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USE OF 3D LASER SCANNER TECHNOLOGY TO MONITOR COAL PILLAR DEFORMATION

Radovan Kukutsch, Vlastimil Kajzar, Petr Waclawik and Jan Nemcik

ABSTRACT: Although the room and pillar mining method is world-known and widely used, in terms of the Czech coal mines located in the Upper Silesian Coal Basin it is still in the testing phase. Unfavourable mining, geotechnical conditions at large depths and the ban by Czech mining authorities prevented this method from being used on rock bolt reinforcement without other roof support. Typically, large amounts of unexploited coal reserves are left in the shaft protective pillars. This coal can be mined if strata subside is minimised. Due to its low subsidence characteristics the room and pillar mining method without pillar extraction has been trialled at the CSM Coal Mine at the end of 2014. During the pillar development phase complex geotechnical monitoring was undertaken including the frequent scanning of pillar movement using 3D laser scanning technology. The laser scanner enabled complex capture of the entire space around the monitored pillars during the period of pillar formation and afterwards. The time-lapse scanning method measured changes in the mine roadway surface profiles including pillar displacements, roof movements, floor heave and other dynamic phenomena. The time-lapse scanning indicated variable pillar rib movement ranging from a few cm to a maximum of 50 cm with an average of approximately 25 to 30 cm. The scans indicated that the bottom of the seam displaced more than the top of the rib side due to large floor heave. The weak floor consisting of siltstone and coal beds experienced large floor heave however, due to floor brushing no reliable floor displacements are available. In contrast to the large movements in the rib and the floor, the strong roof strata did not show any significant movements. The purpose of this work is to highlight the importance of terrestrial laser scanning as an essential engineering design tool to evaluate the displacements and deformations of mine excavations at large depths. The 3D scanning results gave relevant information about displacements and deformations that occurred at the tested site and thereby helped to improve safety underground.

INTRODUCTION

Laser scanning has started to be a widely applied technology in a variety of industries. These scanning systems excel in their ability to provide contactless determination of spatial coordinates of any object such as buildings, interior space, terrain and other structures. To survey the entire area of interest it is usually necessary to take scans from several locations that are automatically stitched together. The method can be used with exceptional speed, accuracy, comprehensiveness and safety. The scanned objects are visualised in the form of a point cloud, which can be subsequently used for a wide variety of analytical tasks, and also to generate 3-dimensional models of these objects.

This technology can be widely used in mines for specific tasks such as monitoring of strata conditions when developing mine excavations, assessing the long term stability of underground workings, measuring convergence profiles, investigating surface movement and enabling volumetric calculations. Based on the intensity of the reflected laser signal, it is also possible to quantify the material type, from the resulting point cloud. The method can also be used in design work connected with CAD / GIS tools.

The primary objective of laser scanning underground is a complete capture of the scanned area geometry at the time of scanning. From these results, it is possible to determine the shape and size of scanned mine workings, the position of mine supports and other parameters (Kajzar et al., 2015). Beyond these basic tasks it is also possible to use the spatio-temporal analysis, combined with the convergence measurements to compare the time related changes that may include: the size variation

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and stability of rock cavities and to identify the place and magnitude of coal pillar deformation and rib conditions or collapse of pillar corners. These tasks require repeated measurements to resolve any geometrical changes between the scans (Kukutsch et al., 2015). In general any number of future scans can be performed and processed to compare with the existing scan results taken in the same area.

MINING CONDITIONS IN THE SCANNED AREA

The geological setting in the area of shaft protective pillar ČSM-North Mine is quite complex. The targeted coal seam No. 30 used for the trials, is at the depth of approximately 700 m to 900 m below the surface. Above the coal seam there is a 300 m thick complex carboniferous rock mass with the overlying tertiary sedimentary rock strata 400 m to 600 m thick with approximately 20 m thick quaternary soil overburden. The strata dip oriented in a north-east direction ranges from 8° to 17°. Occasionally the dip of a coal seam can reach up to 20°.

Within the proposed mining area the thickness of seam No. 30 is very variable. In places the seam splits to several separate coal seam layers. Interchangeable layers of sandstone, siltstone and coal seams are present. Seam No. 30 occurs separately only in the south-east part of the shaft protective pillar with thickness that varies from 1.8 m up to 2.2 m. The seams n.n. (untitled seam), No. 31 and No. 32 merge with seam No. 30 towards the north-west. This substantial and complex coal seam (consisting of seams 30 + n.n. + 31 + 32) has the thickness of up to 5.2 m in the northwest part of the protective pillar area.

In the monitored pillar area (pillars V1 and V2) in the panel V trial area the 3 m thick seam consists of the coal seams 30 and n.n. The stratigraphy of the ground above the coal seam No. 30 are shown in Figure 1.

