DETAILED UNDERGROUND MEASUREMENTS OF ROOF DEFORMATION AND BED SEPARATION

By

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ABSTRACT

To learn more about the fundamental roof behaviour in South African coal mines, accurate underground measurements of roof deflection were conducted in bord and pillar panels during development and pillar extraction. To conduct these measurements a survey levelling technique was adapted. The overall system reading accuracy was established as being within 0.4 mm on a 15 m sighting distance. The underground sites were modelled and, for a roadway development, similar symmetrical curvatures were calculated by a linear elastic model, as were measured underground. In a pillar extraction panel, a significant amount of bed separation was measured and the roof underwent an asymmetric movement due to the close presence of the mined out area at one side of the roadway.

INTRODUCTION

When a rockmass is disturbed by a mining excavation the surrounding strata migrates towards that opening. In the relatively shallow South African coal mines an important safety aspect from a strata control point of view is the roof stability in roadways and intersections of bord and pillar, and pillar extraction panels. In order to design adequate cost-effective roof support it became obvious that a more complete understanding of the roof behaviour was required. To establish a better understanding, three different mining phases were considered.

1. At the face when developing roadways and intersections.
2. In the long term over the designed life span of the developed section.
3. During pillar extraction.

During each of these three periods measurements of roof deflection and bed separation had to be recorded. In order to achieve this, a reliable monitoring method was required. A survey levelling technique was adapted to suit the requirements imposed by this exercise of roof monitoring.

The method has been applied successfully in monitoring roof movement during the development of several longwall roadways and of bord and pillar workings. Detailed data on roof deflection and bed separation was also collected during pillar extraction, until gobbing occurred.

All underground sites were simulated using a three-dimensional boundary element code in the linear elastic domain.

MONITORING METHOD

REQUIREMENTS

Any monitoring technique to measure roof movements in coal mines had to satisfy all, or as many as possible, of the following requirements. It should:

1. Be reliable and have a reading error of less than half a millimeter.
2. Be able to measure absolute roof deflection, including small movements of less than one millimeter.
3. Be able to detect differential movement between various strata (bed separation), including small movements of less than one millimeter.
4. Not interfere with the mining operation (e.g. with the continuous miner and shuttle cars during pillar extraction).
5. Allow frequent measurements to be taken relatively quickly (e.g. after

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6. be able to be installed close to the face and not be disturbed or destroyed by cutting from the continuous miner, or by blast damage,
7. continue to monitor, from a safe location, roof deflection in inaccessible areas (e.g. after pillar extraction until poiting takes place).

It was decided that by adopting the precise survey levelling technique these requirements could be achieved.

**INSTRUMENTATION LAYOUT**

The basic principle of levelling is to compare the relative change in elevation of two points. In this application these points are anchored in the roof and the resulting elevation changes represent the roof deflection. It is not necessary to know the true elevation of the points. All that is required is the change in elevation of the points of interest, relative to a stable point.

In order to eliminate reading inaccuracies in the event of the instrument going out of adjustment, the instrument is set up at a point where the backsight and foresight viewing distances are equal. These viewing distances are typically 15 to 30 m.

An idealised set up is shown in Figure 1. Here the elevation of a point in the area of interest is compared with a point 30 m away. This second point, although assumed to be stable, is also monitored periodically by comparison with a third point a further 30 m away, to check if point 2 remains stationary during the monitoring period. In the event of point 2 undergoing vertical displacement this movement can then be added to the movement measured at point 1 to give the total movement.

The backsights are positioned as close as possible to the side of the roadway for two reasons. The first is stability related, the magnitude of deflection of a roof beam decreases towards the ribside. The second being a practical consideration, positioning the monitoring staff as far out of the travelling way as possible.

