Numerical modeling of mining subsidence in the Southern Coalfield of New South Wales, Australia

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ABSTRACT: Mining subsidence associated with longwall extractions beneath significant natural features such as rivers and streams in the Southern Coalfield of New South Wales has posed risks to the natural environment. In this paper, a case study is presented showing the methodology in two-dimensional UDEC (Itasca 2006) modeling for mining induced subsidence around river valley, taking advantage of the discretization based on Voronoi diagram. The potential three-dimensional modeling method for subsidence is also introduced in this paper.

1 INTRODUCTION

The natural features of the Southern Coalfield of New South Wales in Australia include river valleys, steams, cliff lines and various sorts of water formations. Due to such geomorphology, a number of longwall operations have been or will be completed under the irregular topographic conditions. Figure 1 illustrates the geography conditions, major watercourses, major water bodies and mining works in the Southern Coalfield.

The impacts of underground mining on the natural features in the Southern Coalfield have been studied extensively (Kay & Carter 1992, Klenowski 2000, Waddington & Kay 2001, 2002, NSW Dept. of Planning 2008), and it has been found that mining induced subsidence effects on the natural features are associated with valley closure subsidence effects, resulting in adverse influences on rivers and significant streams and especially the cracking of river beds and underlying strata (Figs. 2a, b), and those environment consequences must be managed.

Subsidence and valley related movements associated with longwall mining have been assessed and predicted by empirical methods currently (Waddington & Kay 2001, 2002), which are based on statistical analyses of previously monitored data from extensive site observations, and they demonstrate high predictive accuracy for surface subsidence. However they have limited capacity to investigate the physical mechanisms within the rock strata. There are also many numerical modeling attempts to study the mechanisms of these behaviors (Kay et al. 1991, Chugh et al. 1994, Gale 1998, 2004, Waddington & Kay 2002), but it is challenging to simulate the mining induced fracture network due to the limitations of the modeling methods (Jing & Hudson 2002). In this paper, a case study is presented showing the methodology in two-dimensional modeling for mining induced subsidence, and potential three-dimensional modeling method for subsidence is also demonstrated, taking into account the mining induced fracturing development.
2 DESCRIPTION OF THE SITE

The Metropolitan Colliery is located in the Southern Coalfield of New South Wales, Australia. It has been mining Bulli Seam coal with an average height of 3.2 m, in the vicinity of the Waratah Rivulet, a major tributary of the Woronora Water Supply Reservoir. The layout of longwall extractions and the location of ground movement monitoring line D are shown in Figure 3a. Figure 3b shows one of the rockbars in the Waratah Rivulet that is affected by the underground extractions.
The surface topography along line D, location of the Bulli Seam coal, depth of cover and the monitoring of subsidence are detailed in Figure 4a (DeBono & Tarrant 2011). The geology in the area of interest mainly includes sedimentary sandstones, shales and claystones of the Permian and Triassic Periods, and the stratigraphic section of the overburden is shown in Figure 4b.

Figure 3. a) Longwall 1 to 18 layout in Metropolitan Colliery and survey line D; b) aerial photo of one of the rockbars affected by mining extraction beneath (Mills 2006).

Figure 4. a) Monitoring data of line D; b) generalized stratigraphic section of Metropolitan Colliery (DeBono & Tarrant 2011).
3 TWO-DIMENSIONAL UDEC MODELING APPROACH

In this section, the work conducted in the development of DEM code UDEC (Itasca 2006) model is outlined to model the mining induced subsidence around a river valley, taking advantage of the two-dimensional domain discretization based on Voronoi diagram.

