Coseismic and aseismic deformations associated with mining-induced seismic events located in deep level mines in South Africa

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ABSTRACT

Two underground sites in a deep level gold mine in South Africa were instrumented by the Council for Scientific and Industrial Research (CSIR) with tilt meters and seismic monitors. One of the sites was also instrumented by JApanese-German Underground Acoustic emission Research in South Africa (JAGUARS) with a small network, approx. 40 m span, of eight Acoustic Emission (AE) sensors. The rate of tilt and the seismic ground motion were analysed in order to understand the coseismic and aseismic deformation of the rocks. A good correspondence between the coseismic and the aseismic deformations was found. The rate of coseismic and aseismic tilt, as well as seismicity recorded by the mine seismic network, are approximately constant until the daily blasting time, which takes place from about 19:30 until shortly before 21:00. During the blasting time and the subsequent seismic events, the coseismic and aseismic tilt shows a rapid increase. Much of the aseismic deformation, however, occurs independently of the seismic events and blasting and was described as ‘slow’ or aseismic events.

During the monitoring period a seismic event with M_W 2.1 occurred in the vicinity of the instrumented site. This event was recorded by both the CSIR integrated monitoring system and JAGUARS acoustic emission network. More than 21,000 AE aftershocks were located in the first 150 hours after the main event. Using the distribution of the AE events the position of the rupture area was successfully delineated. The tilt changes associated with this event showed a well pronounced after-tilt. The distribution of the AE events following the main shock was related to after-tilt in order to quantify post-slip behaviour of the source. No evidence was found for coseismic expansion of the source after the main slip. Therefore the hypothesis of the post-seismic creep type behaviour of the source was proposed to explain the large amount of tilt following the main shock. Previous studies using numerical modelling and analytical tools show that for this specific event and rupture area, the amount of measured tilt is highly sensitive to seismic activity in specific regions, in particular, to the bottom corner of the source area. Thus, it is concluded that the post-seismic creep behaviour, if present, most probably occurred in the bottom corner of the rupture area, a region also characterised by large amounts of aftershock activity.

Key words: induced seismicity, mining seismology, rock mechanics, coseismic and aseismic deformations.

INTRODUCTION

Seismicity associated with deep-level mining has long been a problem, leading to rockbursts and other similar hazards. Several studies using ground tilting have been completed in an attempt to understand the phenomena better, and ultimately to reduce the risk. McGarr et al. (1982) and McGarr and Green (1978) related measurements of tilt and strain to seismicity and mining. In recent years, the focus of long-term deformation measurements in deep-level mines has been on the relationship between seismicity and the volume or area mined (Milev and Spottiswoode, 2002); and seismicity and stope closure, applied to the design of stope support (Malan, 1999).

Spottiswoode and Milev (2006) show the relationship between the tilt changes and the capabilities of loads carried by the dip pillars as well as their behaviour during their formation.

In this study, high-resolution tilt data recorded underground are used to analyse the coseismic and aseismic deformation of the rock.

EXPERIMENTAL CONFIGURATION AND SITE DESCRIPTION

Two underground sites in a deep level gold mine in South Africa were instrumented by the Council for Scientific and Industrial Research (CSIR) with tilt meters and seismic monitors, Figure 1. One of the sites was also instrumented by JApanese-German Underground Acoustic emission Research in South Africa (JAGUARS), with a small network, approx. 40 m span, of eight Acoustic Emission (AE) sensors (Yabe et al., 2009).

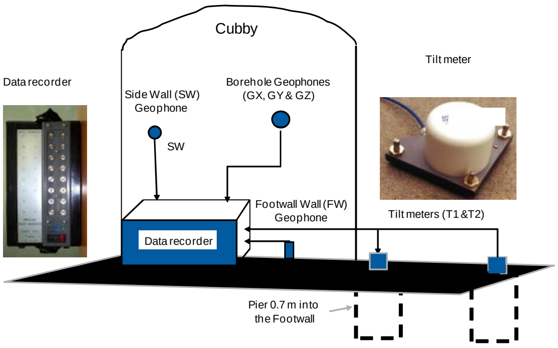

Figure 1. Schematic diagram showing the position and the type of the integrated recording configuration; T1 and T2 are surface mounted tilt meters; GX, GY and GZ is a triaxial geophone installed in a borehole, SW is the sidewall and FW is the footwall geophone

The underground monitoring configuration comprises of two surface mounted tiltmeters installed on specially built piers coupled to the bedrock and a number of geophones installed on the sidewall and the footwall. One triaxial geophone was installed in the borehole drilled into the sidewall. The tiltmeters and the geophones were connected to an integrated data-logger providing single time base for both types of data.

