Seismic and geotechnical investigations following a rockburst in a complex French mining district


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Abstract

This paper presents the results of seismic and geotechnical studies carried out after a fatal accident that occurred during mining of the Frieda5 coal seam at Merlebach mine of HBL (Houillères du Bassin Lorrain, East France). On June 21, 2001, a violent rockburst (local magnitude of 3.6) affected the Frieda5 seam at depth of approximately 1250 m. The zone of the accident is located in the main gate 200 m ahead of the longwall face. Subsequently, an investigation was carried out to determine the causes of the accident and to understand the induced phenomenon. The program included an analysis of a comprehensive set of seismic data and the collection of in-situ stress measurements. The objectives were twofold: (1) to provide input data for the back analysis of the rockburst and (2) to identify other potential high-risk zones in the next panels to be mined. The joint analysis of the seismic, geological and geotechnical investigations suggests that the rockburst is largely due to a specific geological phenomenon, a sandstone channel in the floor of the coal seam characterized by high horizontal stresses.

Keywords: Rockburst; Seismic; Overcoring; Stress; Analysis; Mine

1. Introduction

Mining operations, at relatively great depths, induce a redistribution of the stress field based on the rheological and mechanical behavior of the rockmass. This can lead to substantial microseismic activity (Ben Slimane et al., 1990; Linkov et al., 1997; Kanelo et al., 1999), and is often accompanied by rockbursts (Senfaute et al., 1997, 2001). A rockburst consists of a brutal expulsion of the worked seam accompanied by a violent shock mainly felt in the vicinity of the coal seam where it can cause significant damage such as roadways and pillars closures or coalburst. In most mines, an integrated seismic monitoring system is set up to identify zones of rockburst risk. The mining-induced seismic activity occurs in different ways depending on natural conditions and the geometry.
of the mining (successive panels mined skin to skin or with small pillars in multiple layers). Major dynamic events are generally associated with important seismic activity. The back analysis and the interpretation of this activity play a major role in the prediction of these hazards in future mining areas.

This paper describes and interprets the seismic activity that associated a major rockburst and in-situ stress measurements carried out in a longwall mine in Eastern France.

2. Site description

Since the middle of the 19th century, the Houillères du Bassin de Lorraine (HBL) collieries have been actively extracting coal in the Lorraine coal field, one of France’s most important coal districts, located in the eastern part of the country near the German border. The exploitations of the coal field are carried out in a very complex geological setting, characterized by two faulted and asymmetrical anticlines separated by a central syncline (Fig. 1). The geological formations consist mainly in multiple coal seams with intermediate Westphalien shale intrusions. The coal is extracted from two main series separated by a so-called Merlebach conglomerate, and overlain by a 200-m to 300-m-thick sandstone layer.

In the investigated zone, the mined seam Frieda5 lies in the upper series dipping 20° westward. The Frieda5 panel was mined over a thickness of approximately 3–4 m using a longwall caving method, with a panel length and width of 1200 m and 250 m, respectively. The longwall caving method uses two roadways and extracts coal along a straight front having a large longitudinal extension. The stopping area close to the face is kept open to provide a secure zone for the personal and the mining equipment. The mining operations on the Frieda5 panel started in the beginning of February 2001 with an average daily advancement of 4 m.
3. The 21 June 2001 rockburst

On June 21, 2001, after 300 m advancement of the Frieda5 longwall panel, a fatal rockburst affected the main gate and induced a strong seismic event recorded by the regional network with a local magnitude of 3.6. This seismic event occurred at a depth of 1250 m in a complex mining environment, involving a large number of panels exploited in a multiple seam configuration (Fig. 2). The event was related to a violent rockburst that affected the main gate 200 m in front of the Frieda5 longwall face and induced the collapse of roadway and an important floor heave of more than 2 m high (Fig. 3).

Fig. 2. Orthogonal view (a) and schematic cross section (b) of the mined panels in the studied mining district at the end of March 2003. Only panels mined between depth 1140 m and 1250 m are presented in view (a).
Based on the results of mine planning studies, the affected zone was not expected to be prone to rockbursts. Indeed, the presence of old works above and below the Frieda5 panel suggested that the vicinity of the planned mining was already de-stressed. Therefore, it appeared fundamental to understand the mechanism responsible for the dynamic phenomena so that a prevention program and monitoring methodology could be defined to assure security and safety during the mining.

Investigations based on the back analysis of seismic data and in-situ stress measurement using the overcoring technique were carried out in order to identify the source responsible for the rockburst and to identify any high-risk zones in the next panels to be mined.