3.1 Model basics

The Voronoi tessellation technique has been well accepted for simulating rock microstructure and crack propagation (Nygård & Gudmundson 2002, Zhang et al. 2005, Li et al. 2006, Lan et al. 2010, Kazerani 2010). It creates randomly sized polygonal blocks, and the contact forces and displacements of polygonal blocks are found by tracing the movements of the individual blocks. In the process of calculation, the displacement of the block is governed by Newton’s second law; and the contact forces resulting from the relative motion are determined by the force-displacement law (Itasca 2006). Figure 5 depicts the calculation algorithm within the Voronoi block model. The equations in Figure 5 are described below.

\[ \begin{align*}
\vec{F}^i &= \sum_c \vec{F}^i_c \\
\vec{M}^i &= \sum_c \vec{x}^i_c \times \vec{F}^i_c
\end{align*} \]

Motion law for particle

Constitutive law for contact

In the process of calculation, the motion of each Voronoi particle is governed by Newton’s second law, which can be written as (the one-dimensional motion of a single mass)

\[ \frac{d\vec{u}}{dt} = \frac{F(t)}{m} \]  

(1)

where \( \vec{u} \) is the velocity, \( t \) is the time, \( F(t) \) is a varying force and \( m \) is the mass. The central difference scheme for the left-hand side of Equation 1 at time \( t \) can be written in the form

\[ \frac{d\vec{u}}{dt} = \frac{\vec{u}^{(t+\Delta t/2)} - \vec{u}^{(t-\Delta t/2)}}{\Delta t} \]  

(2)

Substituting Equation 2 in Equation 1 and rearranging yields

\[ \vec{u}^{(t+\Delta t/2)} = \vec{u}^{(t-\Delta t/2)} + \frac{F(t)}{m} \Delta t \]  

(3)

With velocities stored at the half-time step point, displacement can be express as

\[ u^{(t+\Delta t)} = u^t + \vec{u}^{(t+\Delta t/2)} \Delta t \]  

(4)

Figure 5. Solution algorithm within the Voronoi block model.
The force/displacement calculation is done at one time instant because the force depends on displacement. For blocks in two dimensions, taking into account gravity and other forces, the velocity equations become

\[
\dot{u}_i(t+\Delta t/2) = \dot{u}_i(t-\Delta t/2) + \left(\frac{\Sigma F_i(t)}{m_i} + g_i\right) \Delta t
\]

\[
\dot{\theta}(t+\Delta t/2) = \dot{\theta}(t-\Delta t/2) + \left(\frac{\Sigma M_i(t)}{I_i}\right) \Delta t
\]

where \(\dot{\theta}\) is the angular velocity of particle around centroid; \(I\) is the moment of inertia of particle; \(\Sigma M\) is the total moment acting on it; \(\dot{u}_i\) is the velocity component of particle centroid; \(g_i\) is the gravitational acceleration component. In Equation 5 and those that follow, \(i\) denotes components in a Cartesian coordinate frame. The new velocities in Equation 5 are utilized to determine the new particle location according to

\[
\chi_i(t+\Delta t) = \chi_i(t) + \dot{u}_i(t+\Delta t/2) \Delta t
\]

\[
\theta(t+\Delta t) = \theta(t) + \dot{\theta}(t+\Delta t/2) \Delta t
\]

where \(\chi_i\) are the coordinates of particle centroid and \(\theta\) is the rotation of particle about centroid.

Each time step results in new particle positions which generate new contact forces. Linear and angular accelerations of each particle are calculated based on resultant forces and moments, and particle velocities and displacements are determined by integration over increments in time. The calculation is repeated until a satisfactory state of equilibrium or continuing failure results (Itasca 2006).

As for contact constitutive law, in the normal and shear direction, the contact law is assumed to be linear and determined by the normal stiffness \(k_n\) and the shear stiffness \(k_s\)

\[
\Delta F_n = -k_n \Delta u_n
\]

\[
\Delta F_s = -k_s \Delta u_s
\]

where \(\Delta F_n\) and \(\Delta F_s\) represents the effective normal stress increment and the increment of elastic shear force, respectively; \(\Delta u_n\) is the normal displacement increment while \(\Delta u_s\) represents the shear displacement increment.