RESULTS AND DISCUSSION

Tilt and seismic ground motion were analysed in order to understand the coseismic and aseismic deformation of the rocks. Two type of tilt were defined:

1. Coseismic or dynamic tilt, defined as the tilt during seismic events and blasting, and.
2. Aseismic or quasi-static tilt, defined as the tilt between two seismic events.

“Fast” seismic events (seismic events associated with large tilt steps) usually lack significant after-tilt. It is concluded that a large seismic event causes a sudden change in the state of stress, rather than a gradual release and changing strain rate afterwards. An example of “fast” seismic event is shown in Figure 2.

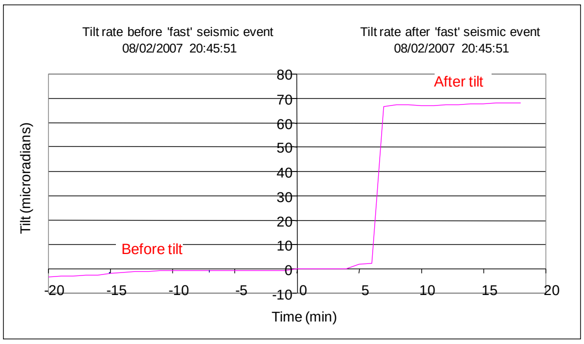

Figure 2. An example of “fast” seismic event described as tilt changes during the seismic event

Large but gradual changes in tilt were also observed that were not associated with any seismic activity. These were designated “slow” seismic events. In most cases the tilt change is smaller than that associated with coseismic tilt steps. An example of “slow” seismic event is shown in Figure 3.

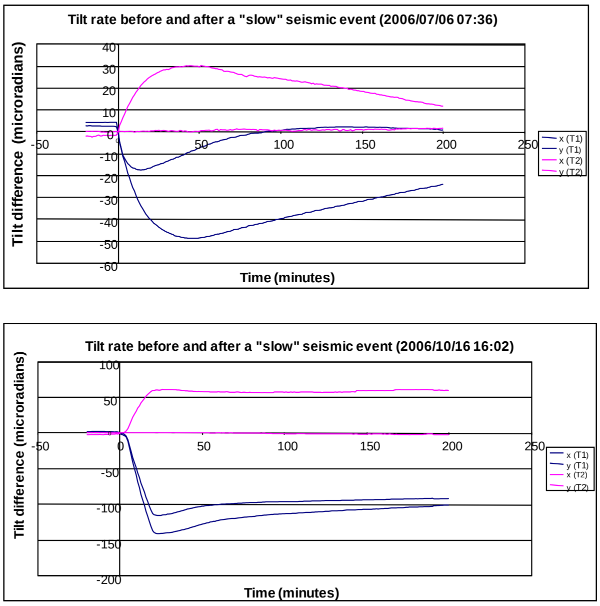

Figure 3. An example of “slow” seismic event described as tilt changes between two consecutive seismic events

The amount of both coseismic and aseismic tilt was analysed as a function of the hours of the day in order to relate the production cycle to the rock mass deformation around the mining excavations. The rates of coseismic and aseismic tilting and seismicity as recorded by the mine network are approximately constant until the daily blasting time, which takes place from about 19:30 until shortly before 21:00. The increased rates during the blast window (Figure 4) are most pronounced for coseismic tilting and least pronounced for aseismic tilting. After this time, all parameters show a decreasing rate. Figure 4 also shows the cumulative number of events recorded by the mine network with moment-magnitude greater than zero. The tilt data shown above illustrate the time-dependent behaviour of the rock mass during the production cycle. Two orders of relaxation can be identified:

- The first order of relaxation, related to the coseismic tilt, is characterized by a jump in the tilt during a strong seismic event and blasting, and
- The second order of relaxation, related to aseismic tilt, is characterized by slow creep type of aseismic deformation taking place between two seismic events.

