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INTEGRATED FIELD STUDIES FOR OPTIMAL GOAF GAS DRAINAGE DESIGN IN MULTI-SEAM LONGWALL MINING

Qingdong Qu¹, Hua Guo², Clint Todhunter³, Hamish Kerr⁴, Luke Babic⁵ and Rohan McGeachie⁶

ABSTRACT: Optimisation of mine goaf gas drainage design needs to fully recognise mine geological conditions, mining induced caving characteristics and gas flow dynamics. This paper presents the integrated geotechnical and gas field studies carried out at the Blakefield South mine for optimisation of longwall goaf gas drainage. A set of instruments including extensometers, piezometers, gas pressure gauges, tracer gases and borehole cameras were adopted in these studies. The overburden strata caving processes, coal seam pore pressure changes, multi-seam gas flow paths, goaf gas pressure dynamics, and drainage borehole stability were observed. The studies enabled a clear identification of the extent and characteristics of mining influence, sources of gas emissions in both the roof and floor and goaf gas flow dynamics, and have led to a successful design and implementation of an optimal goaf gas drainage system at the Blakefield South mine.

INTRODUCTION

Longwall gas emissions in multi-seam mining conditions are very complex as they are a dynamic process associated with the interaction of mining induced strata, groundwater and gas behaviours. Previous studies (Guo et al., 2012, 2014, 2015 and Qu et al., 2015) have showed that a clear understanding of this dynamic and coupled process is critical to the development of an optimal goaf gas drainage design. In addition, goaf gas drainage performance such as drainage methane concentration is also influenced by the interaction between ventilation, gas drainage and goaf gas emission. Integrated field studies covering all of these aspects are of significance to optimisation of coal mine methane drainage and emission abatement.

Supported by the Coal Mining Abatement Technology Support Package (CMATSP), a collaborative research project, entitled “Mine methane capture optimisation and maximisation of emissions abatement” is being undertaken by CSIRO and the Glencore Bulga Underground Operations. The project aims at developing and demonstrating a holistic and optimal approach to planning, design and operational control of mine gas drainage through a better understanding of coupled strata, ground water and gas behaviour during mining.

Integrated field geotechnical and gas studies were therefore implemented at the Blakefield South mine of Bulga Underground Operations. These studies covered a series of monitoring and measurement programs including overburden movement, ground water pressure changes, seam gas migration patterns, gas content changes before and after mining, gas flow patterns in the goaf, and surface vertical drainage borehole stability. This paper introduces the integrated field studies and presents the key results.

MINE CONDITIONS

The Blakefield South mine is located 15 km southwest of Singleton in New South Wales. It lies in the Hunter Coalfield, Northern Sydney Basin. The strata associated with the coal seams were laid down

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during the Permian Period and comprise the Wollombi and Wittingham Coal Measures of the Singleton Supergroup. The Wollombi Coal Measures are stratigraphically higher and contain poor quality coal seams while the Wittingham Coal Measures contain better quality and thicker coal seams.

The Blakefield South mine uses a three heading gate road development system to access longwall panels, which are 400 m wide (rib-to-rib) and up to 3.5 km long. Figure 1 shows the mine plan as of September 2013. The longwalls (bright yellow lines) are operated underneath existent goafs (dark yellow lines), mined by the South Bulga Mine in 1994-2003. The South Bulga mine extracted coal from the lower Whybrow coal seam, which lies approximately 70-100 m above the current mining seam. Panels in the Whybrow longwall were about 250 m wide with pillars between panels at 25 m.

![Figure 1: Mine plan of The Blakefield South mine as of September 2013](image)

The Blakefield South mine comprises four coal plies, 300, 301, 302 and 303 while the longwall extracts coal from the top three plies with a cutting height ranging from 2.8 m to 3.4 m. The Blakefield seam generally dips from north to south at 3 degrees, and its depth of cover above LW1 to LW3 varies between approximately 130 m and 260 m.

