Observational Study to Mitigate Seismic Risks in Mines:a new Japanese - South African collaborative project

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ABSTRACT

Mining-induced earthquakes pose a hazard to workers in deep South African mines, while natural earthquakes pose a hazard to people living close to plate boundaries. We introduce a 5-year Japanese-South African collaborative project entitled *"Observational study to mitigate seismic risks in mines"*. The principal investigators are H. Ogasawara (Japan) and RJ Durrheim (South Africa). The project, which seeks to develop human and instrumental capacity in South Africa, will build on previous studies carried out by Japanese and South African seismologists and rock engineers in deep gold mines. This knowledge will be used in efforts to upgrade seismic hazard assessment schemes and to mitigate the seismic risks in deep mines. The knowledge is also relevant to the study of the mechanisms that generate tectonic earthquakes. The project was conditionally approved in April 2009 by the Japan Science and Technology Agency (JST), an external agency of the Ministry of Education, Culture, Sports, Science and Technology, and the Japan International Cooperation Agency (JICA), an external agency of the Ministry of Foreign Affairs. It is anticipated that the agreement between the Japanese and South African governments will be concluded by the end of the 2009 financial year and that research work will commence in 2010.

Key words: seismic hazard, mine seismology, rockbursts, deep gold mines

INTRODUCTION

Mining-induced earthquakes pose a serious risk to workers in deep mines in South Africa, while natural earthquakes pose a serious risk to people living in Japan and other regions that are close to plate boundaries. We introduce a 5-year Japanese-South African collaborative project entitled *"Observational study to mitigate seismic risks in mines"* that seeks to address these risks. The principal investigators are H. Ogasawara (Japan) and RJ Durrheim (South Africa). The project has three main aims:

1. To learn more about earthquake generation mechanisms through near-source monitoring in South African gold mines. This knowledge will contribute to efforts to upgrade schemes of seismic hazard assessment and to limit and mitigate the seismic risks in deep and highly stressed mines and in areas vulnerable to natural earthquakes.

2. To develop human and technical capacity in South Africa.

3. To upgrade the South African national seismic network.

The project is carried out under the auspices of the JST-JICA program *"Countermeasures towards Global Issues through Science and Technology Research Partnership"*, which was launched in the 2008 financial year. JST and JICA are acronyms for the Japan Science and Technology Agency and the Japan International Cooperation Agency, respectively. JST is an external agency of the Ministry of Education, Culture, Sports, Science and Technology, while JICA is an external agency of the Ministry of Foreign Affairs. The joint JST-JICA program aspires to acquire new knowledge to tackle global issues like environment/climate change, infectious diseases, water shortages, natural disasters, and bio-resources. In the 2009 financial year, 21 projects were conditionally approved, six with African countries. Our project is one of two projects to be carried out in South Africa. Our goal is to advance the understanding of earthquake generation processes, and

to use this knowledge to mitigate seismic risks, not only in South African mines but also in Japan and elsewhere in the world.

BACKGROUND

Japan is an earthquake-prone country, having an M>7 event every year, on average. In 1995 the Kobe earthquake (M_w=6.9) caused more than 6 400 fatalities, damaged more than 64 000 houses, and caused economic losses amounting to about ZAR10[12]. A future M8 earthquake may cause even greater losses. Consequently, there have been strong demands to predict earthquakes and mitigate seismic risks in Japan. Following the 1995 Kobe earthquake, very dense seismic and GPS networks were deployed (station spacing typically a few tens of kilometres) to record the spatio-temporal variation of seismicity and the rupture process of every large event. Yet the hypocenters are too deep (typically 10-20 km) for the details of the earthquake preparation and generation processes to be seen. Thus Japanese scientists have been seeking for opportunities to have a closer look at these processes.