![Figure 1: 3D model of monitored pillars in panel V (locality A). Coal seams – blue, siltstones – green, sandstones - yellow](image)

There are several faults of regional importance in the area of the ČSM-North shaft protective pillar (see Fig. 2). There is a wide tectonic zone of the Albrechtice Fault with total throw up to 420 m located in the west area. The dip of this fault ranges 60° to 65° towards the West. In the northern area “Fault A” is present with a throw of up to 100 m and the dip of 60° towards the North. “Fault B” in the south part of area has a throw of around 10 m with the dip ranging 55° to 70° towards the South.
The significant regional tectonic fault zone “Eastern Thrust” divides the area of the protective pillar into two separate blocks with different geotechnical conditions. According to the existing knowledge the Eastern Thrust has a very small dip ranging from 10° to 35°. The Eastern Thrust strike is generally in the NE-SW direction with the dip towards the NW. The vertical displacement fluctuates at around 5 m mark, but the range of horizontal displacements is usually much greater and can exceed tens to hundreds of meters. Characteristic changes in the Eastern Thrust dip with depth have been observed and may be correlated with the transition to interlayer slips. The experience shows that these thrust fault features have a significant effect on the geotechnical conditions within the rock mass.

Inside the protective pillar area surrounded by faults of regional importance, the rock mass is typically disturbed by a system of small so-called seam faults. The uplift on these seam faults is mostly greater than 0.1 m but typically do not exceed 1 m.

Figure 2: Tectonic situation and position of monitored pillars in panel V (locality A) and panel II (locality B)

**MONITORING – DESCRIPTION**

Stress monitoring and the deformation state of the rock mass is an essential requirement for the design of a safe and successful room and pillar method that can be applied in the Czech part of the Upper Silesian Coal Basin (USCB). The room and pillar mining method is usually designed on the basis of experience and practices that are observed under different geological conditions and depths. The geology in the area and depth of cover indicate that the empirical methods of calculating the pillar loads may not be appropriate and could be unreliable. No experience of the room and pillar method exists within the USCB area therefore the pillar monitoring had to be used to measure the capacity and the deformation characteristics of the coal pillars.

An extensive monitoring system was installed to measure the load profile across the coal pillar and the deformation characteristics of the pillars during mining. The monitoring was performed in two coal pillars within the panel V. The pillars diamond in shape and with slightly irregular sides were approximately 860 m² and 1200 m² in size and 3.5 m high.

In the context of stress and deformation monitoring the following parameters were measured:

- deformation of rock overlaying the room and pillar roadways,
- pre-mining stress and stress changes in rock and coal during mining,
- deformation of coal pillars,
To monitor roof deformation, fourteen pairs of 5-level multipoint extensometers monitored roof displacements and eleven strain gauged rockbolts were installed at various locations. Two 3-dimensional CCBO stress overcoring cells were used to measure the pre-mining stress in the area and eight 3-dimensional CCBM stress change monitoring cells were installed to measure stress changes during mining. Four 1-dimensional hydraulic stress monitoring cells were installed at various depths into each pillar to measure vertical stress, four 5-level multipoint rib extensometers measured displacements of all sides within each monitored pillar, seven hydraulic dynamometer load cells measured the cable bolt loads installed at the roadway intersections and the roof and rib convergence was measured at key locations. The coal rib displacements together with the convergence measurements, changes in vertical pillar loads and the monthly 3D laser scanning of the overall roadway displacements (roof, rib and floor heave) provided data to evaluate pillar stability. Large seismology and seismo-acoustic monitoring was also undertaken to supplement the data.

### 3D LASER SCANNER MONITORING – DESCRIPTION

For monitoring of spatio-temporal changes to the coal pillar V2 rib profile compact pulsed terrestrial laser scanner Leica ScanStation C10 was used. It is a device with a long range laser beam (up to 300 m) which provides measurements with accuracy in space (6 mm / 100 m), length (4 mm / 100 m) and angle (±60 micro-radian) and high scanning speeds (up to 50,000 points / s) (Leica – C10 Data Sheet).

Since this is a site with a potentially explosive atmosphere and the surveying equipment does not correspond to the safety criteria, monitoring was performed in all cases with a special permit and the use of a comprehensive gas monitoring system.

Up-to-date the laser scanning has been carried out six times within the approximate time interval of 5-6 weeks (see Table 1). The initial scan has provided geometry of the newly developed coal pillar V2 within the roadways V300501 and V3006 (see Fig. 3). When the pillar sides were completed the subsequent scans established the pillar boundaries within the corridors V3005 and V300502 (see Fig. 4). Following scans measured any subsequent changes due to strata displacements. Scanning was performed with a resolution of 1 cm / 10 m, while approximately 14.5 million spatial points from each scanning positions were obtained.

