

Observational studies in South African mines to mitigate seismic risks: a mid-project progress report

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ABSTRACT

Mining-induced earthquakes pose a risk to workers in deep mines, while natural earthquakes pose a risk to people living close to plate boundaries and even in stable continental regions. A 5-year Japan-SA collaborative project "*Observational studies in South African mines to mitigate seismic risks*" was launched in 2010. Here we report on progress since the report at Geosynthesis 2011 in Cape Town. Acoustic emission sensors, accelerometers, strainmeters, and controlled seismic sources have been installed at sites in Cooke, Moab-Khotsong and Sibanye gold mines to monitor the deformation of the rock mass, the accumulation of damage during the earthquake preparation phase, and dynamic stress as the rupture front propagates. These data are being integrated with measurements of stress, stope closure, stope strong motion, and seismic data recorded by the mine-wide network.

Key words: mine seismology, earthquake precursors, rockbursts

INTRODUCTION

Seismicity poses a serious risk to workers in deep and overstressed mines, such as the gold mines in the Witwatersrand basin of South Africa, as well as inhabitants of earthquake-prone regions such as Japan. A 5-year collaborative project entitled "*Observational studies in South African mines to mitigate seismic risks*" was launched in 2010 to address these risks, drawing on over a century of South African and Japanese research experience with respect to mining-related and tectonic earthquakes, respectively (Ogasawara et al., 2009; Durrheim, 2010; Durrheim et al., 2010; Utsu, 2003). Here we report on the progress that has been achieved since the last report at a SAGA meeting, Geosynthesis 2011 in Cape Town.

The project has three main aims (see Figure 1):

1. To learn more about earthquake preparation and triggering mechanisms by deploying arrays of sensitive sensors within rock volumes where mining is likely to induce seismic activity.
2. To learn more about earthquake rupture and rockburst damage phenomena by deploying robust strong ground motion sensors close to potential fault zones and on stope hangingwalls.
3. To upgrade the South African surface national seismic network in the mining districts.

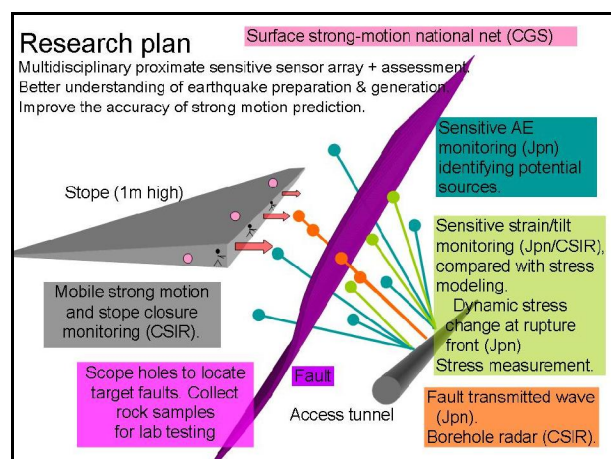


Figure 1. Schematic illustration of the research design. Jpn - Japanese researchers; CSIR - Council for Scientific and Industrial Research; CGS - Council for Geoscience

The knowledge gained during the course of the project and the new infrastructure installed will improve seismic hazard assessment methods in mines and

mitigate the risk of rockbursts. It is also anticipated that new knowledge of earthquake physics will mitigate the risks posed by tectonic earthquakes.

METHODOLOGY

Research sites have been established at mines operated by Gold One (Cooke #4 Shaft), AngloGold Ashanti (Moab-Khotsong) and Sibanye Gold (Hlanganani Shaft) (Durrheim et al., 2012). Boreholes were drilled to locate faults that are considered likely to become seismically active as a result of mining activity. Acoustic emission sensors, strain- and tilt meters, and controlled seismic sources were installed to monitor the deformation of the rock mass, the accumulation of damage during the earthquake preparation phase, and changes in dynamic stress produced by the propagation of the rupture front (see Figure 1 and Table 1). The suite of sensors has greater sensitivity and dynamic range than those typically used in civil or mining engineering applications, making it possible to record very small changes in stress and strain as well as violent rock mass deformation associated with large seismic events. These data will be integrated with measurements of stope closure, stope strong motion, seismic data recorded by the mine-wide network, and stress modelling. The Council for Geoscience deployed 10 surface seismic stations in the Far West Rand district and installed the Antelope Seismic Processing System to handle the large volume of data.