By eliminating the effects of possible floor heave, the levelling technique has a definite advantage over conventional closure meter readings taken between the roof and the floor. Another disadvantage of the floor-roof closure technique, by which the levelling technique is not affected, is that regular vehicle transport damages the floor and, in particular, the floor pin installed. In comparison with the use of an extensometer with a number of monitoring points at various horizons in the roof, the levelling technique is more appropriate in determining absolute movement values. It is also able to continue monitoring roof movements in non-accessible areas, without sacrificing expensive instrumentation. Both the extensometer and the levelling technique make use of a reference point that is assumed to be stable. In the case of the extensometer, it is usually the point deepest in the roof at the site of interest, which means it is close to the mining operations. However, in most levelling applications the reference point is deliberately positioned as far as is practically possible outside the direct zone of influence of the mining operation. The monitoring of roof deflection during pillar extraction, using the levelling technique, has proved to be very effective. The observer being able to take readings from a remote safe point...
without interfering with the mining operations. To use an extenso-meter in similar conditions would be both dangerous and impractical.

- Unless a remotely read extenso-meter is used, the observer would be put in a potentially dangerous situation with respect to mobile mining equipment and the possibility of a roof collapse.
- Associated with the approaching goaf, the whole strata up to surface undergoes movement. Hence, the reference point undergoes a movement too.

The photographs in Figure 2 illustrate the use of the levelling technique during pillar extraction.

1. Figures 2.a to 2.c were taken during successive mining steps; before, during and after the extraction of the adjacent pillar until the goaf occurred. The reflective staves were anchored at different levels in the roof, in order to measure bed separation. One staff was anchored in a strong sandstone layer above the 1.2 m thick weak shale layer in the roof. The other staff was anchored in the immediate roof skin.

2. Figures 2.d and 2.e illustrate the pivoting mechanism of the staves. Readings were taken during shuttle car change overs or whenever the opportunity presented itself. Between readings the staves were remotely pulled up out of the way, against the roof.

**ACCURACY**

In order to ascertain the overall accuracy of the system a comprehensive series of tests were carried out. These were performed in passage ways inside a building and involved four different observers. A comparison was also made between induced and measured movement.

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Fig. 2.a - Before the start of the pillar extraction.

Fig. 2.b - During pillar extraction.

Fig. 2.c - After pillar extraction, but before the goaf occurred.

Fig. 2.d - Pivoting mechanism of staves.

Fig. 2.e - Pivoting mechanism of staves.

Fig. 2 - Illustration of the use of the levelling technique during pillar extraction.
Reading accuracy related to different observers

Four observers with different degrees of levelling experience each took 50 sets of readings between two staves with a sighting distance of 15 m. The staves did not have a common zero point and a slight elevation difference therefore existed between them. The measured differences are presented in Figure 3 in the form of histograms. No result, no matter how far out, was disregarded.

From the four histograms given in Figure 3, the minor variations between the four observers' reading styles can be seen. These produce average elevation differences, between the staves, of 6.2 to 11.2 units. One unit is 0.05 mm, or one millimeter on the staff is the equivalent of 20 units on the micrometer. By using the same observer, wherever possible, personal bias effect can be neutralized.

The other interesting observation to come out of this test was the variation in the spread of each of the observers, from a low of 15 units (0.75 mm) to a high of 45 units (2.25 mm). This appears to be linked to the experience of the observer and was to be expected. It is, however, obviously not acceptable. To improve the accuracy, the far out, or peripheral, readings need to be recognized, rectified and discarded by the observer on site. It is for this reason that the criteria of 2 successive reading differences within 5 units or 3 within 10 units was developed. Incorrect readings become obvious and are rejected before misleading results are derived. The average is calculated for each set of the accepted reading differences.

Applying the above criteria to the readings for histograms A and B in Figure 3, new histograms were plotted and are shown in Figure 4. The accuracy was improved in both cases. Observer B had a reduction in spread from 15 to 12 units, while observer A was dramatically reduced from 45 to 6 units.

Comparison between read and measured displacements

An apparatus was designed that could accurately displace one staff in increments as small as 0.1 mm. The staves and instrument layout remained the same as for the previous tests. The underground reading technique with its associated criteria (2 within 5 or 3 within 10) was applied.