The Blakefield seam is surrounded by a number of gassy coal seams. It is overlain by the Redbank Creek, Wambo and Whynot seams, and underlain by the Glen Munro and Woodlands Hill seams. All these coal seams were predicted to be gas emission sources according to the FLugge model. Figure 2 shows a cross section of the Blakefield South mine with the gas content of each coal seam marked.

**INTEGRATED FIELD MONITORING AND MEASUREMENT PROGRAMS**

Prior to the development of the integrated field studies, extensive site characterisation of in-situ strata, hydrogeological and gas conditions were carried out at the Blakefield South mine. Furthermore, longwall gas drainage technical and operational data were collected and reviewed. It was decided that the following key aspects needed to be studied in order to provide adequate information to optimise gas drainage design for this specific mine.

- Caving process, extent and magnitude under the existing overlying Whybrow goafs
• coal seam pore pressure changes in response to mining
• gas emission sources, patterns, and dynamics as longwall advances
• effect of the existing Whybrow goafs on gas drainage performance
• surface goaf vertical well stability
• interaction between gas drainage, ventilation, and barometer pressure.

To study the above aspects, integrated monitoring and measurement programs were developed and implemented at the Blakefield South mine LW3. Figure 3 shows the plan view of the monitoring instrument locations. The key monitoring programs are described below.

**Figure 2: Cross section of the Blakefield South mine**

**Figure 3: Plan of the integrated monitoring programs**

**Surface deep-hole multi-anchor extensometers**

Two surface extensometers were installed, with one located at 142 m to the longwall panel maingate (MG) edge and the other 123 m to the tailgate (TG) edge. Each extensometer consisted of 11 anchors
covering a depth range from 11 m above the mining seam to 10 m below the ground surface. Most of the anchors were placed in the interburden between the Whybrow goaf and the working section. Both extensometer boreholes were cased to about 10-15 m below the Whybrow goaf to maintain borehole integrity. A surface data logger system, equipped with a solar panel, was installed to continuously record the readings at 15 minute intervals. Figure 4 (a) shows one of the extensometers surface data logger systems.

**Surface deep-hole multi-sensor piezometers**

Several piezometers were installed within the project period to monitor coal seam pore pressure dynamic changes with longwall mining and to assess gas desorption and migration processes in various coal seams. A key instrument was P3 (as denoted in Figure 3), which was installed at the MG chain pillar zone with a distance of 52 m from MG edge. This location was selected to avoid cable failure which might be caused by strata movement and surface subsidence. A total of seven piezometers were installed in this hole into all major coal seams from Redbank Creek to Woodlands Hill, as well as into interburden between the coal seams. Fibre optic piezometers were selected for this hole to avoid the risks of lightning strike. The piezometer readings were continuously recorded at 15 minute intervals by a surface data logger, as shown in Figure 4 (b).

**Goaf gas pressure dynamic changes using pressure gauges and tubes**

The mine uses a force-exhaust ventilation system to minimise pressure difference between the Blakefield South workings compared to the Whybrow old workings and to the surface. Monitoring goaf gas pressure dynamics is critical to assessing the effect of this ventilation system on the control of goaf gas emissions as well as goaf gas drainage performance. It is also of significance to understand the dynamic goaf gas pressure environment for development of an optimal gas drainage system.

Goaf gas pressure monitoring was achieved by connecting a tube between the goaf and a pressure gauge sitting on the ground surface to sense the variation of differential pressure between the goaf and surface atmosphere. Monitoring locations of goaf gas pressure changes included the Whybrow goaf, the Wambo seam and a few locations on the MG side of the active LW3 goaf. The surface pressure monitoring system (Figure 4(c)) was connected to the mine’s monitoring system Citec and the pressure gauge monitoring data was continuously recorded.