ROCK PROPERTIES

By March 2013, more than 70 boreholes (totalling more than 2.8 km in length) had been drilled at project sites to locate fault zones accurately and to deploy sensors. The tensile strength, uniaxial and triaxial compressive strength, Young's modulus and Poisson's ratio of the strata surrounding the research sites are being measured using the rock testing machines in the School of Mining Engineering, University of the Witwatersrand.

IN-STOPE GEOTECHNICAL MAPPING

Stopes near to the instrumented target faults are surveyed from time to time to provide baseline data that can be used to assess the quasistatic and dynamic response of the rock mass to mining. A tape measure is laid along the face, and the face, hanging- and footwall and installed support are mapped at ca. 5 m intervals (Figure 2). Rock types, joints, faults, veins and stress-induced fractures are recorded (Figure 3), as well as the installed support units. Any anomalies between the observation points (e.g. faults, dykes, brows) are mapped, as well as any falls-of-ground.

New technologies that are being developed for in-stope mapping at CSIR include an electronic sounding device and thermal camera to map loose hangingwall slabs, a sonic closure meter, a strong ground motion sensor, and

an autonomous robotic platform (Durrheim et al., 2013). The ultimate objective of this work is to improve our understanding of the factors that affect the vulnerability of a stope to seismic shaking, and to develop practical systems to map the stope and guide proactive interventions that will reduce the rockburst risk.



Figure 2. Mapping joints and fractures in a stope in Cooke #4 Shaft Pillar

ACOUSTIC EMISSION MONITORING

Masao Nakatani and his team have installed a large number of acoustic emission (AE) sensors in a volume spanning 95 m (N-S) x 50 m (E-W) x 30 m (depth) at a depth of about 1 km at Cooke #4 mine (Table 1; Figure 4) (Naoi et al. 2012; Moriya et al. 2012). The 50 kHz AE sensors are installed in 60 mm diameter boreholes. In the period from 30 September to 5 October in 2011 the monitoring system automatically located 40,555 AE, some of which were located by Moriya et al. (2012) using the joint hypocenter location method (Figure 3).

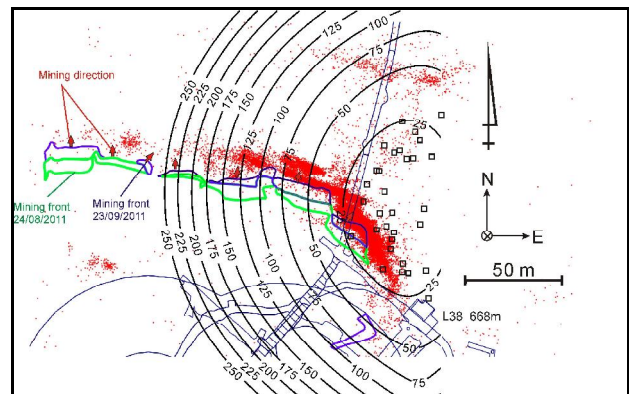


Figure 3. A plan view of the Cook #4 research site showing AE sensors (squares), epicentres of 8273 AE events that occurred from 30 September to 5 October 2011 (red dots), condition number (black contours), tunnels and the mining front (after Moriya et al. 2012).

Moriya et al. (2012) confirmed that the condition number (a measure of the location error, Lee and Stewart, 1981) is low enough for the location to be useful over a sufficiently wide area (see the extent with condition number < 200 in Figure 3). Moriya et al.

(2012) also applied the multiplet and the double-difference analysis to the selected multiplets, successfully delineating multiple planar structures. A similar AE network is being completed at Moab Khotsong mine.

