Subsidence analysis using airborne laser scanning data

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This project applied airborne laser scanning technology for the detection of mine subsidence over a broad area, a commercial application not widely used in the Australian underground coal mining industry. The objective of the project was to prove the latest generation airborne laser technologies as a reliable and objective source of vital subsidence monitoring data for an underground coal mine and to demonstrate its potential as a complementary or alternate method to conventional geodetic subsidence detection and monitoring.

Mandalong Mine is wholly owned by Centennial Coal Company and is located close to Morisset in the City of Lake Macquarie, New South Wales, Australia. The underground mine lies within the catchment of Lake Macquarie with the topography ranging from the broad flat floodplain of Stockton and Morans Creeks up to the foothills of the Watagan Mountain Range. The surface above the mine consists of a floodplain with an elevation of approximately 10 m above Australian Height Datum (AHD) together with ridge and valley topography with a maximum elevation of 170 m AHD as shown in Fig. 1. The surface land is used for low-intensity agriculture and rural residential retreats.

The mine commenced longwall extraction in January 2005 in the West Wollarah Seam, which ranges in depth between -150 m and -240 m AHD. The mine uses an innovative mine design and subsidence prediction method which utilises relatively narrow width longwall panels (160 m) and a massive conglomerate rock beam that is present in the overburden to minimise subsidence. This design provides reduced levels of subsidence, minimising the impact on property, the floodplain and the environment, as well as complying with stringent State Government development consent conditions.

Mandalong’s unique method of mining meant that there was no available subsidence information from other mines that could be used to validate the subsidence prediction model. As such regulators took a cautious approach when negotiating subsidence monitoring agreements to ensure that any subsidence greater than the predicted level would be detected. Monitoring methods consisted of conventional surveys on longwall centreline marks and perpendicular crosslines at specific points. Centreline and crossline monitoring as shown in Fig. 2, provides an accurate sectional view of the subsidence occurring in that vicinity, but does not provide data across the whole of the undermined area. Therefore another method of proving/detecting subsidence across the whole mine in comparison to predictions was necessary.

Airborne laser scanning (ALS) data was originally acquired over the mining area in 2003 by AAM Geoscan for the purposes of producing topographic contours for the mine. This method was chosen over photogrammetric methods because of airborne laser scanning technology’s ability to penetrate the gaps in the vegetation canopy and capture separate returns from vegetation and from the ground. This feature ensured that an accurate and reliable terrain model was derived and initially used to model flooding levels. ALS surveys have been successfully used by open cut coal operations for a number of years to calculate stockpile and void volumes from scans of locations before and after an event. It was subsequently theorised that the pre-mining ALS data, together with ALS data acquired post-mining could be processed together to measure the level of vertical subsidence that had occurred across the mining area in a similar way, albeit with the added difficulty of thick vegetation and steep terrain.

**Project overview**

The objective of the project was to use airborne laser scanning to bring transparency to the subsidence.
monitoring process along with the ability to quantitatively demonstrate the magnitude of subsidence and other environmental changes across the whole of the mining area.

Pre-mining ALS data was sourced for the mine by AAM GeoScan (now AAM) in June 2003 and February 2004, with subsequent post-mining ALS data acquired in August 2006 and June 2008. AAM used various models of Optech Airborne Laser Scanners on each occasion, including use of the Optech ALTM GEMINI 167 kHz in 2008.

Umwelt (Australia) were engaged to undertake a comparison of ALS data of a 6 km² area of the Mandalong Valley for pre-mining and two post-mining datasets provided by AAM. This comparison was undertaken to determine whether ALS is a suitable method of measuring subsidence as a result of longwall mining in the Mandalong Valley by comparison to data collected by conventional survey methods, and the actual subsidence over the mined longwalls.

Datasets

Pre-mining ALS data was sourced for Longwalls 1 to 4 of the mining area on 18 June 2003. ALS data for the remainder of the Mandalong Valley was sourced on 8 February 2004. Ground support (i.e. a GPS base station) was provided by local surveyors, C R Hutchison & Co. The ground check points acquired by the surveyors allowed an assessment of the accuracy of the ALS data. One hundred and eleven ground check points were used, which concluded a vertical standard error of 0.04 m for points on open clear ground (AAMHatch, 2003). The supplied point cloud of the 2003 ALS data (ground strikes only) has a 2.06 m estimated average point density (i.e. points per m²) (AAM GeoScan, 2003).

Since the commencement of underground mining two additional ALS datasets have been sourced. The first post-mining ALS data was acquired on 12 August 2006. This data corresponds to the completion of mining of Longwalls 1 and 2 and part of Longwall 3. Ground check points were again used by AAM to assess the accuracy of the ALS data. The supplied ground check points were in the same area as the check points for the previous 2003 ALS survey. One hundred and sixty three check points were used for validation, resulting in a vertical standard error of 0.024 m for points on open clear ground. The supplied point cloud of 2006 ALS data (ground strikes only) has a 7.81 m estimated point density (AAMHatch, 2006).