In Figure 5, the results of a micro test are presented, during which one staff was lowered in 0.2 mm steps until the displacement totaled 2.6 mm. Compared with the induced displacements, the measured displacements all fell within an error band of ±0.2 mm. As is to

Fig. 3 - Reading accuracy related to four different observers.

Fig. 4 - Technique reading accuracy.
During the first 8 days after mining is presented, the centre of the roadway, a roof movement of 4.4 mm was measured. At 0.5 m from the ribside, much smaller movements were detected (0.5 and 1.5 mm respectively).

Previous studies (Vervoort, 1991) showed that, for numerical simulations in the linear elastic domain, the deflection calculated in the centre of an intersection was only slightly higher than at the outside points, while the underground measurements showed a significant difference. This finding was based on three underground measuring points across the intersection and on 2 m wide elements in the model. As in previous studies (Vervoort, 1991), the site discussed in this paper was also simulated using the three-dimensional boundary element program MINDAY (Nardle, 1989) in the linear elastic domain. When a numerical simulation model is being established, the most simplified model possible should first be tried. If such a model can correctly answer the questions to be addressed, there is no need to develop time-consuming models, of which the input parameters are often not well known. In Figure 6, the elastic roof movement calculated is presented. The model was composed of small elements (0.1 m x 0.1 m). As the aim was to compare the curvatures, the curve calculated was moved upwards so that it intersected with the coal pillar corners at the roof interface. The Young's modulus of the coal seam and of the surrounding strata was assumed to be 3 and 4 GPa respectively, and the Poisson's ratio was...
taken as 0.25. Although the roof deflection measured is slightly smaller at the sides than the calculated movement, the curvatures can be considered as similar. However, with larger element sizes, the discrepancy increased. In Figure 7, various calculated curves are presented. Again, the curves are moved upwards to intersect the coal pillar corners. With larger elements the curvature becomes flatter in the middle of the roadway, resulting in a larger difference compared to the underground measurements. In conclusion, a linear elastic model can be applied satisfactorily to simulate the underground deflection of the roof in a roadway development, provided the element size is small enough.

**INCREASE IN ROOF DEFLECTION DURING PILLAR EXTRATION**

The extraction of coal pillars in a bord and pillar panel creates a state of continuously changing stress distributions above the remaining pillars. This causes an increase in roof movement in the roadways and intersections. In Figure 8, the variation in roof deflection of three points in the middle of a roadway is presented as a function of time starting at day 0. The bord and pillar panel was developed in a 2 m high bottom seam, situated at a depth of 260 m. The monitoring points were positioned at three different horizons, as indicated in Figure 9. During pillar extraction the pillars of the bottom seam and the entire top seam were mined, including the shale-sandstone parting. However, up until mining of the top seam takes place, the entire roof of the bottom seam has to remain stable. The conventional drill and blast method was used. The monitoring started on day 0, when the pillar extraction had advanced to the position indicated in Figure 9.

The support installed in the roadway was composed of a double row of timber props at both sides of the roadway with a timber tape on top of them (see Figure 10). The spacing between rows varied between 1.0 and 1.5 m.

Figure 8 shows the significant amount of roof separation that occurred during the extraction of adjacent pillars. One of the reasons for conducting these measurements was to establish if there is a need to install additional support in the section (e.g. roof bolts or cable anchors). After 23 days of monitoring there was a differential movement of 9.3 mm between the point anchored in the thin shale-sandstone seam and the point in the top coal. Between this latter point and a point

![Graph showing roof movement over time](image)

**Fig. 8** - Variation in roof deflection measured as a function of time during pillar extraction.

![Diagram of pillar extraction sequence](image)

**Fig. 9** - Sketch of pillar extraction sequence.

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supported in the sandstone (top roof), an additional 3.2 mm difference was measured. Referring to previous underground sites monitored by COERCO (Vervoort, 1990), the movement of the top coal seam roof (4 mm after 2½ days) can be considered as acceptable and within a realistic maximum allowable limit. However, the movement of the shale-sandstone parting, four times as large, is excessive and could create unsafe working conditions in the roadways close to the goaf edge. Over a period of 2½ days, 16.5 mm of roof movement was detected or an average of 0.7 mm a day.

