Observational studies in South African mines to mitigate seismic risks: challenges & achievements

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Mining-related earthquakes

M=5.2
Welkom,
8 December
1976
M=5.3, Stilfontein, 9 March 2005
The event and aftershocks caused serious damage to several buildings, and minor injuries to 58 people.
Damage to dwellings in Khumo caused by Orkney $M_L5.5$ earthquake, 5 August 2014

Failure of cantilever wall
17 January 1995
M=6.9 Kobe
Japan Earthquake

> 6400 fatalities
SeeSA 1995-2009

1995  W. Holdings
1996  WDL <100m, 9 accel.
1997
1998
1999  Bambanani
       A single strainmeter < ~10m from an M2 fault
2000
2001
2002
2003
2004
2005
2006
2007
2008  Near a dyke, AE, on-fault accelerometers and proximal two strainmeters

Mponeng
Proximal two strainmeters < ~10 m from fault gouge

Tautona

Bambanani

W. Holdings

Buffelsfontein

Mponeng

Flooded mines
Clear forerunner found prior to a M-1 slow event
Mponeng mine at a 2.9km depth (2003-2005)

Ishii sensitive strainmeter x 2
Within several meters from fault gauge

SeeSA 1995-present
JAGUARS collaboration
(Japanese-German Underground Acoustic emission Research in South Africa)

JAGUARS* AE network (Mponeng, 2007 Jun. - 2009 Jan.)

- 3.5 km depth in Mponeng Mine (Anglo Gold Ashanti)
- in a dip pillar, 90 m below reef being actively mined.
- has delineated the rupture plane of a nearby M1.9 event, by capturing a planar cluster of more than 10,000 aftershocks down to M-4.5.

* JAGUARS group (Japanese-German Underground Acoustic Emission Research in South Africa. Participants include Tokyo Univ., Tohoku Univ., Rits Univ., GFZ Potsdam, CSIR)

* 8 x borehole contact-type AE sensors (2 kHz - 200 kHz)
* 1 x Tri-ax Accelerometer (0.05 kHz - 25 kHz)

Dyke = Gabbro
Host Rock = Quartzite

Vp = 6.90 km/s, Vs = 3.92 km/s
Vp = 6.00 km/s, Vs = 3.65 km/s

In-situ ultrasonic transmission tests.
Shot and run in this 55 m borehole
1200V on PZT reached up to 40m. (up to 40 kHz)
Strain monitoring

Stress change in dyke
\[ = 1.5 \times \text{stress change in host rock.} \]

AE monitoring

>1,000 foreshocks for 3 months showed mainshock fault.
OBJECTIVES

1. To learn more about earthquake preparation and triggering mechanisms.
2. To learn more about earthquake rupture and rockburst damage phenomena.
3. To upgrade the South African national seismic network.
4. To develop human, technical and infrastructural capacity in South Africa.
11 March 2013 SATREPS seminar at West Wits Conference Centre
sponsored by JICA. About 80 people from JICA, JST, Japanese research organizations, from CSIR, CGS, and Wits. Univ. and from AngloGold Ashanti, Gold One, Sibanye Gold, Ground Work, IMS, OHMS, SRK, Seismogen and others joined.

photo by Takashima
1. Investigation of the rock mass and target faults
2. High-sensitivity studies of the earthquake preparation zone
3. Hazard assessment
4. Strong motion studies
5. Upgrading of the South African National Seismograph Network (SANSN)
Research plan
Multidisciplinary proximate sensitive sensor array + assessment
Better understanding of earthquake preparation & generation
Improve the accuracy of strong motion prediction

Surface strong-motion national net (CGS)
Sensitive AE monitoring (Jpn) identifying potential sources
Sensitive strain/tilt monitoring (Jpn/CSIR), compared with stress modeling
Dynamic stress change at rupture front
Fault transmitted wave
Borehole radar

Mobile strong motion and stope closure monitoring (CSIR)
Stope (1m high)
Access tunnel
Fault
Output 1: Mapping of face, faults, fractures and support
Output 1: In situ observations
Output 1: In situ observations & lab experiments
Drilled core samples

Gabbro
Experimental setup

Record ultrasonic waveforms at 32 PZT sensors with 100MHz, 16bit A/D.