Post-mining ALS data was again sourced on 10 June 2008. This data corresponds to the completion of Longwalls 1 to 5 and part of Longwall 6.
Ground check points were again used to assess the accuracy of the ALS data. The supplied ground check points were in the same area as the check points for the previous 2006 ALS survey. Two hundred and fifteen points were used for validation, resulting in a vertical standard error of 0.051 m for points on open clear ground. The supplied point cloud of 2008 ALS data (ground strikes only) has a 4.6 m estimated point density (AAMHatch, 2008).

**Expected accuracy and data limitations**

Information provided by AAM indicated that the horizontal accuracy of ALS data points on open clear ground is: 0.55 m in 2003, 0.55 m in 2006 and 0.2 m in 2008, with a stated vertical accuracy of all datasets is 0.15 m to 1 sigma (i.e. 68% of the ALS point data utilised by Umwelt in their analysis was plus or minus 0.15 m of its true elevation).

AAM has also indicated that accuracy estimates for terrain modelling refer to the terrain definition on clear ground. In addition, ground definition in vegetated terrain may contain localised areas with systematic errors or outliers that fall outside this accuracy estimate.

Laser strikes were classified into “ground” and “non-ground” by AAM, based upon algorithms tailored for the major terrain/vegetation combinations existing in the project area. AAM has indicated that the classification algorithm may be less accurate in isolated pockets of dissimilar terrain/vegetation combinations and under trees.

AAM has also confirmed that the algorithm used to classify points as “ground” or “non-ground” may have differed between the 2003 dataset and the 2006 and 2008 datasets, resulting in significant differences in some areas. This effect was particularly noticeable in areas of high relief (e.g. creek banks and steep terrain) and low thick vegetation (e.g. noxious weed Lantana camara), for the comparison between the 2003 and 2006 datasets.

Future scope of work will specify the application of the data sets so that identical sensor settings and algorithm for processing are utilised. This will increase the suitability of the ALS datasets for this important temporal work.

**Analysis approach**

The ALS data points sourced by AAM in 2003, 2006 and 2008 were interpolated to obtain grid based digital terrain models (DTM) with grid spacing of 2.0 m.

Subsidence values were calculated by comparing the elevation differences between the corresponding points of the DTMs.

The analysis of the elevation differences of the datasets (i.e. 2003 to 2006 and 2003 to 2008) shows well defined subsidence zones around the areas of longwall mining (refer to Figs. 3 and 4). The analysis also indicated some areas of significant observed differences between the datasets. These differences are discussed further later on in the article. The calculated subsidence using the ALS data was also compared against
subsidence monitoring line data surveyed by Centennial Mandalong (refer to Analysis of ALS results versus geodetic survey).

Umwelt utilised customised in-house database applications, MySQL, Bentley Microstation and ArcView GIS software in the analysis of the ALS data.

Comparison of ALS datasets 2003 to 2008: An analysis of the elevation differences of the 2003 and 2006 datasets shows a wide range of difference in elevation, from approximately minus 6 m to approximately plus 6 m. The analysis also indicates that 99.7% of the elevation differences are within the range of minus 1.5 m to plus 0.5 m. Some of these differences between the two ALS datasets can be explained by processes other than subsidence, including limitations of horizontal and vertical ALS data accuracy, differences in the classification of “ground” and “non-ground” data of two ALS surveys, changes in elevation of water surfaces (i.e. dams and creeks) at localised landform features within the study area and changes/improvements made to the processing algorithms used when processing the ALS in 2003 and 2006 (refer to previous section entitled Expected accuracy and data limitations).

Additional calculations revealed that in areas where subsidence has not occurred, the average elevation of 2006 survey was 0.05 m higher than the average elevation of pre-mining survey. Even with these discrepancies, it is considered that the difference between the 2003 and 2006 ALS datasets provides an accurate description of subsidence associated with Longwalls 1 and 2.

2003 to 2008: An analysis of the elevation differences of the 2003 and 2008 datasets shows a wide range of difference in elevation, from approximately minus 86 m to approximately plus 10 m. The analysis also indicates that 99.6% of the elevation differences are within the range minus 1.75 m to plus 0.21 m. Some of these differences between the two ALS datasets can be explained by processes other than subsidence. Again many of these differences are likely the result of changes/improvements made to the processing algorithms used when processing the ALS in 2003 and 2008.

Additional calculations revealed that in areas where subsidence has not occurred, the average elevation of 2008 survey was 0.082 m higher than the average elevation of pre-mining survey.

<table>
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<tr>
<th>Cross section name</th>
<th>Date of geodetic survey</th>
<th>Number of points</th>
<th>Average elevations difference to ALS data (m)</th>
<th>Minimum elevations difference to ALS data (m)</th>
<th>Maximum elevations difference to ALS data (m)</th>
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<tr>
<td>Crossline 1</td>
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<td>Centreline 3</td>
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<td>-0.319</td>
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</tr>
</tbody>
</table>

Table 1: Summary of 2006 subsidence differences along survey lines [5].

Again, even with the discrepancies, it is considered that the difference between the 2003 and 2008 ALS datasets provides an accurate description of subsidence of Longwall 1 to Longwall 5.