4. Seismic analysis

4.1. Monitoring networks

In the HBL collieries, two different microseismic monitoring systems are integrated:

- A seismic network capable of monitoring the mining operations at a regional scale and consisting of 14 recording stations (11 free-field and three underground) with vertical component geophones (natural frequency of 1 Hz). The seismic activity is recorded in the frequency band of 1–30 Hz.
- A seismoacoustic network monitoring the mining operations at a local scale in the vicinity of the coal face. It is composed of 14 high-frequency geophones (natural frequency of 14 Hz) installed along the main and head gates. This network provides a continuous recording in the frequency band of 14–400 Hz and allows daily analysis of the released seismoacoustic energy.

4.2. Event location from the regional microseismic network

The P-wave first arrivals have been used to estimate the spatial location of the 3.6 magnitude seismic event (Fig. 4). The focus of the event is located 200 m below the main gate of Frieda5 panel, approximately 150 m in front of the longwall face. This corresponds to depth of 1400 m below surface level.

The magnitude 2.4 event that preceded rockburst is localized at the same position in the main gate but at a shallower depth (1157 m). Since the start of mining...
operations and before the rockburst, the strongest recorded seismic events (magnitude greater than 2.5) were attributed to a pillar effect caused by the so-called Louise pillar (un-mined blocks in between longwall panels) located behind the Frieda5 panel. Stress concentration due to old mining panels surrounding this pillar systematically induces seismic activity in adjacent coal faces (McGarr and Wiebols, 1997).

4.3. Seismoacoustic analysis

The seismoacoustic network has recorded more than 1000 events related to the mining operations of the Frieda5 and the underlying Erna3 panel (Fig. 5). Note that all seismoacoustic events are not systematically recorded by the regional network. Indeed, the small events are generally filtered through their propagation in the overburden. Fig. 5 shows that the events are localized mostly ahead of the Frieda5 face and behind the face of the almost mined out Erna3 panel. The data show a progressive concentration of seismic events up to the June 21 rockburst 200 m ahead of the Frieda5 face. The detailed time analysis of the seismoacoustic activity reveals that the events in the accident zone started a few months before the rockburst, approximately 400 m ahead of the front of Frieda5.

In addition, the seismoacoustic activity was analyzed in terms of elastic energy (Fig. 6). The analysis is commonly based on the estimation of the energy release rate (Joule/meter advance) that is used to explain the occurrence of the mining-induced seismicity (Anonymous, 1988; Renaud et al., 2002).

We have examined the daily evolution of the cumulated energy with respect to the number of recorded
events. The results shown in Fig. 6 highlight three main phases:

1. During the first 2 months, the increase of the energy level was associated with the seismic events localized on Louise pillar (high stress concentration).
2. The second phase corresponds to an important increase of recorded events but the dissipated energy remains relatively low, the estimated dissipation rate being $0.5 \times 10^6$ J/m.
3. During the last 2 months of mining and before the accident, we observed a slight decrease in the seismoacoustic activity while the elastic energy increased faster and has reached the rate of $2 \times 10^6$ J/m, four times greater than the rate of the second mining phase. On June 21, 2001, the accumulated elastic energy released violently through strong seismic event that had caused a fatal accident.

4.4. Rupture mechanism

In general, mining induced seismic events can imply three types of rupture mechanisms: (1) implosive mechanism associated with common rockmass failures (i.e., block caving); (2) a shear mechanism identified when geological faults are involved; (3) a combination of mechanisms (1) and (2). The associated rupture is rather complex and difficult to interpret particularly when the seismic network coverage is inadequate.

In the case of the major event of 21st June 2001, the analysis of the P-wave first motion allowed the identification of an unusual "explosive" rupture mechanism (pure compression) induced probably by a high horizontal stress field. On the other hand, the magnitude 2.4 event that was recorded at 9:38 PM, about 20 min before the rockburst-related event, revealed a shear mechanism. Fig. 7 illustrates an empirical rup-
ture mechanism model to explain the rockburst phenomenon. In the proposed model, the redistribution of stresses caused by the specific mine layout generated unusually high levels of local static loading, which in turn triggered a dynamic fracturing event in the underlying sandstone. The presence of a competent sandstone layer below the mining zone associated with high horizontal stresses (tectonic origin) seems to be a major contributing factor for the rockburst phenomenon (Renaud et al., 2002).

Fig. 6. Cumulated seismoacoustic energy and number of recorded events during the mining of Frieda5 coal face.

Fig. 7. Schematic representation of the inferred rupture mechanism associated with the rockburst.
A back analysis has been carried out on the historical seismic activity related to the cutting faces located in the Frieda sector. The results highlighted four events of local magnitude greater than 2.0 localized exactly in the affected zone of Frieda5. The events, recorded in January 1999, show an explosive source mechanism, identical to the one identified on the strong event of 21st June 2001. These observations suggest that the anomaly in the accident zone did exist in the past, but was seismically less active before the face Frieda5 was mined.