In 1991, the late Prof. Louis Nicolaysen of the University of the Witwatersrand submitted a proposal *"Semi-controlled experiment on seismic events"* to the International Association of Seismology and Physics of the Earth's Interior. After the proposal was endorsed by IASPEI, Prof. Nicolaysen visited Japan to promote the proposal to the Japanese Seismological Society (Nicolaysen, 1992). Since then, a Japanese-South African cooperative research program has monitored the earthquake generation process in great detail in close proximity to hypocenters (e.g. Ogasawara et al. 2002, 2009). The project has been referred to as *"The Semi-controlled earthquake-generation experiments at deep gold mines, South Africa (SeeSA)"* (Figure 1).

The first pilot experiment was performed at Western Holdings mine in 1995. A very sensitive borehole strainmeter (Ishii, 1997) able to detect fine details of rock mass deformation and record large, sudden changes associated with large events was installed (Ogasawara et al., 2002, Van Aswegen and Laas, 2003). The rock mass deformation was correlated with seismicity monitored by the Integrated Seismic System (Mendecki, 1997). A 200 m array of nine borehole triaxial accelerometers installed along a footwall haulage revealed that the rupture processes of M_L=0~1 earthquakes were as complex as natural great earthquakes and that the stress drop and energy efficiency were almost the same (Yamada et al., 2005, 2007).

A sensitive Ishii strainmeter that was installed in a fault loss at Bambanani mine, successfully tracked rock mass deformation (Ogasawara et al., 2005). Mining-associated strain accumulation and earthquake-associated strain release, followed by relaxation

corresponding to ~ 10 MPa stress change, could clearly been seen. The largest event occurring close to the strainmeter was an M_w2.9 event in February 2003. Frequent non-seismic slow strain changes were noted, some being accompanied by clear forerunners (Naoi et al., 2006).
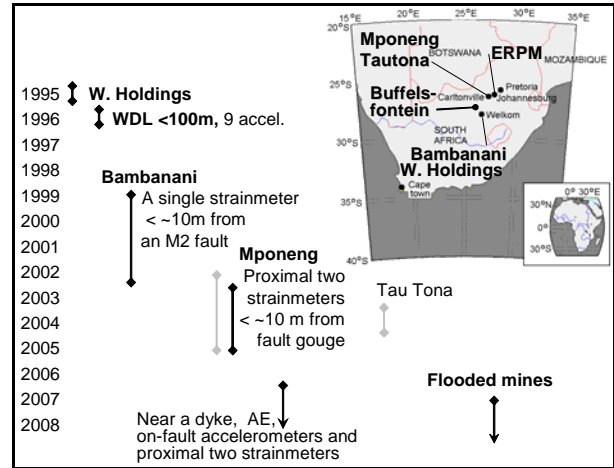
Figure 1. Semi-controlled earthquake-generation experiments in deep South African gold mines up to 2008 (after Ogasawara et al., 2009). Periods of monitoring are shown by vertical lines. Flooded mines: ERPM and Buffelsfontein.

Much clearer forerunners were seen at Pretorius fault zones at Mponeng mine (Figure 2). Two strainmeters near to the slow events showed that they were caused by slip on the distinctive fracture zones in the fault zones (Yasutake et al., 2008). However, the mine's seismic monitoring was not sensitive enough to delineate the source fault of those major events, limiting the investigation.
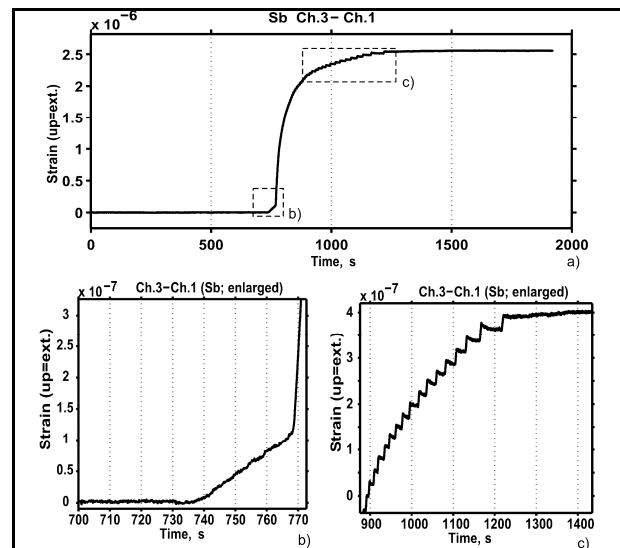
Figure 2. An example of slow strain changes with clear forerunner after 735 s observed at the Pretorius fault zone, Mponeng mine (after Ogasawara et al. 2009 and Yasutake et al. 2008).