Analysis of ALS results versus geodetic survey
Geodetic surveys using conventional leveling and traversing techniques are conducted on a regular basis along subsidence monitoring lines in the longwall mining area. The geodetic subsidence monitoring line data was compared with the ALS survey data for both datasets. For each dataset the geodetic survey closest in time to the ALS survey capture date was used in the analysis. Rigorous comparison of ALS and survey data over a range in topography and vegetation densities was possible due to the extensive subsidence monitoring network installed by the mine, allowing the technology to be proven with a variety of environmental variables.

2003 to 2008: The subsidence monitoring line data with the closest date to ALS survey data (i.e. 12 August 2006) was compared to the ALS analysis of subsidence up to 2006. Survey data was available at 478 points along nine survey lines (refer to Fig. 3). Each supplied survey point was compared against the ALS dataset. The difference is calculated as surveyor’s elevations minus ALS elevations.

Table 1 shows the average, maximum and minimum differences calculated from the geodetic subsidence survey minus ALS subsidence.

The analysis indicates that there is a good correlation between the geodetic survey measured subsidence and the ALS analysis subsidence for all subsidence monitoring lines, except Centreline 3. The average elevation difference between the ALS data and the geodetic survey data (excluding the data for Centreline 3) is 0.031 m. The area where Centreline 3 varies between the two methods is immediately to the south of Deaves Road. An inspection of this area from Deaves Road during February 2007, did not indicate any aspect of the area that might significantly influence the ALS data acquisition or accuracy. As such, the differences in this area are yet to be determined. Fig. 5 shows Crossline 5 comparison between Geodetic survey and ALS.

2003 to 2008: The subsidence monitoring line data with the closest date to ALS survey data (i.e. 10 June 2008) was compared to the ALS analysis of subsidence up to 2008. Survey data was available at 1250 points along 16 survey lines (refer to Fig. 4). Due to the expansion of the mining area additional cross sections were included for the 2008 analysis. In addition, some of the survey lines included in the 2006 analysis were not included as these lines have not been recently surveyed. Survey dates for the subsidence monitoring lines are typically within one month from the ALS survey date.
Each supplied survey point was compared against the ALS dataset. Table 2 shows the average, maximum and minimum differences calculated for the geodetic survey subsidence minus ALS subsidence. A representative sample of the comparison graph for Crossline 3 can be seen in Fig. 6.

The analysis indicates that there is a good correlation between the geodetic survey measured subsidence and the ALS analysis subsidence for all subsidence monitoring lines, except Centreline 8. It is likely that as the geodetic survey data available for these lines is six weeks after the ALS survey, additional subsidence from the mining of Longwall 6 may have contributed to these differences. The differences in the geodetic survey measured subsidence and the ALS analysis on Centreline 5 is a result of water ponding on the surface in the subsidence trough and providing a false ground reading on the ALS survey. The false ground reading is estimated to be in the order of 0.3 m. The average elevation difference between the ALS data and the geodetic survey data (excluding the data for Centreline 8) is minus 0.013 m.

The analysis also indicates that there is a wider variability of minimums and maximums of elevation differences of the same cross sections for the 2008 survey to the 2006 survey. This variability can likely be explained by the increase in the number of points along the cross sections suitable for a comparison in the 2008 survey and a longer time gap between the monitoring lines and ALS survey dates for the 2008 survey.

Conclusions

A solid technical appreciation has been attained for the data collection and analysis specifications to ensure accurate subsidence monitoring. This data can supplement the other monitoring undertaken by the mine. The data from the ALS technology provided a detailed dataset enabling temporal comparisons of terrain surface across a broad area that can be utilised to supplement the extensive conventional subsidence monitoring program. ALS also provided the ability to obtain data in areas with access difficulties and on private land that would otherwise have been without monitoring.

Specifications for the stringent Scope of Works in data collection and analysis have been developed for land subsidence while showcasing the reliability, safety and accuracy achievable from the latest generation of aerial laser technology.

The comparison of the ALS data for the Mandalong Valley for the pre-mining and two post-mining datasets indicates that even with consideration of the outliers in the analysis, the ALS survey produces highly representative terrain data that can be considered to provide a relatively accurate description of the subsidence that has occurred over the entire mining area with a variety of surface topography and vegetation. It should be noted that the accuracy of this analysis is governed by the vertical accuracy of the ALS data (i.e. 0.15 m vertically) – though higher accuracy can be obtained.

It is envisaged that ALS monitoring will continue to be used in combination with conventional monitoring, such that the extent and frequency of conventional monitoring may be reduced. Future data capture using ALS technology should ensure that as far as possible the parameters are consistent between surveys, including ground point density and processing algorithms. Major subsidence line comparisons must be surveyed as close to the date of data capture as possible to reduce any issues surrounding movement occurring between the dates of the two surveys. To improve the accuracy of the capture and processing of future data, ALS flight paths should be planned such that they are perpendicular to the slope of terrain to reduce the effect that horizontal position error has on height. The ability to improve the accuracy of the ALS subsidence calculation, particularly in areas of steep terrain by generating higher resolution digital terrain model grids from existing and especially new data should also be investigated.

Acknowledgment

This paper was presented at FIG Congress 2010 in Australia and is republished here with permission.

References