A local coordinate system is required to tie all surveyed results together. For the scanning instrument to locate itself, several permanent (overlaying) target locations need to be established and marked (usually on the steel bolt plates that do not move). During each survey several magnetic targets (minimum of three) are placed onto these locations with some overlap between the targets that were used in the adjacent scans (common targets). The instrument can be set up anywhere at a desirable location where the targets are visible. The instrument then locates itself automatically and tie all the surveyed points together.

<table>
<thead>
<tr>
<th>Color</th>
<th>Scan No.</th>
<th>Date</th>
<th>Number of positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>■</td>
<td>1</td>
<td>2015, February 10</td>
<td>6</td>
</tr>
<tr>
<td>■</td>
<td>2</td>
<td>2015, March 17</td>
<td>8</td>
</tr>
<tr>
<td>■</td>
<td>3</td>
<td>2015, April 21</td>
<td>6</td>
</tr>
<tr>
<td>■</td>
<td>4</td>
<td>2015, June 4</td>
<td>7</td>
</tr>
<tr>
<td>■</td>
<td>5</td>
<td>2015, July 21</td>
<td>8</td>
</tr>
<tr>
<td>■</td>
<td>6</td>
<td>2015, September 3</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 3: Part of the pillars V2 at the intersection of corridors V 300501 aV3006 (1st scan)

Figure 4: Shape of the pillars V2 - top view (6th scan)

DYNAMICS OF COAL PILLAR DISPLACEMENT

Raw data were processed using Leica Cyclone, Trimble RealWorks and CloudCompare software. After each survey it was necessary to merge the data (taken on the day) together (registration process). The second process consists of interconnecting the current survey with the previous surveys into a new single point cloud.

From the resultant data clouds the relatively accurate locations of the scanned surfaces are calculated and displayed. The individual profiles of each scan can be plotted as shown in Figure 5 showing the roadway cross-sections. The readily available software can be used to study individual displacements at the points of interest. Further visual display options of the calculated net displacements between each scan include the colour plot of the surface displacements as shown in Figure 7. These tools enable further study of the overall displacements and substrate conditions of each scanned surface as they develop in time. These surveys clearly indicate the overall pillar displacements, roof conditions and floor heave as they develop during mining and afterwards.
From the comparison in Table 2 it is clear that:

- Varying degrees of rib displacement rate change in time (Figure 6) occur in the whole profile of the pillar. Significant coal pillar deformation, accompanied by a continuous coal rib spall into the roadway area were encountered in the roadways V3006, V300501 and V300502. Rib displacements of up to 50 cm were measured in the coal pillars. These results correlate with the outcomes and findings from the convergence and extensometer measurements. Within the belt roadway V3006 the pillar deformation was much lower.

- The reinforcement performance and functionality can also be assessed from the scanned roof or rib bolt movements and the overall roof convergence. As in the case of rib displacements it is possible to detect significant changes in floor deformation. However these changes are difficult to assess as they are affected by a combination of different factors such as floor heave, floor brushing and moving mining equipment. The 3D laser scanning technology also enables the long term monitoring of strata conditions and thus proved to be beneficial for this project where pillar creep may occur.

![Figure 5: Cross-sections of the roadways V300501 and V3006 1st scan (black) to 6th scan (red)](image)

<table>
<thead>
<tr>
<th>Cut No.</th>
<th>Width 1st scan (m)</th>
<th>Width 6th scan (m)</th>
<th>Difference (m)</th>
<th>Change (%)</th>
<th>Height 1st scan (m)</th>
<th>Height 6th scan (m)</th>
<th>Difference (m)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>7.31</td>
<td>6.74</td>
<td>0.58</td>
<td>7.90</td>
<td>2.88</td>
<td>2.56</td>
<td>0.33</td>
<td>11.32</td>
</tr>
<tr>
<td>C2</td>
<td>5.76</td>
<td>5.05</td>
<td>0.72</td>
<td>12.46</td>
<td>3.30</td>
<td>2.98</td>
<td>0.32</td>
<td>9.67</td>
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<tr>
<td>C3</td>
<td>7.63</td>
<td>7.39</td>
<td>0.23</td>
<td>3.05</td>
<td>4.37</td>
<td>3.73</td>
<td>0.64</td>
<td>8.34</td>
</tr>
<tr>
<td>C4</td>
<td>6.56</td>
<td>6.10</td>
<td>0.46</td>
<td>7.00</td>
<td>3.74</td>
<td>3.48</td>
<td>0.26</td>
<td>3.93</td>
</tr>
</tbody>
</table>

In Figure 7, parts A and B show the dynamics of the rib in a timeframe of approximately 7 months (6 scans) during and after the V2 pillar development. The part A shows the rib displacements ranging 15-20 cm in five weeks after the pillar was formed. In the following five weeks the rib displacements increased by 5-7 cm to approximately 20 to 27 cm. These were the maximum changes measured in the timeframe of seven months. It appears that the bottom of the rib side displaced more than the top. This phenomenon may be related to the large floor heave, which partially affected the bottom half of the pillar...
where the displacements of more than 40 cm can be seen. Another reason may be the uneven cut in the V300501 roadway (see Fig. 4). Thus this cut may have a negative effect on the adjacent rib movement. This can be investigated further by plotting horizontal movement together with the rib geometry in a plan view.

