Semi-controlled seismogenic experiments in South African deep gold mines


Synopsis

To study the preparation process of an earthquake, we should get closer to the hypocentre. In co-operation with ISS International, we had an experimental field (~200 m x ~200 m) without dykes and faults in a South African deep gold mine. We have monitored more than 20,000 seismic events ($M$>2) with borehole tri-axial accelerometers. We used a data acquisition system with 15 kHz sampling and 120-dB dynamic range. In a remnant area at a distance of 100–200 m, an earthquake sequence associated with an $M$=2 event occurred. Significant changes in seismic parameters such as stress drop, $b$-value, energy index were observed associated with the sequence.

We installed Ishii's borehole strainmeters and could monitor as large a strain change as $10^{-4}$ associated with mining. However, sampling was only 4 times per hour and 12 bit A/D. A distance from the $M$2 sequence was ~100 m, being not close enough. Therefore, we found another field with several crosscut tunnels excavated across a fault where an $M$=2-3 event is expected. We installed the strainmeter within several metres of the fault to monitor both shear and normal strains on the fault. The strains are continuously digitized with a 24-bit 25-Hz A/D conversion. The Earth Tide ($10^{-8}$) is clearly detected.

Seismicity induced by longwall mining can be compared to earthquake swarm induced by fluid intrusion to vertical dykes. We also found a decrease in energy index in the source area of $M$>5 events a few days before the major events.

Keywords: seismic monitoring, strain monitoring, seismic parameters, preparation process of an earthquake, South African gold mine.

Introduction

To understand an earthquake preparation process or rockmass behaviour during the process, we should get closer to the hypocentre. We should put multiple sensors in the seismogenic zone to monitor the slightest stress within the seismogenic area in addition to external loading or bulk deformation of rockmass in a seismogenic area. However, it is not easy with natural earthquakes because hypocentres are usually a great distance from the earth's surface. A lengthy term of seismograms tells us to some extent about sources. However, the surface layer with a low $Q$ disguises information considerably on an earthquake source. Some researchers have attempted to drill holes to seismogenic depths to measure the stress. However, the costs are considerable and the holes are not always close enough to monitor seismogenic processes clearly.

In South African deep gold mines, thin tabular gold reefs are excavated. Seismogenic areas move with the advance of mining. Therefore, we can install instruments in situ in future seismogenic areas, and we can monitor earthquakes from the closest proximities. Early works, for example, McGarr and Green, McGarr et al. attempted seismic monitoring and compared these with tiltmeters or the Sacks-Evertson dilatometer. Nicolaysen referred to such an attempt as a semi-controlled experiment on seismic events. In 1992 he showed the Japanese Seismological Society that South African deep gold mines are good experimental fields for the study of earthquakes. Accordingly, we looked for a good experimental field in some South African gold mines and established the first experimental field in 1996 at a mine in Carletonville, South Africa, in co-operation with ISS International, Welkom, South Africa. In the first field, more than 20,000 events ($-2 < M < 2$) were monitored within 200 m from our network from February to October 1996. Most events occurred within 200 m of our monitoring network. In this report, we review some of our results, particularly those
related to rockmass instability obtained in the first field. In the first field, however, the distance was still too far from the hypocentres. Therefore, from September 2000 in the second experimental field, we started monitoring several metres from a fault where $M=2-3$ event was expected. In this paper, we introduce a feature of our new attempt in the second field12.

We attempted to apply our experience gained in South African gold mines to interpret natural earthquakes swarm in Japan. In this report, we briefly introduce a successful case study13.

The first phase in Carletonville

Experimental field and monitoring system9

As illustrated in Figure 1a, our first experimental field was deployed in a footwall haulage tunnel at a depth of 2600 m and 50 m beneath a gold reef 20 degrees dipping south-east. Nine boreholes were drilled within ~200 m along the haulage tunnel, in which tri-axial accelerometers were installed. Each borehole was 15 m deep, to be away from free surface and fracture-rich zones around the haulage. Country rock was Precambrian quartzite with Vp~5.5 km/s.

Figure 2 shows the configuration of mining, the haulage tunnel and our instruments. The thick line is the haulage tunnel 50 m beneath the gold reef. During the first experiment period (Feb.–Oct. 1996), the light gray areas were being mined.