If the maximum tensile stress exceeds the tensile strength for joint \((-F_n^{\max} \geq F_n)\), then \(F_n = 0\). The shear stress \(F_s\) is limited by a combination of cohesive strength \((C)\) and frictional strength \((\phi)\). So if

\[
|F_s| \geq F_s^{\max} = \tan \phi F_n
\]

then

\[
F_s = \text{sign}(\Delta u_s) F_s^{\max}
\]

Contact breaks when the joint strength between Voronoi blocks is exceeded. Because the particles are assumed to have an elastic behavior, the failure is controlled only by the contact constitutive law. More detailed description of the Voronoi diagram can be found in the literature (Zhou & Zhao 2011, Itasca 2006).

### 3.2 Model setup

The UDEC modeling work in this paper is focused on simulating the extractions of longwall 11, 12 and 13, which are beneath the Waratah Rivulet. The model geometry is depicted in Figure 6.
The surface topography is generated using the coordinates of the survey points D41 to D119 on line D. The geometry modeled is longwall panels 11, 12 and 13 progressively extracted at 163 m widths with a 35 m pillar, based on the mining geometry of Metropolitan Colliery. A mining height of 3 m is used as the average thickness of the Bulli Seam is around 3.2 m, as mentioned in section 2. Based on the geological research (Geosensing Solutions 2008), there are no significant geological structures near line D for the mining of longwall 11 to longwall 13, thus no structural element such as faults is included in the modeling.

According to the field measurements, the fracture system is mainly developed within the Hawkesbury Sandstone formation, thus in order to achieve manageable computational time and memory requirements, Voronoi tessellation is used only in the Hawkesbury Sandstone, and the region of interest is discretized into 7 m large Voronoi blocks based on the recommendations of Pells (1993), which recommends the joint spacing in Hawkesbury Sandstone is around 7 to 15 m.

![Figure 6. Numerical model layout.](image)

In the model, the constitutive model of Mohr Coulomb is used. The bedding planes and vertical joints are assigned a friction angle of 25 degree based on the recommendations of Waddington & Kay (2002). In the UDEC Voronoi block model, the polygons merely represent the discrete flows in the rock numerically, rather than the real rock structures, thus the model is calibrated to the material’s actual macroscopic response by modifying the micro mechanical parameters. The procedures recommended by Kaiser & Kim (2008) and Kazerani & Zhao (2010) are followed for the calibration of the Voronoi blocks representing the Hawkesbury Sandstone. Table 1 and 2 list the macro-properties of the Hawkesbury Sandstone and the calibrated micro-properties. Other geomechanical conditions for the model are derived from the study of Waddington & Kay (2001, 2002), Sharrock et al. (2009) and Tarrant (2006).

<table>
<thead>
<tr>
<th>Table 1. Macro-properties of the Hawkesbury Sandstone.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (GPa)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>UCS (MPa)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. Calibrated Micro-properties representing the Hawkesbury Sandstone.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint normal stiffness (GPa)</td>
</tr>
<tr>
<td>Joint shear stiffness (GPa)</td>
</tr>
<tr>
<td>Joint Cohesion (MPa)</td>
</tr>
</tbody>
</table>

3.3 Comparisons of the modeled subsidence with field data

Subsidence monitoring has been conducted to measure the ground movements along Line D. In order to assess the influence of single panel extraction on ground movements, incremental subsidence is used for the analysis, which is referred to as the difference between the subsidence at
a point before and after a panel is excavated. The incremental subsidence monitored on the D line associated with the extraction of longwall 12, 13 is shown in comparison with the additional vertical displacement from the UDEC model in Figure 7. It should be noted that the subsidence due to longwall 11 extraction is the reference value for the calculation of the incremental subsidence, so it is not included in the figure. The summary of the observed and modeled subsidence movement is listed in Table 3.

Table 3. Summary of modeled and observed subsidence.