5. Stress analysis

Unlike the seismic techniques, in-situ stress measurements are not commonly used to systematically monitor the mining operations. In HBL, stress measurements carried out following the 21st June 2001 rockburst provided valuable information for understanding the dynamic phenomenon. This encouraged the systematic use of this method in the design of future planned panels.

Altogether, 21 overcoring tests were performed at 10 different locations spread over the area of interest. The tests location are displayed on Fig. 2. Of these, 16 gave usable results.

5.1. Stress measurement technique

The technique used for in-situ stress measurements is the overcoring of CSIRO Hi12 cells (Amadei and Stephansson, 1997). At each measurement point, a main borehole was first drilled from the roadway in the roof and in the wall, depending on local geological setting. A CSIRO cell was then settled in a pilot hole, coaxial to the main hole, and drilled at a sufficient distance from the roadway to ensure that the latter had negligible influence on the measured stress. Overcoring was then carried out and the overcore was retrieved for evaluation of its elastic properties using a biaxial test. When the overcore was found inappropriate for biaxial testing (insufficient length, presence of fractures), rock samples were collected from the overcored zone and brought to the laboratory for triaxial testing. For redundancy, several overcoring
tests (typically two) were usually performed in a same borehole.

Fig. 8 shows an example of the response curves observed on the 12 strain gauges during an overcoring test as a function of the distance overcored. The local stress tensor \( \sigma \) was estimated from the measured strain variations \( \varepsilon \) through the following inversion system:

\[
\varepsilon^{12*1} = A^{12*6}\sigma^{6*1}
\]

(1)

where the influence matrix \( A \) is given by the analytical solution for strain on the walls of an infinite circular

Fig. 9. Typical samples of overcored rock. Top—core sample for rock testing; middle—ex core; bottom—overcore.

Fig. 10. Biaxial test strain curves for an overcore from the Dora1250-panel (point 300, overcoring test 1).
hole drilled in an homogeneous linear elastic medium and submitted to a far-field stress tensor $[\sigma]$. Such inversion was done using the SYTGEmath software, developed by INERIS. The reliability of the stress estimate was assessed using a qualitative indicator $Q$ ranging from excellent (E) to fair (F) through to very good (VG) and good (G). For each overcoring test, $Q$ was established on the basis of the distance between the measured and the predicted strains (coefficient of variation), the number of gauges considered in the inversion, the quality of the strain curves (mostly tension strains, stable final values) and on whether the elastic parameters were determined by a biaxial test or by triaxial tests, the former being considered as more reliable than the latter. As a general rule of thumb, we can state that the uncertainty of the stress values and orientations is about $\pm 15\%$ in a ‘good’ to ‘excellent’ test and $\pm 20\%$ in a ‘fair’ test.

5.2. Properties of the overcored rock

The typical overcored rock was a homogeneous fine to coarse-grained sandstone with relatively scarce thin embedded schistose layers (Fig. 9). In six overcoring tests out of 21, the overcore was retrieved in a state suitable for biaxial testing. The results of this test, presented in Fig. 10, showed a recurrent non-linearity in the stress–strain curves. Such non-linearity was also observed in triaxial tests (see further).

For each biaxial test, we used systematic checks on the results to identify a possible elastic heterogeneity or anisotropy of the overcored rock. Rock anisotropy,
although moderate, was observed in all biaxial tests. On the other hand, tests on the heterogeneity of the elastic properties at the scale of the overcore (comparison of gauges 1 and 7) showed no indication of heterogeneity in the tested overcores.

In all cases where it was not possible to perform a biaxial test, the rock elastic parameters were determined by triaxial tests on samples with an aspect ratio of 2 and a diameter of 38 mm. Those tests were performed at different confining pressures and for each confining pressure, several estimations of the elastic parameters were made at different values of the deviatoric stress (Gaire, 2002; Schoumaker, 2002).

A compilation of those results, presented in Fig. 11, shows a clear dependency of the Young modulus on both the applied mean stress and the reduced deviatoric stress \((\sigma_1 - \sigma_3)/(\sigma_1 + \sigma_3)\). Increasing the mean stress tends to stiffen the rock and hence, to increase the Young modulus while increasing the reduced deviatoric stress tends to soften the rock (probably by inducing damage) and hence, to reduce the Young modulus. A similar dependency appears for the Poisson’s ratio on those two parameters, although this is less clear on the graphs of Fig. 11.

Therefore, we were particularly cautious, when using elastic parameters for inverting overcoring data, to choose average elastic parameters calculated on a range of stresses (mean and deviatoric) as close as possible to the range of stresses actually applied on the rock during overcoring. The values of the Young modulus \(E\) and Poisson’s ratio \(\nu\) used for each overcoring test are indicated in Table 1.