AE MONITORING OF DYKE FAILURE

Nakatani et al. (2008) deployed a small network (approx. 40 m span) of eight acoustic emission (AE) sensors covering a frequency range up to 200 kHz in a seismically active hard rock pillar at 3300 m below surface in the Mponeng gold mine, South Africa (Figure 3). The site is located at the contact of a major gabbroic dyke within quartzite host rock about 90 m from mining cavities. The Japanese – German - South African international cooperative project is referred to as JAGUARS (JApanese-German Underground Acoustic emission Research in South africa). German participants are GeoForschungsZentrum and GMuG. South African participants are CSIR.
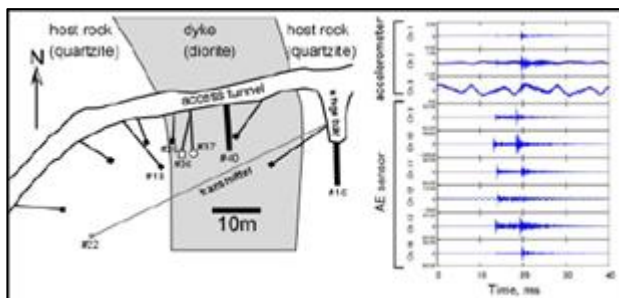
Figure 3. Plan view of the geology and mining configuration around the JAGUARS site at Mponeng Mine with examples of recorded wave forms. Tunnels shown are at 116L (tunnel floor at z = -3543.5 m, datum is 275.8 m above shaft collar). The tabular reef dips SSE at 26.5°. Solid square: AE sensor, white square and circle: 25kHz accelerometer and hydrophone, respectively, thick lines: boreholes with Ishii borehole strainmeter near the end.

This was the first implementation of a high-frequency AE network at seismogenic depth in hard rock formations monitoring AE and microseismic events at frequencies >10 kHz. High-frequency waveforms with >100 kHz components were successfully observed for events with hypocentral distance of up to 50 m, many of which occurred in pristine rock formation outside the damage zones caused by various mining activities. Lower-frequency events were recorded as well, the observation window overlapping the mine's routine monitoring up to 2 kHz.

The network recorded a nearby M_w 1.9 (M_L 2.1) event. In the 150 hours following the event, more than 21,000 aftershocks were located within 100 m of the network (Yabe et al., 2008). In the same period the mine's geophone network, with a magnitude detection threshold of approximately M_w -0.5, detected only 9 events in the same area, demonstrating the huge gain in detectability of microearthquakes. We determined seismic velocities using in-situ ultrasonic transmission tests within the frequency range of the observation band of our network (1 kHz – 180 kHz), using shot points

spread along a borehole spanning a distance of about 50 m, measuring fairly high velocities indicative of good rock quality. The acoustic emission system successfully delineated a fault near the Pink and Green dyke that was the source of the M_L 2.1 event. Mining-induced temporal changes in strain were also successfully tracked, showing that the dyke was approaching failure (Katsura et al., 2008).