**Tracing seam and goaf gas flows**

Tracer gases were released from various locations of LW3 to study gas flows in the overburden fractured strata and the goaf. These tests included the injections of Sulfur hexafluoride (SF₆) into the Whybrow goafs, injection of SF6 into a packer-isolated borehole section at the Wambo seam, injections of helium into the LW3 intake corner, and injection of helium into the LW3 MG intake-goaf corner as well as into the LW3 deep goaf. Gas samples were taken through the mine’s tube bundle system from various designated locations in the LW3 goaf, ventilation return, and surface vertical goaf drainage wells. Gas composition measurements were taken with the mine’s Gas Chromatography for helium and CSIRO’s Gas Chromatography for SF6.

The tracer tests were to understand gas flow characteristics and paths within the flow field between the Whybrow goafs, overburden fractured strata, surrounding coal seams, Blakefield goafs, and the ventilation return. The tests also helped assess the effectiveness and mechanisms of goaf gas drainage.

**Coal seam gas content before and after LW3 excavation**

Measurement of coal seam gas content before and after longwall extraction directly identifies gas emission sources and evaluates gas release levels from various coal seams during longwall operation. Gas content measurements at different locations above the longwall panel can also reveal the emission
patterns around the longwall panel. Literature review shows that very limited data of gas content measurement before and after mining are available.

Gas content measurements were carried out at three locations of LW3, approximately along a line across the panel width. The two extensometers boreholes, E1 and E2, and the piezometer borehole P3 were drilled with coal cores taken from various coal seams for pre-mining gas content measurement. Three other holes were drilled after LW3 was finished at locations a few meters away from each of the pre-mining gas content measurement boreholes.

**Surface vertical goaf drainage wells inspection using special cameras**

The surface vertical goaf drainage wells at the Blakefield South mine were not satisfactory in controlling goaf gas emissions, particularly in the initial 400 m from the longwall start-up. Some drainage wells were operated for only a few days and then closed due to unacceptable high levels of oxygen in the drainage gas. In addition, the surface vertical wells were observed as having limited effect on reducing ventilation methane levels despite the high drainage flow rate in the wells. It was therefore valuable to inspect the drainage well integrity and stability status to further analyse issues associated with the poor performance of the surface vertical wells. The inspection results were also expected to be critical to the study of vertical well gas drainage mechanisms.

The inspection was conducted using SIMTAS special borehole cameras. A total of ten surface vertical wells at both LW3 and LW2 were inspected after LW3 was completed. These inspected boreholes were located at various locations relative to both the LW3 goaf edges and Whybrow goaf edges, with an aim of comparing the effect of drainage well locations on their stability and integrity.

![extensometer](image1.png) ![P3 fiber optic piezometer](image2.png) ![goaf gas pressure](image3.png)

**Figure 4: Some field monitoring systems implemented at the Blakefield South mine**

**KEY RESULTS AND ANALYSIS**

**Overburden caving process and features**

Both the extensometers successfully obtained the dynamic movement of overburden at different levels versus time. It is noted that the E1 gave more typical results than E2 as the former was located in the mid Whybrow goaf zone while the latter was located on the edge of Whybrow pillar zone. Figure 5 shows the monitored overburden movement by the extensometer E1.

Key observations from Figure 5 include:

- Strata movement at a level 11 m above the mining seam started at 12 m inbye the longwall face, and mining induced fractures and delaminations extended up to the Redbank Creek seam at 31 m inbye of the longwall face. This shows a quick response of overburden movement and relaxation as a result of mining which can lead to a quick release of coal seam gas.
• The dynamic process of overburden movement along the longwall retreat direction was clear. The overburden moved quickly once being inbye of the longwall face, reached the maximum delamination at about 60 m inbye, and became stable in another 60 m of retreat.

• Significant delaminations occurred through and up to the Whybrow goaf (as shown in Figure 5 (b)), indicating a high horizontal permeability was present in the goaf and the interburden.