An accelerometer sensor used was Vibra Metrics Inc. 1136 with frequency range (±3dB) of 1-10,000 Hz. They could record as great an acceleration as 48 G14. A fifth-order Bessel filter with a 2-kHz cutoff frequency was used as an anti-aliasing filter. Accelerograms were recorded with ISS International Inc. PS with a sampling frequency of 15 kHz and a dynamic range of 120 db.

Location of seismic events and the M~2 event

Hypocentres were determined using both P- and S- arrival times and a P-wave polarity. Homogeneous infinite elastic medium with Vp = 5.5 km/s and Vs = 3.65 km/s were assumed. XMTS V.7.2 (ISS International Inc.) was used to pick phases and determine hypocentres. An accuracy for hypocentres at a distance of 200 m is less than ~10 m. Figure 3a shows the epicentre distribution of events from Feb. to Oct. 1996. Accelerometers are indicated by black triangles. More than 20,000 epicentres with $M>-2$ migrated from February to October 1996 with the advance of mining. In the vertical cross-section along the line A-A’ (Figure 3b), we can see hypocentres concentrate around gold reef ~20 degree dipping south-east and around haulage tunnels.

If we delete all minor events, we find larger events occurring at ~100 m from our nearest seismic stations (Figure 4). $M$~2 events occurred on 15 July 1996 in a solid remnant area (see the area with a star in Figure 2). Note that three sides of this area had been already mined, high stress being induced in the area. The source radius of the $M$~2 event is nearly equal to that of an entire part of the remnant area.

Strain change outside of the seismogenic area of the M~2 event

In Figure 2, circles denote the places where two boreholes were drilled to install 3-component Ishii’s borehole strainmeters15. Ishii’s borehole strainmeter measures diameter changes in three directions. Diameter

Figure 1—Schematic illustration to roughly show the configuration of mining, our monitoring network and faults. Perspective illustrations (left) and vertical sections normal to gold reef's strike (right). (a) Our first experimental field in a mine in Carletonville area contains a gold reef with a dip angle of 20 degrees and a haulage tunnel 50 m beneath the reef. (b) A typical geological setting in a mine in the Welkom gold field with faults segmenting gold reef. An example of a monitoring network is shown. A: accelerometer, S: strainmeter. Crosscut tunnels crossing the fault can be used to install instruments. A strainmeter can be installed very near a fault to monitor shear and normal strains on the fault

Figure 2—Configuration of mining and our monitoring network in plan view. The thick line represents the haulage tunnel 50 m beneath the gold reef, where boreholes were drilled to install accelerometers and strainmeters. The light gray areas represent working areas while we monitored seismic events (Feb.–Oct., 1996). A star indicates the remnant area with an $M$~2 event, which is central to this report.
change is mechanically amplified up to forty times with a metal plate with well-designed slits so that the remnant works as cascaded levers. A magnetic sensor monitors the amplified diameter change with a sensitivity of $10^{-9}$ strain. So far, Ishii et al.\textsuperscript{15} successfully monitored a subtle change preceding earthquake swarms in Japan. Ishii’s strainmeter also has a wide dynamic range. United with a battery-driven data logger, Ishii et al.\textsuperscript{15} successfully carried out \textit{in situ} stress measurements by an overcoring method. In our first experimental field, we used Ishii’s strainmeter to monitor very large strain change associated with mining.

Figure 5 represents strain changes\textsuperscript{10} in the same period as that of epicentre distribution. From February to June, we can see significant strain changes caused by mining. If we assume 70 GPa that is typical for quartzite in the field, the strain changes correspond to stress changes larger than 10 MPa. In contrast, after July, the strain changes are not so significant. This suggests no significant stress change around the remnant area when the $M \geq 2$ events took place on 15 July. We emphasize that there was little such artificial disturbance as blasting-induced seismicity that can mask preparation process in rock mass. In Figure 5, almost all events were directly induced immediately after an abrupt stress change by blasting. However, the events after July 1996 in a polygon in Figure 3 are the events in a fore-, main- and after-shock sequence with little direct effect of mining.

\textbf{Seismic parameter change associated with the $M \geq 2$ event}

In Figure 6a, a cumulative number of events in the polygon in Figure 3 is shown with a magnitude of each event shown by a bar. In Figure 6b, squares represent static stress drops averaged over a moving 50-event window. Diamonds show $b$-values for the moving 50-event window. The stress drops clearly decreased after the $M \geq 2$ event. In contrast, $b$-value clearly increased after the event. It seems very interesting. However, we must be careful because there exists a tendency that smaller events have smaller apparent stress. In other
words, larger $b$-value is equivalent to a tendency of many smaller events, resulting in lower stress drop if we averaged over 50 events. If such a tendency is clear, such seismic stress parameters as stress drop or apparent stress are not good measures to learn what’s going on in the seismogenic area. We must take moment dependency on energy or apparent stress into consideration. One of the effective ways to solve the problem is to introduce an energy index, as described in the next section.