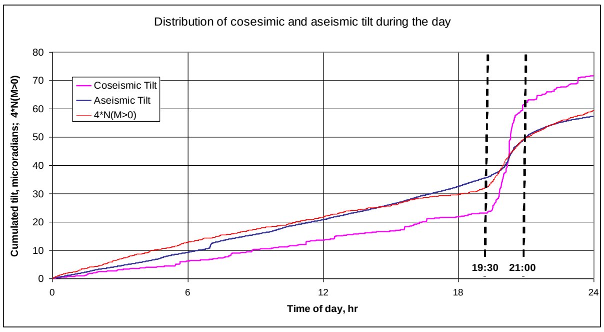

Figure 4. Cumulative absolute tilt changes stacked over 24 hours. The cumulative number of events with M>0 was also plotted as an index of seismicity (Spottiswoode and Milev, 2006)

M$_W$2.1 EVENT, MPONENG MINE

During the monitoring period a seismic event with M$_W$2.1 occurred in the vicinity of the instrumented site. This event was recorded by both the CSIR integrated monitoring system and JAGUARS acoustic emotion network. The tilt changes associated with this event showed a well pronounced after-tilt (Figure 5). The aftershock activities were well recorded by the acoustic emission network. More than 21,000 AE aftershocks were located in the first 150 hours after the main event (Naoi et al., 2011). Using the distribution of the AE events the position of the rupture area was successfully delineated. The distribution of the AE events following the main shock was related to after-tilt in order to quantify post-slip behaviour of the source. Incremental snapshots of 1000 aftershocks were taken in time, starting 4.67 hours after the main event. Each group from plotted individually, and added together (Figure 6, bottom right) in order to search for some additional expansion of the source following the main slip.