MONITORING OF QUASI-STATIC AND DYNAMIC DEFORMATION DUE TO MINING

Two underground sites in Mponeng gold mine in South Africa were instrumented by CSIR with tilt-meters integrated with seismic monitors (one was the JAGUARS site described above). Both the rate of tilt, defined as quasi-static deformations, and the ground motion, defined as dynamic deformations, were analysed in order to understand the behaviour of the rock mass around deep level mining (Spottiswoode and Milev, 2006; Milev and Spottiswoode, 2008). It was found that 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 rapid increase (Figure 4).
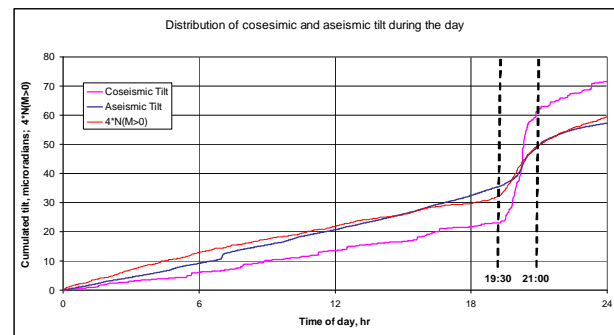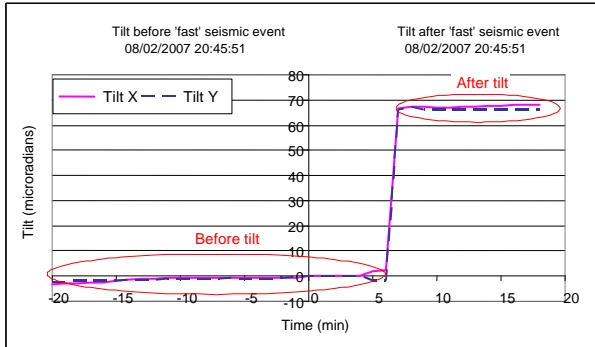

**Figure 4. Distribution of coseismic and aseismic tilt during the day at Mponeng mine.**

The tilt rate before and after a seismic event was also studied. It is interesting to note that lack of after-tilt was found for smaller co-seismic tilt steps (e.g. no change in the tilt visible between 0.1and 100 microradians after a seismic event). An example of the tilt rates before, during, and after a normal 'fast' seismic event is shown in Figure 5. In most cases there was no after-tilt. Much of the quasi-static deformation, however, occurs independently of the seismic events and blasting and is described as 'slow' or aseismic events.

The tilt changes associated with an M_w 1.9 (M_L 2.1) seismic event are shown in Figure 6. It is interesting to notice that the event has well pronounced after-tilt, which is most probably the result of the aftershock sequence following the event. The distribution of the tilt
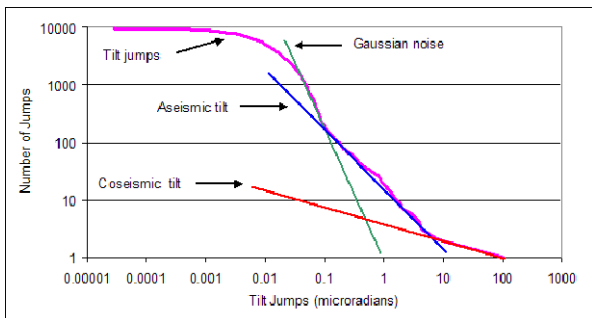
changes associated with M_L 2.1 event is shown in Figure 7. Three populations of tilt jumps can be identified: (i) small tilt jumps representing the Gaussian noise, (ii) intermediate size tilt jumps interpreted to be aseismic tilt changes, and (iii) the coseismic tilt changes.

Figure 5. Distribution of coseismic and aseismic tilt before and after a normal fast event
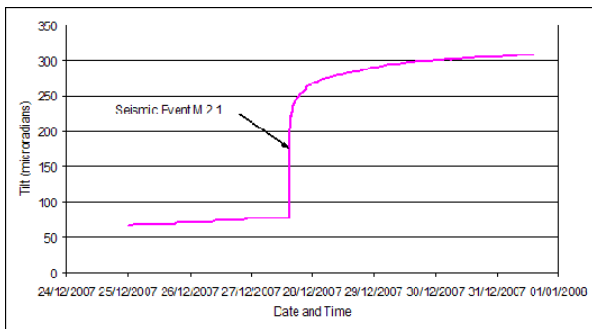
Figure 6. Tilt associated with an M_L 2.1 event

Figure 7. Interpretation of tilt changes associated with M_L 2.1 event on 27/12/2007 at Mponeng mine.