**Energy index change associated with the $M$–2 event**

If we plot seismic energy versus seismic moment, a regression line (a solid line in Figure 7) does not always coincide with the line suggesting a constant apparent drop (a dashed line in Figure 7). In such situations, an absolute value of apparent stress is not a good measure of stress state in rockmass. For example, the event A is beneath the solid line in Figure 7. This suggests that it has lower apparent stress compared with those typical for events with a similar moment. On the other hand, the event B is above the solid line in Figure 7. This suggests that it has higher apparent stress, compared with other events with similar moments. However, an apparent stress is the same for these events A and B. Therefore, an apparent stress itself may lead to misunderstandings. To avoid such misunderstandings, an energy index is a good measure proposed by Van Aswegen and Butler. The energy index, $EI$, is defined as:

$$EI = E / E(Mo)$$

where $E$ is the energy of an event. $E(Mo)$ is the energy that is expected by a regression line for a given moment $Mo$. A standard is the regression line. The energy index is high for events above the regression line, and conversely, low for those beneath the line (Figure 7).

Figure 8 shows the change in the median of energy index for a 2-day or 5-event moving window in July 1996. During the period, strains increased monotonically. An energy index initially increased, suggesting elastic response of rock mass to increase in load by mining. Thereafter, an energy index started to decrease. In this period, no significant change in strain trend is seen, suggesting no significant change in loading. Therefore, we think this decrease suggests initiation of instability of rockmass after peak strength, followed by the $M$–2 event.

**Other attempts in the first experimental field**

In addition to the above results, using the data obtained in our first experimental field, scaling relationship between moment and corner frequency is studied. A stress dependency of shear wave splitting is investigated. Dependency of duration time of initial phase on seismic moment is discussed. We attempted to monitor electromagnetic emission associated with a seismic event.

**The second phase in Welkom**

We wanted to have more case studies in the first experimental field in the Carletonville area. However, no more mining was planned near the first field. In and around the first experimental field, there were no existing faults that we could anticipate a closer, larger event. The smallest distance that we could monitor larger events with $M$–2 was ~100 m. Although we should monitor strain within the seismogenic area, strainmeters were still outside the seismogenic area. It
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was too far to monitor very subtle strain change preceding major events. Therefore, we gave up this field. We looked for another field with an existent fault and tunnels to get close to the fault.

We found the second field in Welkom. In the Welkom gold field\(^2\), some major normal faults have a throw larger than 1000 m. Sub-fault systems are also well developed. Gold reefs are often segmented as shown in Figure 1b. In a geological situation with some sub-faults, horizontal tunnels, called crosscuts, are excavated across the faults with constant horizontal and vertical intervals (Figure 1b).

Our second experimental field has a fault with a throw about several tens of metres. The fault actually had an \(M=3\) event in 1998. Another large event is expected associated with further mining. As shown in Figure 9, we drilled a borehole 14 m deep parallel to the fault strike. We installed Ishii’s borehole strainmeter to monitor diameter change in three directions orthogonal to borehole axis to monitor shear and normal strain on the fault. This time we added a sensor to monitor strain along the borehole axis.

In our first experimental field, accelerometers cover wide frequency and dynamic ranges of a velocity field (Figure 10a). However, strain was sampled only four times an hour. A large gap was therefore seen in coverage of the frequency range. Strain data were digitized with only 12-bit A/D, as important as resolution is to detect subtle change. In order to fill the frequency gap and extend dynamic range, we used a specially designed ISS International MS with a 24-bit 25-Hz A/D conversion, as illustrated in Figure 10b.

Figure 11 shows an example of recordings of strain for two days—a weekend in September 2000. An Earth Tide on the order of \(10^{-8}\) is clearly recorded. We are expecting to monitor a preparation process of an earthquake that begins with a very slow and subtle deformation.

An attempt to interpret natural earthquakes\(^1\)

We should recall our experience in South African gold mines in the study of natural earthquakes.

In South African gold mines, maximum principal stress is usually nearly vertical. So, normal-faulting earthquakes often occur ahead of a thin tabular cavity with a small dip angle. This situation can be compared to strike-faulting earthquakes adjacent to a vertical dyke with a strike parallel to a direction of the maximum horizontal compression.

