
Normal
μ=0.928
σ=0.492
Max=0.477
Normal
μ=0.941
σ=0.477
A DFN is a three-dimensional geometric representation of a geological structure based on statistical information of its characteristics measured on the field (Pierce, 2017).

- Orientation
- Fracture Density
- Joint Size

Exposure 4. Coastal cave in a layered rock mass, UK (Hudson & Xia, 2015)
5.4. PRELIMINARY NUMERICAL MODEL (3DEC)
5.4. PRELIMINARY NUMERICAL MODEL (3DEC)

- Inner section: Fractured rock mass
  - Cut by 4 DFNs (20 m x 20 m x 20 m)
- External section: Massive rock mass – Fixed blocks
- Excavation Dimensions
  - 20 m length
  - 12.8 m width
  - 7.6 m height
- Stresses @ 700 m deep
  - $\sigma_v = 18.54 \text{ MPa}$
  - $\sigma_h = 20.39 \text{ MPa}$
5.4. PRELIMINARY NUMERICAL MODEL (3DEC)

- Rigid block model (Blocks assumed infinitely stiff)
- Rock Density = 2.7 ton/m³
- Mohr - Coulomb Constitutive Model for Fractures
  - $\phi = 30^\circ$ & cohesion = 0
  - $J_{ks} = 30$ MPa/mm
  - $J_{kn} = 300$ MPa/mm  
    (Bandis, Lumsden, & Barton, 1983)
- 1000 Initial cycles
- Progressive excavation (6 stages) – 5 m sections
  - 1000 cycles elastic – Damping
  - 1000 cycles plastic
  - time step of $3.81 \times 10^{-6}$ s
5.4. PRELIMINARY NUMERICAL MODEL (3DEC)
5.5. STOCHASTIC DISCRETE ELEMENT MODEL
5.5. STOCHASTIC DISCRETE ELEMENT MODEL - RESULTS
5.6. MODEL VALIDATION
6. CONCLUSIONS

- TLS was proved to be a powerful tool for rock mass characterization.

- An adequate Laser scan project planning allowed
  - to save time during the scanning process
  - reduce errors on the resulting point clouds
  - obtain the necessary information required for virtual discontinuity mapping.

- DEM software such as 3DEC is a powerful tool to interpret and analyze structurally controlled instability in underground excavations.

- TLS and DEM were successfully integrated to estimate the probability of rock falls in an underground excavations.
6. CONCLUSIONS

- A clear understanding of the geological model of the site is important in order to improve the results from virtual discontinuity mapping and the fractured rock mass model.

- A rigid block model assumption yielded results that agreed with the field observations and laser scanning results.

- A stochastic Discrete element modeling approach was selected for the analysis due to the stochastic nature of DFNs.

- The present methodology can be used as a method for rock fall hazard identification in underground limestone mines. It can be easily integrated into a groundcontrol risk management system.

- The case study mine offered an ideal environment to apply both technologies.
QUESTIONS?
REFERENCES

REFERENCES

### 5.1. LASER SCANNING - OPERATIONAL CONDITIONS

<table>
<thead>
<tr>
<th>Scan</th>
<th>Resolution</th>
<th>Quality</th>
<th>Real Scan time [hh:mm:ss]</th>
<th>Point Count</th>
<th>Average Point Cloud Density [Points/cm²]</th>
<th>Overall Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-006</td>
<td>44.4</td>
<td>1/4</td>
<td>0:05:12</td>
<td>38,103,388</td>
<td>11.42</td>
<td>5.04</td>
</tr>
<tr>
<td>S-007</td>
<td>44.4</td>
<td>1/4</td>
<td>0:06:06</td>
<td>41,229,797</td>
<td>12.48</td>
<td>4.31</td>
</tr>
<tr>
<td>S-008</td>
<td>44.4</td>
<td>1/4</td>
<td>0:07:53</td>
<td>41,684,133</td>
<td>12.64</td>
<td>3.36</td>
</tr>
<tr>
<td>S-009</td>
<td>44.4</td>
<td>1/4</td>
<td>0:12:28</td>
<td>41,229,797</td>
<td>12.66</td>
<td>2.34</td>
</tr>
<tr>
<td>S-010</td>
<td>28.4</td>
<td>1/5</td>
<td>0:05:27</td>
<td>26,273,301</td>
<td>8.06</td>
<td>4.79</td>
</tr>
<tr>
<td>S-011</td>
<td>28.4</td>
<td>1/5</td>
<td>0:06:36</td>
<td>26,573,225</td>
<td>8.13</td>
<td>3.96</td>
</tr>
<tr>
<td>S-012</td>
<td>28.4</td>
<td>1/5</td>
<td>0:08:54</td>
<td>26,630,099</td>
<td>7.97</td>
<td>2.95</td>
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</tbody>
</table>