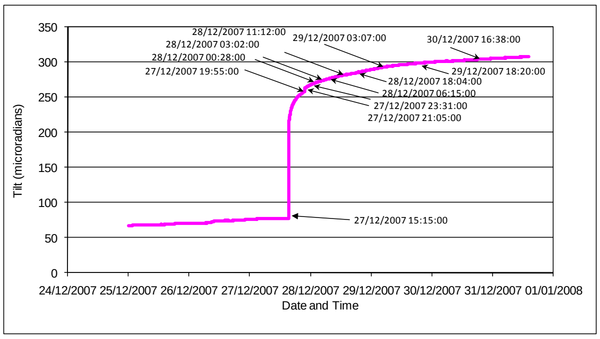

Figure 5. Tilt associated with M=2.1 event on 12/27/2007 at Mponeng mine

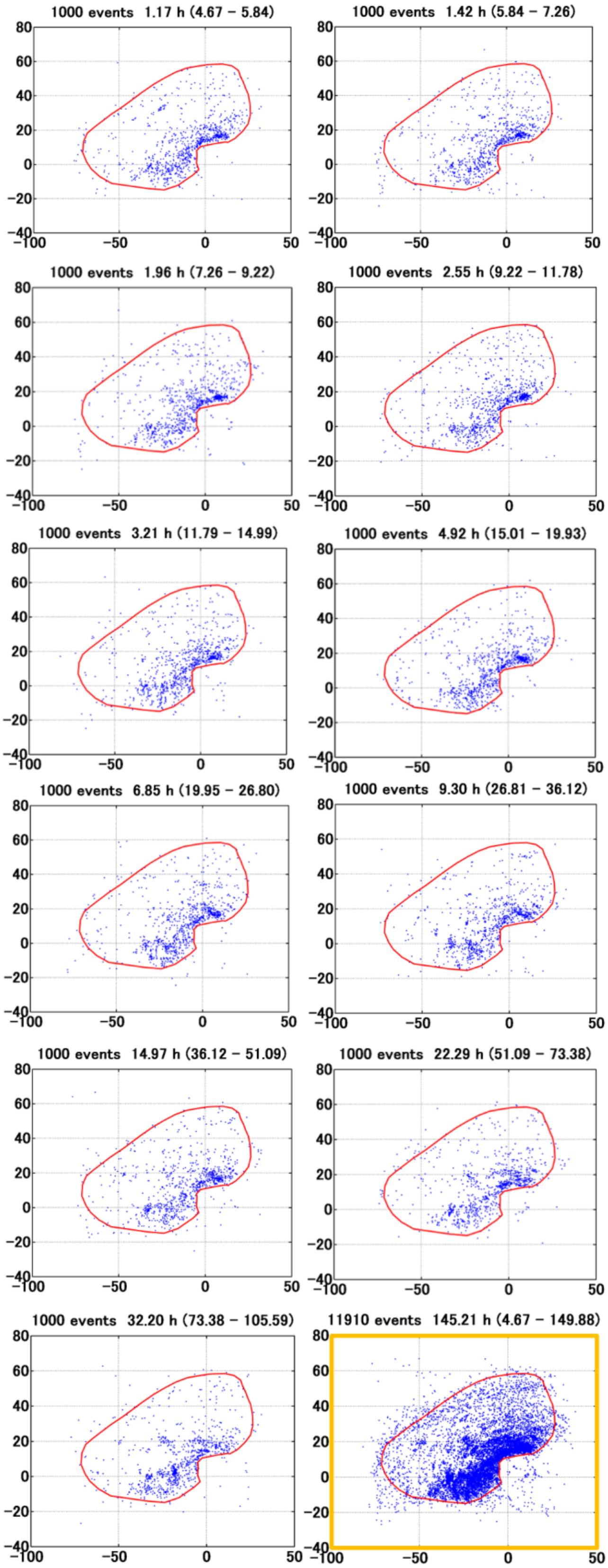

Figure 6. Incremental snapshots 1000 aftershocks in time. Each group from 4.67 hours after the main event, plotted individually, and added together (bottom right)

After-tilt is usually associated with the systematic expansion of a seismogenic zone following the main slip, which can be coseismic or aseismic (Sholz, 2002, 2010). In this particular case, coseismic expansion is unlikely as all the aftershocks clearly locate within a specific area and are especially dense in the bottom right corner of this area. If aseismic expansion is a possibility, it will most likely occur within the identified area after the main slip occurred, especially in the bottom right corner of the area where a dense collection of aftershocks are present, (Figure 6). Modelling using numerical and analytical tools (Share et al., 2013) show that tilt measurements are highly sensitive to seismic activity to the bottom right of the seismogenic zone, where numerous aftershocks appear. Figure 7 illustrate the concept of post seismic creep expansion of the source following the main slip.

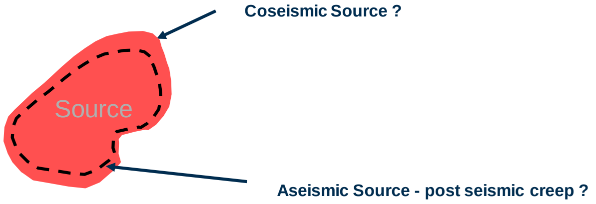

Figure 7. Hypothetical model of the post-seismic creep type of deformation of the source after the seismic slip

CONCLUSIONS

Tilt increases rapidly during seismic events and blasting. This type of changes was described as “fast” seismic events. However, a great deal of deformation was found to occur independently of seismic events and were described as ‘“slow”’ or creep-type events.

The fault plane position of the M_W2.1 seismic event was delineated by AE events location. The distribution of the AE events following the main shock showed no evidence of coseismic expansion of the source region after the main slip. Therefore, the hypothesis of aseismic, creep-type deformations within the source region following the main slip were introduced. Observing the high aftershock activity to the bottom right of the source area, and taking into account previous modelling done showing tilt sensitivity versus the location of seismic activity, it is concluded that the post-seismic creep most probably occurred in the bottom right of the source area.

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