The Geomechanics of Single-Seam and Multi-Seam Longwall Coal Mining

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I hereby certify that the work embodied in this thesis contains published paper/s/scholarly work of which I am a joint author. I have included as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publication/s/scholarly work.

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<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>curve fitting coefficient</td>
</tr>
<tr>
<td>$a$</td>
<td>rock mass constant used in Hoek-Brown failure criterion</td>
</tr>
<tr>
<td></td>
<td>dimensionless constant in the equation of Terzaghi strain-stiffening material</td>
</tr>
<tr>
<td>$B$</td>
<td>thickness of interburden between top seam and second seam, also referred to as IB</td>
</tr>
<tr>
<td>$b$</td>
<td>curve fitting coefficient</td>
</tr>
<tr>
<td>$b$</td>
<td>bulking factor</td>
</tr>
<tr>
<td>$c$</td>
<td>rock mass cohesion</td>
</tr>
<tr>
<td>$D$</td>
<td>thickness of bedding layers</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s Modulus of the strata</td>
</tr>
<tr>
<td>$E_c$</td>
<td>Young’s modulus of coal</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Young’s modulus of the goaf</td>
</tr>
<tr>
<td>$E_i$</td>
<td>initial tangent Young’s modulus of the Terzaghi strain-stiffening material</td>
</tr>
<tr>
<td>$E_o$</td>
<td>Young’s modulus of overburden strata</td>
</tr>
<tr>
<td>$E_s$</td>
<td>secant Young’s modulus</td>
</tr>
<tr>
<td>$E_t$</td>
<td>tangent Young’s modulus</td>
</tr>
<tr>
<td>$G_{iso}$</td>
<td>isotropic shear modulus</td>
</tr>
<tr>
<td>$G'$</td>
<td>independent shear modulus</td>
</tr>
<tr>
<td>$GSI$</td>
<td>Geological strength index</td>
</tr>
<tr>
<td>$H$</td>
<td>depth of top seam, also referred to as OB</td>
</tr>
<tr>
<td>$h_c$</td>
<td>height of caving above the longwall panel roofline</td>
</tr>
<tr>
<td>$h_g$</td>
<td>height of caved zone above the longwall panel floor</td>
</tr>
<tr>
<td>$h_f$</td>
<td>maximum height to failing surface</td>
</tr>
<tr>
<td>$K$</td>
<td>ratio of horizontal in situ stress to vertical in situ stress</td>
</tr>
<tr>
<td>$K_s$</td>
<td>relative shear stiffness value of a joint set</td>
</tr>
<tr>
<td>$N$</td>
<td>stability parameter</td>
</tr>
<tr>
<td>$M$</td>
<td>stability parameter</td>
</tr>
<tr>
<td>$m_i$</td>
<td>material constant used in Hoek-Brown failure criterion</td>
</tr>
<tr>
<td></td>
<td>reduced value of material constant used in Hoek-Brown failure criterion</td>
</tr>
<tr>
<td>$Q$</td>
<td>stability parameter</td>
</tr>
<tr>
<td>$R$</td>
<td>shear compliance of a joint set</td>
</tr>
</tbody>
</table>
s  rock mass constant used in Hoek-Brown failure criterion
si  convergence of the roof and the floor of a longwall panel at the time of contact with caved goaf
S  percentage sandstone in the interburden
    regular spacing of a joint set
S_{edge}  vertical subsidence above the edge of the longwall panel
S_{max}  maximum vertical subsidence above the longwall panel
S_{max1}  maximum incremental subsidence above a first seam longwall panel
S_{max2}  maximum incremental subsidence above a second seam longwall panel
T  extracted coal seam thickness
T_{x}  extracted thickness of seam, where x is the order of seam extracted
W  width of longwall panel from centreline of gateroad
W_{eq}  equivalent extracted width for horizontal stress redistribution
(W/H)_{crit}  critical width of cavity corresponding to the boundary of subcritical and supercritical failure of the overburden
w  width of pillar (rib to rib)
\beta  abutment or shear angle
\gamma  unit weight of rock mass
\varepsilon  strain
\theta  the angle between the failure surface and vertical
\sigma_{ci}  uniaxial compressive strength of intact rock
\sigma_{n}  normal stress
\sigma_{t}  tensile strength of the rock mass
\sigma_{t*}  tension cut-off, i.e., prescribed maximum tensile strength of the rock mass
\sigma_{h}  horizontal stress
\sigma_{hi}  initial horizontal stress before mining of the first seam
\sigma_{v}  vertical stress
\sigma_{vi}  initial vertical stress before mining of the first seam
\sigma'_{i}  effective major principal stress
\sigma'_{2}  effective minor principal stress
\sigma'_{3max}  upper limit of \sigma'_{3} for calculating equivalent Mohr-Coulomb parameters
\tau  shear stress
\nu  Poisson’s ratio
\[ \phi \] rock mass friction angle