In one point (Dora1250-panel, point 1180), it was decided to estimate the rock anisotropy by performing triaxial tests on samples oriented axially and transversely to the schistose layers. The anisotropy turned out to be relatively moderate, with an anisotropy factor of 1.23 (Gaire, 2002). Inversion of the overcoring data obtained in that point with the assumption of a transverse isotropic rock and comparison with the results obtained in the isotropic rock assumption showed that accounting for anisotropy in the overcoring data reduction did not change significantly the estimated stress tensor. For this reason, all stress inversions presented in the following were carried out assuming an isotropic elastic behaviour of the rock.

5.3. Stress measurement analysis

In order to obtain information on the state of stress existing prior to the accident, it was decided to perform two overcoring tests in the main gate of the Frieda5 panel at point 800. This point is outside the accident zone (i.e., the measured stress field is not influenced by the accident zone) and close enough so that the measured stress field remains representative of the pre-existing state in the accident zone before the rockburst occurrence. Two other overcoring tests were carried out at point 900, i.e., in the affected zone.

Out of the four overcoring tests performed, two tests provided exploitable results. The principal stresses \(\sigma_1, \sigma_2\) and \(\sigma_3\) (modulus \(M\), azimuth \(\text{Az}\) and dip), the vertical and horizontal stresses, as well as the major-to-minor \((A_{13})\) and major-to-intermediate \((A_{12})\) principal stress anisotropy factors determined at each point are presented in Table 1. Fig. 12 shows the display, provided by SYSTGEOmath, of the principal stresses orientation in a polar coordinate diagram (OX: north, OY: upward vertical, OZ: east).

Green, blue and red clouds of points indicate the directions of \(\sigma_1, \sigma_2\) and \(\sigma_3\) respectively.
One first important result to notice in Table 1 and Fig. 12 is the very different stress tensor determined at the two points, both in terms of orientation (e.g., $\sigma_1$ rotates by an angle of 90° from point 800 to point 900) and modulus (e.g., the vertical stress $\sigma_v$ is much lower at point 800 than at point 900). It is not surprising to observe that the occurrence of the accident has totally modified the stress distribution in the accident area.

Secondly, the stress tensor at point 800, which is supposed to represent the stress tensor in the accident zone before the occurrence of the event, shows a very anisotropic state ($A_{13} = 6.33$) with a high vertical distressing ($\sigma_v \approx \sigma_3 = 6$ MPa, i.e., 0.2 times the overburden load). This, coupled with relatively high horizontal stresses (38 MPa and 19 MPa for $\sigma_1$ and $\sigma_2$ respectively), has probably caused the bending and the subsequent rupture of the competent sandstone layer located below the mining zone, as suggested the numerical model (Renaud et al., 2002).

6. Conclusions

The seismic and geotechnical back analysis of the 21 June 2001 rockburst that affected the main gate of the Frieda5 panel in the HBL collieries revealed the following results:

1. The rockburst-induced seismic event recorded with a local magnitude of 3.6 was located under the main gate of the Frieda5 panel at depth of 1250 m and 200 m in front of the longwall face.
2. The involved rupture mechanism was of explosive type (total compression). It was induced by high horizontal stresses. This result is in agreement with field observations (heaving of the floor).
3. The back analysis of the historical seismic activity provided evidence of events with an explosive mechanism in the same zone that occurred during the mining of cutting faces in 1999. This observation suggest that the anomaly in the accident zone did exist in the past, but was seismically less active before the face Frieda5 was mined.
4. Prior to the rockburst, seismoacoustic events occurred in the accident zone at approximately 400 m ahead of the longwall face. This seismic behavior can be attributed to a “precursor phenomenon” of the big event. Time analysis of the cumulated elastic energy showed different seismic patterns during successive stages of mining. A fast increase
of the energy release rate (from $0.5 \times 10^6$ to $2 \times 10^6$ J/m) was observed approximately four months prior to the rockburst.

5. Seismic analysis has proven its capabilities in monitoring mining activities and identifying risk zones. However, this study also points out the difficulties of predicting major mining induced phenomena merely on the basis of seismic analysis.

6. The analysis of in-situ stress measurements contributed significantly to the identification of the risk zones associated with mining activity. At the Merlebach mine, stress measurements have provided crucial data for analysing the causes of the 21st June 2001 accident. They have also been used to formulate specific prevention plans for the mining of the next longwalls, which to date have met successful results.

The results provided by the joint analysis of the geotechnical and seismic data suggest that the presence a local geological anomaly is responsible for the observed strong seismic event. A sandstone channel in the floor of the coal seam and overall high horizontal stresses are regarded as the main contributing factors for the rockbursts event.

References