STRESS MEASUREMENTS

Reliable evaluations of seismic hazard depend on a reasonably accurate description of the initial stress conditions, either as an input to numerical modelling of the stress field, or as in-situ stress information. However, stress measurements are rarely carried out in South African mines. One of the main reasons is that the drilling diameter required for overcoring (76 mm NX) is much larger than the diameters used for regular geological drilling, typically AX (48mm) or BX (60mm). The drilling of large diameter holes is slower and more expensive. A single overcoring measurement often takes several days to perform.

The compact conical-ended borehole overcoring (CCBO) technique determines the 3D stress tensor by a single overcoring of a strain cell consisting of 16 or 24 strain gauges (Sugawara and Obara, 1999). However, CCBO was designed for NX holes. Ogasawara et al. (2012) reduced the overcoring and associated tools to BX size while keeping the aspect ratio unchanged so that the published strain coefficients could be used. This modified method was tested at 3 km depth at Moab Khotsong, and, after further improvements, at 3 km at TauTona and 3.4 km at Mponeng. It was demonstrated that three overcoring measurements can be made within two shifts (Ogasawara et al., 2013).

CONCLUSIONS

The mid-point of the 5-year project has passed. Most instruments have been deployed and we are now entering a period of intense monitoring. Important new observations of stress and the response of the rock mass to mining have been made, and many more are expected in the next two years as the mining front sweeps through the monitoring arrays. Ultimately we hope that this project will produce knowledge and technology that will reduce the risk posed by earthquakes.

ACKNOWLEDGMENTS

The Japanese - South African collaborative research project would have been impossible without the assistance of AngloGold Ashanti, First Uranium, Gold Fields and Gold One. The Japanese activities have been partly supported by the Japan Science Promotion Society grant in aid, by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan (No. 21224012), under its Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions, and by Ritsumeikan University and Tohoku University. The South African activities have

been partly supported by the Council for Scientific and Industrial Research, the Council for Geoscience, and Department of Science and Technology through the South African Research Chairs Initiative, and the University of the Witwatersrand.

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Table 1: The project status as at the end of March 2013. *Installation not yet completed, # not yet procured

Owner (Shaft)	Gold One (Cooke #4)	Anglogold Ashanti (Moab-Khotsong)	Sibanye Gold (Hlanganani)
Ore body at experimental site	Several reef packages 10s of metres thick	Single thin tabular reef (<2 m), many faults	Single thin tabular reef (<2 m), few faults
Mining scenario	Extraction of shaft pillar, 400 m dia.	Extensive scattered mining	Sequential grid mining
Depth	About 1 km	About 3 km	About 3 km
Concern	Instability of faults in the shaft pillar	Instability of large faults	Instability of dip pillar
Fault characteristics	Fault gouge a few 10s of cm thick	Fault zone a few 10s of m thick	Fault gouge a few cm thick
Applicability of research to mining	Final stage mining e.g. shaft pillars	Mining in highly faulted districts	Sequential grid mining at depth
Japanese Contributions			
Acoustic emission	A few tens of sensors	Installed 75% of a few tens of sensors	-
Strain	2 strainmeters	Installed 3 strainmeters	3 strainmeters
Velocity & attenuation	1 Tx, 3 Rx	2 Tx, 3 Rx*	-
Rupture dynamic stress	3 instruments near fault	-	4 instruments near fault
Slow fault slip	1 sensor	2 sensors*	-
Stress	Planned	Completed	Planned
South African Contributions			
Borehole radar	-	Survey completed	-
Tilt	-	Procured 2 tilt meters; Installed 1 tiltmeter	Installed 2 tilt meters
Stope closure	-	1 set [#]	1 set [#]
Stope ground motion	-	1 set accelerometers [#]	1 set accelerometers [#]
Surface ground motion	Completed JICA	New network*	Completed JICA
Status on February 2013	Have accumulated underground data for about two years	Completed drilling and 80% of underground installation	Completed Japanese installation