**Parameters for Wilson’s equation for vertical stress distribution around a longwall panel (Wilson, 1980)**

- \( F \): constant
- \( C \): stress dissipation constant
- \( k \): Rankine passive stress state constant
- \( M \): height of extraction
- \( p \): restraint on boundary of opening
- \( q \): overburden stress
- \( \sigma_0 \): unconfined compressive strength of coal
- \( \sigma'_0 \): unconfined compressive (residual) strength of failed coal
- \( \hat{\sigma} \): peak abutment stress

**Parameters for Gerrard’s equations for equivalent elastic moduli of a rock mass consisting of orthorhombic layers (Gerrard, 1982)**

- \( t \): thickness of a stratum layer with constant Young’s modulus
- \( \alpha \): constant
- \( \beta \): constant
- \( \gamma \): constant
- \( \zeta \): constant
- \( \lambda \): constant
- \( \chi \): constant
ABSTRACT

In coal mining, the most favourable and most easily won coal reserves are depleted first, typically from within a single coal seam. A recent trend in Australia and elsewhere in the world is to attempt to recover coal from multiple seams within a single site, a practice known as multi-seam mining. With longwall mining becoming one of the safest and most economical means of underground extraction of coal in Australia, we are likely to see an increase in the number of multi-seam longwall mining operations. Evidence thus far has indicated that the geomechanics of multi-seam longwall mining differs from that of single-seam longwall mining, especially with respect to variations in mine stability and subsidence.

The overarching aim of this Thesis is to critically compare predicted stresses and deformations for single-seam and multi-seam longwall mines based on commonly used constitutive laws and continuum-based modelling assumptions. The main approach used to predict stresses and deformations is the displacement finite element method. Finite element limit analyses of roof collapse are also considered. In all cases, two-dimensional (plane strain) conditions were assumed, and focus is on relatively wide longwall panels at shallow depth, known as supercritical longwall panels. Key objectives are to predict stress redistributions in multi-seam longwall mines, roof collapse in underground openings, and subsidence profiles above single-seam and multi-seam longwall mines.

The changes in the vertical and horizontal stress distribution due to the extraction of a series of parallel longwall panels were predicted using isotropic and anisotropic linear elastic constitutive laws to represent the coal measure strata. The key finding from the study of vertical stress redistribution is that the abutment angle, the overburden depth, the pillar width and the anisotropic behaviour most influence the change in the in situ vertical stress in the lower seam. The redistribution of horizontal stress originally transmitted through the overburden generates smaller changes to the in situ stresses in the rock strata below the first mined seam than is predicted for the vertical stress. Transversely isotropic material causes the vertical stresses imposed onto the chain pillars to be transferred deeper into the underlying strata. The implications of the findings are that the predicted rapid changes in vertical stress with horizontal distance in transverse isotropic strata behaviour are likely to be reflected in more sudden changes in
rock mass response which pose a safety risk.

The differences occurring in predictions of roof collapse in underground rectangular cavities using the Hoek-Brown and Mohr-Coulomb failure criteria were evaluated. The predicted shape of the failure surface is shown to be governed by the friction angle of the rock mass. The friction angle also governs the so-called critical width, which corresponds to the boundary between subcritical and supercritical failure of the overburden. The predictions of the critical width matches best field observations in the New South Wales coalfields when the linear Mohr-Coulomb failure criterion is used with a friction angle of approximately 30 degrees. The prediction of the critical width when using the Hoek-Brown failure criterion overestimates the value observed in the field. This is because the Hoek-Brown failure criterion corresponds to effectively high friction angles in the range of tensile and very low confining stresses encountered in the strata above underground openings. Stability charts for rectangular cavities using the Hoek-Brown failure criterion and two forms of the Mohr-Coulomb failure criterion are presented to enable designers of underground openings to predict rapidly the safe widths of underground cavities.

Predictions of vertical subsidence profiles above single-seam and multi-seam longwall panels are compared using various constitutive laws to represent the coal measure strata and goaf. A key finding is that the best agreement between the numerical predictions and the field observations, for both the single-seam and multi-seam supercritical longwall cases, is when the coal measure strata is represented as an elastic material with closely spaced frictionless interfaces representing bedding planes. Representing the coal measure strata as a bedded material also allows for the vertical stresses to return to the level of the original overburden stress in the caved goaf material within the first seam, prior to extraction of the second seam. The results show that more sophisticated and numerically taxing constitutive laws do not necessarily lead to more accurate results when compared to field measurements. A case study based on a multi-seam mine in the Hunter Valley assists in validating the conclusions made in the comparative study.

The findings presented in this Thesis will enable engineers to design economically viable multi-seam longwall mines, while still meeting legislative needs in terms of the environment and safety of personnel.