• According to the typical model of overburden deformation (Peng, 2006), the overburden from 11 m up to the Redbank Creek seam could be characterised as the fractured zone as the delamination characteristics through the zone were similar.

![Image of monitored strata movement](https://via.placeholder.com/150)

(a) E1 monitored strata movement

![Image of overburden movement at various locations inbye of LW3](https://via.placeholder.com/150)

(b) overburden movement at various locations inbye of LW3

**Figure 5: Monitored overburden movement by extensometer E1**

### Coal seam pore pressure changes

The surface piezometer P3 was installed at the pillar zone between LW3 and LW4 with a distance of 52 m from LW3 MG goaf edge. Figure 6 shows the monitored pore pressure changes in all the major coal seams with longwall advance. Gas emission sources were also estimated from the monitored pore pressure changes.

The following key observations can be drawn from Figure 6:

• Redbank Creek, Wambo, lower Blakefield and Glen Munro coal seams were significantly depressurised during mining, indicating these coal seams would release gases and therefore are drainage targets.

• Woodlands Hill had no reduction of pore pressure, indicating gas would not be desorbed and released.

• The trend of pore pressure changes among the coal seams were different, indicating different gas desorption and release characteristics. Pore pressures in the two overlying coal seams at a location 500 m inbye of the longwall face were very low (close to atmospheric pressure); adsorbed gases in these coal seams would have mostly been released.

• Coal seam pore pressure started to decline at least 50m outbye of the longwall face, and continued up to 250 m inbye of the longwall face in the case of the Wambo seam.

With the measured concentration and the mine’s monitored flow rate, the quantity of SF6 travelling through drainage vertical wells and the ventilation return could be calculated and thus the SF6 flows
among various paths could be characterised. For tracing tests with helium, however, only major flow paths were able to be characterised due to the impact of background helium level in the goaf.

Figure 6: Coal seam pressure changes as longwall advances

Key observations associated with goaf gas drainage design are highlighted below.

- No SF6 was detected in the LW3 active goaf and in the ventilation return after the tracer was released into the overlying Whybrow goaf. It can be concluded that the Whybrow goaf gases did not flow down to the active goaf and therefore contribute to the ventilation gas makes. In other words, capturing gas from Whybrow goafs did not have an effect on reducing ventilation gas levels.
- High interconnection or conductivity exists within and across the overlying Whybrow goafs. This is indicated by the detection of SF6 from almost all operating drainage wells after releasing SF6 into a Whybrow goaf.
- Almost half of the SF6 released into the Wambo seam section flowed through the ventilation return and another half was captured by vertical drainage wells. This, to some extent, reflects the effectiveness of vertical drainage wells in capturing and controlling the coalseam roof gases.
- Deep goaf gases (745 m inbye of the longwall face) could hardly migrate into the ventilation return.

(a)SF6 concentration variation in drainage well 3J   (b) Possible SF6 flow paths
Figure 7: Gas flow characteristics analysed from a tracer test injecting SF6 into Wambo seam

Goaf gas pressure dynamics

Figure 8 shows the monitored gas pressure changes in the Wambo seam section versus methane levels in the ventilation return, for a period of four days. Gas pressure was monitored through a tube...
connecting the isolated Wambo seam section of a borehole to a pressure gauge sitting on the surface. Under the force-exhaust ventilation system, pressures in the active LW3 goaf and ventilation circuit were close to that on the surface. Therefore, the monitored Wambo seam gas pressure also reflects the differential pressure between Wambo seam and the active LW3 goaf.

It can be concluded from Figure 8 that:

- Changes of differential pressure between the Wambo seam and the active goaf correlate well with the changes of methane levels in the ventilation return. Increased differential pressure caused increased methane levels in the ventilation return simultaneously.
- The good correlation suggests that the dynamic barometric pressure change is the primary driver of the variation of the ventilation gas makes. It further indicates that an effective gas drainage system under such circumstances should have a sufficient capacity to be able to control such goaf gas pressure changes.