![Graph](image)

**Figure 6: Dynamic of coal pillar / decrease in displacement/time rate over time**

Part A of Figure 7 corresponds to the location of the pillar extensometer VeH2 (Figure 7, middle of cuts in part A). The extensometry results and the colours obtained from Figure 7 are compared in Table 3. It should be noted that the colour range in Figure 7 and Table 3 can be changed to enable more accurate comparison for interpretation. Figure 7 clearly shows that the rib displacement rate is decreasing over time as shown in Figure 6. Further measurements will be conducted in the future to establish whether the pillar will stabilise. Compared to Part B (Figure 7 and Table 3) there are no significant rib displacements in Part A. Much larger displacements can be clearly seen in Part B.

This method of displacement reading by colour range shows the strength of the laser scanning. The time dependent displacements in space can be easily obtained and interpreted providing a quick and safe method to enable geotechnical assessment of strata conditions underground.

**Table 3: Extensometer VeH2 data corresponding to Fig. 7, part A and B**

<table>
<thead>
<tr>
<th></th>
<th>1st month</th>
<th>2nd month</th>
<th>3rd month</th>
<th>4th month</th>
<th>5th month</th>
<th>6th month</th>
<th>7th month</th>
<th>8th month</th>
</tr>
</thead>
<tbody>
<tr>
<td>VeH2 rib displacement (mm)</td>
<td>72.3</td>
<td>116.3</td>
<td>144.7</td>
<td>170.1</td>
<td>186.7</td>
<td>201.7</td>
<td>211.9</td>
<td>217.6</td>
</tr>
<tr>
<td>Increase in VeH2 displacement (mm)</td>
<td>72.3</td>
<td>44.0</td>
<td>28.4</td>
<td>25.4</td>
<td>16.6</td>
<td>15.0</td>
<td>10.2</td>
<td>5.7</td>
</tr>
<tr>
<td>Corresponding color scale (used in Fig 7 Part A)</td>
<td>not measured</td>
<td>Blue Range 50-150mm</td>
<td>Blue Range 50-150mm</td>
<td>Blue Range 50-150mm</td>
<td>Green Range 150-250m</td>
<td>Green Range 150-250m</td>
<td>Green Range 150-250m</td>
<td>to be measured</td>
</tr>
<tr>
<td>Corresponding color scale (used in Fig 7 Part B)</td>
<td>not measured</td>
<td>Blue Range 50-150m</td>
<td>Green Range 150-250m</td>
<td>Green Range 150-250m</td>
<td>Yellow Range 250-300m</td>
<td>Orange Range 300-400m</td>
<td>Red Range 400-500m</td>
<td>to be measured</td>
</tr>
</tbody>
</table>
The room and pillar method has been trialled in the shaft protective pillar at the CSM Mine within the USCB. A comprehensive coal pillar monitoring was essential as this was the first application of the room and pillar mining method in the Czech Republic at great depth. Two coal pillars located in the seam No. 30 were intensively monitored to ensure stability of the panel and safe mining procedures. Several monitoring instruments were used to measure stresses and displacements in this trial. One of these instruments was the 3D laser scanner to measure strata surface displacements during and after mining took place.

The measurements indicate that the 3D laser scanner is a comprehensive tool enabling both numerically and graphically the express the dynamic changes taking place in the mine roadways. The laser scan results from several subsequent surveys indicted significant coal rib displacements taking place shortly after mining started. The measured rib displacements varied and ranged from 15 to 20 cm when mining took place increasing after 7 months to 20-27 cm at pillar mid height. Post-mining rib displacements were also measured. The results indicate that the lower coal rib suffered greater deformation mainly due to large floor heave that occurred along all sections of mine roadways. In some places the lateral displacements measured mostly at the lower rib exceeded 50 cm. As expected, the roof displacements were negligible and are not discussed here. These scanned data were directly compared with the extensometry results.
Graphic display of the measured changes that occurred, enabled easy and immediate evaluation of the strata conditions up to the measured date. Based on these data the level of risk can be established whether to abandon the mining area in case of severe pillar deformation.

Application of the 3D laser technology to measure strata displacements in underground mines is becoming increasingly popular due to low cost of measurements its ease of use and data quality it produces. Graphic outputs of the measurements enable quick assessments of the situation at hand. Over the coming years this method will inevitably become an essential part of the safe and economic monitoring system used on regular basis to provide quick and reliable information on strata conditions in real time.

ACKNOWLEDGEMENTS

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