Additional support is thus recommended, with the aim of anchoring the parting and the top coal to the stable top seam roof. Further research is being conducted to determine the most effective support system and the optimum pattern. In Figure 11, the change in roof curvature across the roadway is presented for successive days, starting from day 6. On day 7, the effect is already noted of the presence of the goaf at the right side of the panel. At point R, 4 mm of movement was detected, while at point L only 1 mm occurred. Point M in the middle of the roadway, however, underwent the largest amount of movement. After day 14, the difference between left and right became more pronounced and the largest displacement was no longer in the middle of the roadway. This can be explained by higher stresses on the pillar remnant B adjacent to the goaf and by the presence of more fractures in that remnant in comparison to pillar A adjacent to point L.

The panel monitored was modelled and the roof deflection was calculated for the successive mining steps (Figure 12). The aim of the investigation was to see if this pillar extraction panel could be modelled successfully using a three-dimensional linear elastic model. The emphasis was not placed on the absolute values calculated, but on the profile of the roof across the roadway. The properties of the coal were considered to be equal for all pillars: a Young's modulus of 1000 MPa and a Poisson's ratio of 0.2. The modulus of the goaf was selected as 50 MPa, while a bulking factor of 1.2 was assumed. The Young's modulus of the strata was considered to be constant and equal to 5000 MPa. Figure 12 shows that the simulations also indicate an asymmetric profile. The point of maximum deflection is situated at the right of the centre line and moves further to the right during the successive mining steps. However, this linear elastic model underestimates the movement close to remnant pillar B. The discrepancy between measurements and simulations can be considered to be logical, as an elastic model does not induce any fracturing or weakening of the pillar. Further measurements should indicate if an asymmetric support pattern will be required and if it will be more effective than a symmetrical pattern.
DISCUSSION OF FINDINGS

To determine an efficient and cost effective support system for roadways and intersections in South African coal mines, roof deflection measurements are being conducted during the development stage of bord and pillar workings and during pillar extraction. The main objective of the underground measurements is to learn more about the fundamental roof behaviour in coal mines and the effect on the roof of various support types and patterns. All underground monitoring sites are being modelled, this assists in explaining underground observations and, in the long term, it should allow the prediction of roof behaviour with a higher degree of confidence.

To accurately measure roof deflection and bed separation, a survey levelling technique was adopted. The overall system reading accuracy was established as being within 0.4 mm on a 15 m sighting distance. The sighting distance has an appreciable effect on accuracy, as does the reading technique. Additional factors that could influence accuracy include the staff positioning sequence and the instrument collimation.

Underground measurements of the initial roof deflection around the face showed a symmetrical curvature of the roof across the roadway. In the middle of the roadway, 4.4 m of roof movement was detected over a period of 8 days after mining. The measured curvature could be satisfactorily modelled using a three-dimensional boundary element code in the linear elastic domain if the element size is small enough (e.g. 0.1 m). If larger elements are used the curvature flattens out more in the middle of the roadway, increasing the discrepancy with the measurements.

In a roadway in a pillar extraction panel, more roof movement was measured at the side nearest the goaf than at the opposite side. This can be explained by the higher stresses associated with the pillar remnant adjacent to the goaf, weakening the pillar by inducing fractures and increasing the compression. These findings could be partially modelled using a three-dimensional linear elastic model. An asymmetrical curvature was calculated. Close to the remnant pillar, however, the roof movement was underestimated by the model, as an elastic model cannot generate fractures in the coal pillars. The differential movement across the roadway increases the strain in the roof, deteriorating the overall stability. Further measurements should indicate if an asymmetrical support pattern will be required and if it will be more effective than a symmetrical pattern. During pillar extraction a large amount of bed separation occurred indicating the need for additional support.

This study showed that by accurate and detailed underground measurements combined with numerical simulations, a better understanding of the roof behaviour in bord and pillar and pillar extraction panels can be established. An improvement of this basic knowledge should result in the optimum design, resulting in more cost effective support systems and safer working places.

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REFERENCES