SURFACE MONITORING OF MINING-RELATED SEISMICITY

The prime objective of seismic monitoring is to locate seismic events as quickly and accurately as possible. The South African National Seismograph Network (SANSN) is a regional seismograph network that records seismic activity throughout South Africa and large seismic events in southern Africa. The SANSN is equipped with low-frequency instrumentation appropriate for the recording of large events. Stations of the SANSN were upgraded during 2006 to meet

international standards. Presently, the SANSN consists of 23 stations that communicate triggered and continuous data to the Council for Geoscience (CGS) offices in Pretoria, where analysis is undertaken daily to identify seismic events. Results of data processing are disseminated to government agencies and the international scientific community via quarterly seismological bulletins (Saunders, 2009). The CGS also acts as a repository for waveform data recorded by the stations of the SANSN, which can be used by future generations of scientists to re-evaluate findings. Progress in waveform data capture over the past four years has lead to waveform data being kept as continuous records sampled at 20 Hz. The current distribution of seismic stations of the SANSN limits the lower magnitude detection threshold to a Richter Magnitude of about 2.0. The analysis software used by the CGS, though widely used throughout the world, does not facilitate an automatic phase picker and location. Consequently the CGS is unable to locate earthquakes rapidly.

The location error reported by the CGS for mining activity is relatively large, and is a function of the number of stations that record an event, the accuracy of P-wave arrival time picks, and the precision of the velocity model. Eight SANSN stations are currently deployed near the gold and platinum mining regions. The location errors are of the order 1 to 10 km. Consequently the CGS is only able to identify the mining district in which a large event occurs, and not the particular mine or geological structure.

Mining companies and the research organisations affiliated with them focus mainly on safety issues in the stope area. The research of large seismic events in mining districts is not their main focus. However, mechanisms of large seismic events provide insight into local tectonics, allowing a better understanding of the stress regime in the crust. Additionally, it is vital to understand the risks associated with possible ground motion, which occurs in close proximity to the seismic source. The CGS supports projects that contribute towards a better understanding of the mechanisms of damaging seismic events located in the mining districts (Cichowicz 2007, 2008, 2009, Cichowicz et al. 2008, 2009). On 9 March 2005 the Stilfontein earthquake caused a temporary closure of the mine, which was an economic disaster for the whole town owing to job losses. A better understanding of the tectonics of the area could prolong the economic life of the mine.

The question arises, what type of a ground motion caused the damage observed on the surface? Unfortunately, during the Stilfontein earthquake, there was no seismic station on the surface near the town. Therefore, it was not possible to compare actual strong ground motions on the Earth's surface was those predicted by numerical simulations. A method for modelling strong ground motion should be able to

simulate a source-space time evolution and wave propagation from a fault to the receiver. If the scenario earthquake is in the near field, a point source model is not suitable for ground motion prediction. The fault geometry, heterogeneity of slip on the fault plane, and directivity can influence the ground motion in the far and near field. Simulation of an extended seismic source requires that a large fault is divided into sub-faults and each sub-fault is considered as a small point source. The waveform of a small event is time-delayed, scaled, and summed to simulate the ground motion of a large earthquake. The earthquake source is represented as a set of point sources with a source time function. The source time function of the simulated earthquake is represented as a linear combination of the source time function of the sub-events. This approach enables the inclusion of directivity into simulation of the process.

Simulation of the surface ground motion caused by the Stilfontein M 5.3 earthquake at the source-site distance of 5 km is presented on Figure 8. A model with two asperities predicts much larger peak ground accelerations (PGAs), peak ground velocities (PGVs), and amplitude of response spectra than does a simple point source model. The most important parameters for strong ground motion prediction are the size and static stress drop of the asperities.
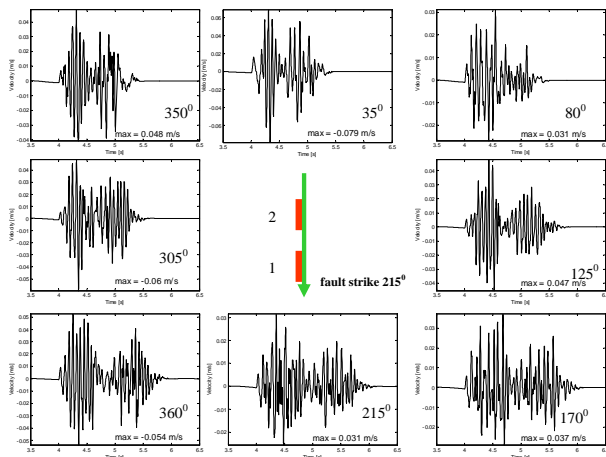
Figure 8. Velocity of ground motion predicted at a distance of 5 km from the epicentre on a hard rock surface. The fault strike, 215° (green arrow) and station's azimuth are displayed next to the waveform. The positions of two asperities are marked with red lines.