**Point Cloud Densities for Structural Mapping**

<table>
<thead>
<tr>
<th>Author</th>
<th>Point cloud density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lato, Diedrichs, Hutchinson and Harrap, 2009</td>
<td>4 points/cm²</td>
</tr>
<tr>
<td>Cacciari &amp; Futai, 2017</td>
<td>16 points/cm²</td>
</tr>
<tr>
<td>Monsalve, Baggett, Bishop &amp; Ripepi, 2018</td>
<td>11 points/cm²</td>
</tr>
</tbody>
</table>
5.1. LASER SCANNING - OPERATIONAL CONDITIONS

- Laser scanner at a distance of 10m
- Laser scanner at a distance of 20m

<table>
<thead>
<tr>
<th>Resolution / Quality</th>
<th>Quality</th>
<th>Observation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>4x</td>
<td>1 µs</td>
</tr>
<tr>
<td>1/32</td>
<td>8x</td>
<td>8 µs</td>
</tr>
</tbody>
</table>

- Increasing the quality reduces the noise in the distance measurement.
  - Thickness of a flat object
  - Scan points in far objects
### 5.1. LASER SCANNING - SCANS REFERENCING

<table>
<thead>
<tr>
<th>Sphere size</th>
<th>145 mm</th>
<th>Sphere size</th>
<th>230 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution Setting Target Distance (max) in m</td>
<td>Resolution Setting Target Distance (max) in m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/16</td>
<td>5</td>
<td>1/16</td>
<td>7</td>
</tr>
<tr>
<td>1/10</td>
<td>7</td>
<td>1/10</td>
<td>11</td>
</tr>
<tr>
<td>1/8</td>
<td>9</td>
<td>1/8</td>
<td>14</td>
</tr>
<tr>
<td>1/5</td>
<td>15</td>
<td>1/5</td>
<td>22</td>
</tr>
<tr>
<td>1/4</td>
<td>18</td>
<td>1/4</td>
<td>27</td>
</tr>
<tr>
<td>1/2</td>
<td>37</td>
<td>1/2</td>
<td>55</td>
</tr>
<tr>
<td>1/1</td>
<td>73</td>
<td>1/1</td>
<td>110</td>
</tr>
</tbody>
</table>

**Recommended target spacing**
## 5.1. LASER SCANNING - DATA REGISTRATION

<table>
<thead>
<tr>
<th>Scan Point Statistics</th>
<th>Obtained Values</th>
<th>Acceptable values</th>
<th>Unacceptable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Point Error</td>
<td>6.7 mm</td>
<td>&lt; 8 mm</td>
<td>&gt; 20 mm</td>
</tr>
<tr>
<td>Mean Point Error</td>
<td>4.3 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Overlap</td>
<td>25.2 %</td>
<td>&gt; 25.0 %</td>
<td>&lt; 10.0 %</td>
</tr>
</tbody>
</table>
8. FUTURE WORK

- Site Scanning and Discontinuity Characterization
- Pillar Strength Determination
- Stress level Estimation
- Stochastic Analysis and Probability Distribution Estimation
- Probability of Failure Estimation

Factor of safety:
\[
F.S. = \frac{S_b}{S_{\text{cr}}}
\]

Limit state function:
\[
g(S_p, S) = S_b - S_p
\]

Failure set:
\[
P(\text{failure}) = P(F.S. < 1) = P(S_b < S_p)
\]

Reliability index:
\[
\beta = \frac{S_b}{S_p}
\]

Expected value of the limit state function:
\[
\mu_g = \mu_S + \mu_p
\]

Standard deviation of the limit state function:
\[
\sigma_g = \sqrt{\sigma_S^2 + \sigma_p^2 - 2\rho_{S_p}\sigma_S\sigma_p}
\]

Pillar probability of failure:
\[
P_f = 1 - \Phi(\beta)
\]