<table>
<thead>
<tr>
<th>Subsidence index</th>
<th>Modeled value</th>
<th>Field value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum incremental subsidence due to LW12 extraction</td>
<td>898.3 mm</td>
<td>835.6 mm</td>
</tr>
<tr>
<td>Maximum incremental subsidence due to LW13 extraction</td>
<td>832.3 mm</td>
<td>770.3 mm</td>
</tr>
</tbody>
</table>

Figure 7 illustrates good correlation with the subsidence troughs in the field and indicated from modeling. It can be seen from Table 3 that the maximum observed subsidence is slightly less than modeled subsidence for both longwall 12 and longwall 13. The movements are within the level of accuracy, based on the recommendation of Mining Subsidence Engineering Consultants (2008), which suggests that the calculations should be accurate to within 50 mm difference of subsidence. Thus, the UDEC Voronoi block model has been validated to provide good capability in simulating the mining induced subsidence.

The near surface shear failure is illustrated in Figure 8. It should be noted that in the two-dimensional UDEC model, the model is treated as being in plane strain. The UDEC Voronoi model presented here is merely based on the two-dimensional cross-section of the ground surface. Future modeling in three-dimensions will be validated against results from the field. The two-dimensional application discussed in this section of the paper was conducted as part of the initial modeling exercise.
4 THREE-DIMENSIONAL POTENTIAL MODELING APPROACH

Three-dimensional modeling of mining induced subsidence in the Southern Coalfield has been conducted by many researchers using both continuum and discontinuous numerical modeling codes (Chugh et al. 1994, Waddington & Kay 2002, Guo et al. 2004). Figures 9a, b illustrate an example of the three-dimensional modeling of mining beneath the intersection of the river gorges.

It is difficult for the current three-dimensional modeling to build the grain structure of the rock in order to simulate the mining induced rock fracturing around the natural features. 3DEC model with polyhedron output using Voronoi tessellation is a promising way to work on this issue. The numerical formulation for a three-dimensional distinct element code 3DEC is more complex than that in the two-dimensional version. The major elements of this formulation are the scheme for contact detection and representation in three-dimensions, and the mechanical calculations for motion and interaction in three-dimensions. Details are provided by Cundall (1988) and Hart et al. (1988).

It is necessary to note that the three-dimensional Voronoi volume element structure for 3DEC is still under development. Herbst et al. (2008) pioneer the use of Voronoi element in 3DEC. It is possible to use either rigid or deformable Voronoi elements in 3DEC for modeling rock mass. Figure 10 shows calculation results using Voronoi body provided. Figure 11 illustrates the fracturing of the model with rigid Voronoi elements under horizontal load at the top and fixed bot-
tom, and the contour of vertical displacements for the deformable Voronoi body with fixed bottom and compressive force acting at the top.

Figure 10. Rigid Voronoi bodies (left) and deformable with zones (right) in 3DEC (Herbst et al. 2008).

Figure 11. Fractured and deformed shape for the rigid Voronoi bodies (left) and Y-displacements for the Voronoi blocks with deformable zones (right) in 3DEC (Herbst et al. 2008).

5 CONCLUSIONS

This paper simulates the mining induced subsidence using the UDEC Voronoi block model. The results presented in the study shows the capability of the UDEC model for simulating the complex mining subsidence displacement in terms of both pattern and magnitude. Due to utilization of the Voronoi tessellation technique, the UDEC Voronoi block has advantages in dealing with the rock failure around the nature features, compared to the regular UDEC model. It should be noted that in the two-dimensional UDEC model, the model is treated as being in plane strain. The UDEC Voronoi model presented here is based on the cross-section of the ground surface. It is difficult to model the fracture development associated with mining subsidence realistically and in high accuracy, because the real world issues are in three-dimensions. 3DEC with Voronoi elements is considered to provide better capability to simulate the overburden fracturing above longwall excavations, though the three-dimensional Voronoi volume element structure for 3DEC is still under development.

The study of the fracture systems in three-dimensional would improve the understanding of the damage development associated with mining subsidence. Moreover, it should be noted that more detailed information on geology would be vastly helpful to establish a greater degree of accuracy on the simulation of mining subsidence, so extensive field monitoring and validation are essential in the process of modeling to ensure that the subsidence and the mining induced fracture network are being simulated in a realistic manner.
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