PROPOSED JST-JICA PROJECT

Building on previous studies of mine-related seismicity reviewed above, the JST-JICA project ultimately aims to upgrade the schemes of seismic monitoring and risk assessment in deep mines. A dense array instruments will be deployed to monitor the response of the rock mass to mining and to any seismic events that may occur. We hope to record the entire life span of several earthquakes with source regions greater than 100 m in

extent (i.e. with local magnitude $M_L=2$ and greater). The main components of the project are:

(1) Installation of a highly sensitive microfracture monitoring system in an area of high seismic potential with the goal of identifying the preparation zone of impending earthquakes.

(2) Monitoring of the mining-induced stress field using sensitive strain/tilt observations (e.g. Spottiswoode and Milev, 2006), numerical simulation of the deformations, and comparison with stope closure measurements (e.g. Malan et al., 2003). These observations may also pick up precursory activities of the fault.

(3) Monitoring of near-fault dynamic stress during the mainshock rupture to improve the assessment of strong ground motion (e.g. Milev et al., 2003).

(4) Detailed analysis of aftershocks at microfracture level to delineate the mainshock rupture, in order to assess post-seismic rock stability in terms of stress redistribution by the mainshock.

(5) Upgrading of the South African National Seismograph Network (SANSN), enabling quicker processing of seismic information in the mining district.

(6) Assessment of strong ground motion on the surface caused by large mine-related seismic events.

(7) Field observations of the seismic source and the collection and laboratory analysis of rock samples.

This upgrading of the SANSN has two main components: firstly, the installation of a cluster of several seismic stations on the surface in one of the mining districts, most likely in the West Rand and Far West Rand; and secondly, the upgrading of the software in order to be able to process automatically large volumes of data, perhaps several thousands of waveforms per day from the current level of only a few hundred per day. This will enhance the Seismological Bulletin with information relevant to the mining industry. The most parameter that best describes the improvement is the sensitivity of the network. It is expected that the sensitivity will improve from $M_L=2$ to $M_L=1$ for a distances less than 30 km.

It is envisaged that the proposed cluster of strong ground motion seismic stations will greatly contribute to:

- Improvement in the accuracy of location of mining events.

- Identification of seismically active features in the mining district.

- Facilitate various basic analyses, such as focal mechanism determination and regional stress field analysis.

- Development of methodologies for detailed analysis of the largest recorded events in mining districts using both inversion and modelling techniques.

- Development of methodologies to estimate damage at the surface, which is a function of the fault

geometry and the slip direction, complexity of the seismic source, local geology and the distance between source and surface infrastructure.

- Provide standardized magnitude estimation in the mining district.
- Provide seismic information to mine closure and water management projects.

The project was conditionally approved in April 2009 by JST and JICA. The grant for the 5-year project is worth approximately US$3 million. These funds may only be used for equipment and 5-year running costs. The cost for permanent research employees must be recovered from other sources. It is anticipated that the agreement between the Japanese and South African governments will be concluded by the end of the 2009 financial year.

In the previous studies, the grant covered only a very limited range of our research activities. However, in addition to the JST-JICA fund, Japanese researchers also receive grants from the Japanese Society for the Promotion of Science (comparable to South African National Research Foundation) and a 5-year program to promote the observational research to predict earthquakes and volcanic eruptions by the Japanese Ministry of Education, Culture, Sports, Science and Technology that can be used in parallel. With the grants, we will be able to upgrade our activity, eventually resulting in social benefit for both countries.

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