For example, during the 1989 earthquake swarm off the eastern Izu peninsula, Japan\(^2\), a NW-SE striking, nearly vertical dyke (the white bar in Figure 12b) associated with...
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Magma intrusion opened as large as 1 m. Associated with the dyke’s opening, numerous seismic events were induced (Figure 12). The seismicity migrated in synchronization with magma’s migration. A lot of smaller events were located immediately around the dyke. However, rather off the open dyke, the major events with $M=5.2$ and 5.5 occurred on WNW-ESE striking, nearly vertical strike-slip faults (black bars with a star and a diamond in Figure 12a). Though Figure 12b is a plan view, this figure can be applied to learn from a similar situation in a vertical section in South African gold mines. A vertical dyke in a plan view can be compared to a nearly horizontal tabular cavity in a vertical section, and a strike-slip fault in the plan view to a normal-slip fault in the vertical section. In both cases, opening or closure of a thin tabular cavity or dyke stimulates the adjacent faultings.

In order to learn the change in stress state in the seismogenic area, Kawakata et al. analysed 500 m-deep borehole seismograms at the NSI station of the National Research Institute for Earth Science and Disaster Prevention, Japan (NIED). They carefully picked up smaller events (white circles in Figure 12) with unclipped, direct P-pulse preceding the major events. Carefully taking into account source mechanism, rupture directivity and $Q$ effect, they obtained the $EI$, as shown in Figure 13.

Figure 13 also represents tilt at the ITO station and strain at HIZ stations (Figure 12a) outside the earthquake swarm area. The earthquake swarm began on 1 July 1989. On 4 July, seismicity around the seismogenic area of the events $M=5.2$ and 5.5 started to follow the swarm. From 4 to 9 July, the tilt at ITO and strain at HIZ changed monotonically, suggesting the dyke kept opening. However, it is noteworthy that $EI$ increased, but on 6 July, changed to a decrease. This suggests that a decrease in strength of rockmass in the source area of the major events took place on 7 and 9 July.

Concluding remarks

In a remnant area without working stopes, an earthquake sequence was observed at a distance of 100–200 m. Seismic parameters changed during the sequence associated with the largest event ($M=2$). We also successfully demonstrated that Ishii’s borehole strainmeter is sensitive and has a wide dynamic range ($10^{-9}$–$10^{-4}$). It is installed several metres from an existing fault where an $M=2$-3 event is expected. We expect that the strainmeter will reveal a preparation process of an earthquake in detail. Our attempt will contribute not only to the study of rockbursts or mine tremors but also to the study of natural earthquakes, as demonstrated in this paper.

Our experimental fields in South Africa were in nearly dry condition. They are not suitable for studying the effect of pore fluid to an earthquake. For such studies, we should find an experimental field with water-rich faults or in deep mines that are going to be flooded.
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References


Richards Bay Minerals (RBM), the Zululand-based mining company, has won the South African Gold Medal for Excellence in Mining Environmental Management (EMEM) Award.

The award, administered by the Department of Minerals and Energy, recognizes those mining operations, which not only reflect environmental responsibility, but also excel and go beyond mere regulatory compliance. The EMEM award also recognizes the development and application of effective management systems.

RBM was also one of the first mining companies in South Africa to be granted the coveted ISO 14001 international accreditation, for environmental management.

George Deyzel, RBM managing director said that to receive recognition for RBM’s environmental management efforts is not only a reward for all the hard work, but will encourage employees and contractors to continue to strive for even better results.

‘As a world leader in the mining and beneficiation of mineral sands, our goal is to attain a leadership position in sustainable development in the mining industry.

‘We are sensitively aware of the various effects that our operations have on the environment and local communities, and therefore recognize that much work has to be done before we can be confident that our contribution to the global transition to sustainable development, is all it should be’, said Deyzel.

This is the inaugural national award, which will be presented at the national level every second year. Provincial awards will be made in the intervening years—RBM won the KZN award in 2001.

The fundamental objective of the EMEM Awards is the achievement of sustainable development, through:

➤ Motivating the industry to excel in environmental management
➤ Publicly recognize those mining companies which have excelled in their environmental management endeavours
➤ Highlighting examples of excellence in environmental management in the mining industry so that other can take note of new technologies and techniques which have been developed and implemented successfully
➤ Promoting an environmental awareness within the mining company as well as outside
➤ Continual improvement.

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