![Figure 8: Correlation between monitored Wambo seam differential pressure versus methane levels in the ventilation return](image)

**Gas content before and after mining**

Table 1 presents the measured gas contents of various coal seams before and after LW3 excavation at the three measurement locations shown in Figure 9. Key observations are:

- Redbank Creek, Wambo, and Glen Munro seams are obviously significant gas emission sources, while the Woodlands Hill seam is not.
- Special attention needs to be paid to gas emissions from the underlying Glen Munro seam as part of the gas emission most likely to contribute to the gas make in the ventilation return.
- The gas content before mining at various locations across the LW3 panel width are different and appear lower at locations closer to the mined LW2 panel. This suggests that the LW2 excavation made an impact on the gas content distribution of the LW3 panel.
- The extent of gas release from neighboring coal seams extends beyond the direct mining vicinity and into the unmined side area. Coal seams above the unmined side chain-pillar also released a significant percentage of gas.
Figure 9: Locations of gas content measurement boreholes

Table 1: Gas content measurement results before and after the LW3 mining

<table>
<thead>
<tr>
<th>Coal seams</th>
<th>SBD205 zone</th>
<th>SBD209 zone</th>
<th>SBD211 zone</th>
</tr>
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<td>Pre-mining, m3/t</td>
<td>Post-mining, m3/t</td>
<td>Gas released, m3/t</td>
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<tr>
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<td>4.02</td>
<td>2.25</td>
</tr>
<tr>
<td>Woodlands hill</td>
<td>13.345</td>
<td>13.8</td>
<td>-0.455</td>
</tr>
</tbody>
</table>

*Note: SBD209 hole was located only a few meters away from the surface vertical drainage well 3L.*

Figure 10: Different types of borehole blockages inspected by a borehole camera

(a) blockage by rock pieces   (b) blockage by borehole shearing

Effect of drainage borehole location and operational parameter on gas drainage performance

Vertical drainage wells at The Blakefield South LW3 were located at two typical locations: close to the TG (30 m to 80 m offset TG) and in the middle of the longwall block. To assess the drainage performances at the two locations, the total captured seam gas volume of vertical wells at various locations was compared, as shown in Figure 11 (a). In addition, the relationship between suction pressure and gas flow rate of two nearby vertical wells 3H (located in the TG side) and 3J (located in the mid-block) were compared as shown in Figure 11 (b).
Key observations were:

- Vertical wells located in the TG sides of the longwall generally captured more gas than those located in the mid block.

- Under the same suction pressure, the TG side well 3H had about 70% higher flow rate than the mid-block well 3J. This indicates that gas drainage wells located in the TG side of the longwall have better connectivity to rich gases in the goaf and therefore capture more gases.

![Diagram](image)

(a) Total drainage gas volume versus vertical well location (b) Relationship between drainage well suction pressure and gas flow rate (3H: TG side, 3J: mid-block)

**Figure 11: Effect of vertical well location and applied suction pressures on drainage flow**

**CONCLUSIONS**

Supported by the Government CMATSP project “Mine methane capture optimisation and maximisation of emissions abatement”, integrated field studies were designed and implemented at the complex Blakefield South mine to study the coupled strata, ground water and gas behaviours. The objective of these field studies was to provide critical information to develop an optimal longwall goaf gas drainage design.

The integrated field studies covered a number of aspects of mining induced strata behaviour including overburden movement with extensometers, coal seam pore pressure with piezometers, seam gas migration patterns with tracer tests, seam gas content measurement before and after mining, borehole stability inspection, and goaf gas pressure dynamics. These monitoring programs successfully provided insights into the coupled strata, ground water and gas responses to mining. Critical information for gas drainage design, including gas emission sources, zones of strata caving and fracturing, extent of mining influence, multi-seam gas migration patterns and surface goaf well stability, were obtained.

The results have led to an innovative gas drainage design which was trialled successfully at the Blakefield South mine.

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