Pc 75MPa; ~1 μstrain/s
Fault nucleation

Nucleation dimension: 2x5 cm

Foliation?
\( M_L 1.9 \)
- Loading rate: \( \sim 1 \, \mu \text{strain/day} \)
- Found:
  - nucleation (several tens of m)
  - no increase in AE rate just prior to the mainshock
  - strength 160MPa at 75MPa

Satoh’s laboratory experiment
- Loading rate: \( \sim 1 \, \mu \text{strain/s} \)
- Found:
  - almost linear stress-strain relationship
  - nucleation (2 x 5 cm)
  - increase in AE rate prior to the failure only
  - strength: \( \sim 600\text{MPa at 75MPa CP} \)
Output 1: Compact conical-ended borehole overcoring technique

Much easier and faster than CSIRO HI or CSIR triaxial. In a standard procedure 3 overcorings are carried out with an interval of about 20cm.

ML = 2.1 – 4.0

Previously published measurements

Stress, MPa

Depth, m

L104 CCBO x 3
CSIRO x 1

L115 CCBO x 1
NELSAM

L120 CCBO x 1
NELSAM

EZULWINI

M1.5 damage

130207TTN b

Overcoring time, s

Stein, 10^6
Output 2: Preparation and forerunners of earthquakes
28 x AE sensors (~100m extent; 3D)
3 x 10kHz & 3 x 25kHz tri-ax accelerometers
1 x Transmission line
4 x Strong motion and fault slip sensors
2 x Strainmeters
Output 2: Preparation and forerunners of earthquakes

Because time evolution can be tracked in AE data, the forthcoming AE research will allow us to describe, in detail, the time evolution of fracturing and stress due to mining.

Figure 7 Left: the shaft pillar (white circular area in the middle) currently being mined, is at about 1.0 km depth from surface, surrounded by old stopes not back-filled. The network location of Nakatani (2013) is 4000 m.
After Naoi et al. (2012)
Cluster A

Low detectability due to paucity of live AE sensors

(a) Cumulative number of events

(b) Magnitude of events

(c) b-value

Inset graph:

- 1: $b = 2.49 \pm 0.23$
- 2: $b = 1.87 \pm 0.11$
- 3: $b = 1.34 \pm 0.07$
Output 3: Assessment of hazard

The concept

The application
Appropriate Sensing Devices – Acoustic sounding

Monitors stability of hangingwall through neural network-based interpretation of the conventional ‘sounding’.
Appropriate Sensing Devices – *Thermal imaging*

- Hot host rock (say 35 °C)
- Cold ventilation air
Stope mapping

- Good results from all
- Kinnect is ideal:
  - Fast
  - Cheap
Output 5: Expand national seismograph network

Before 2010 CGS had 23 stations in South Africa, only a few of which were in mining districts.
Figure 4 -1 Far West Rand districts (Carletonville area) with 10 JICA seismic stations (yellow) and two CGS stations (orange).
1. Established of research sites in three deep mines
2. Mapped the face, faults, fractures and support elements
3.Logged 70 boreholes and cores (totalling 2.8 km)
4. Measured rock properties in the lab
5. Developed / adapted technologies to:
   - Measure stress,
   - Monitor closure and strong ground motion,
   - Assess the integrity of the hangwall by remote electronic sounding and thermal imaging,
   - Locate seismic events
6. Studies of
   - Precursors
   - Scaling (G-R linear from $-4<M_w<2$)
   - Minimum nucleation size
7. Expanded national seismograph network
Drilling into Seismogenic Zones of M2.0–M5.5 earthquakes in deep South African gold mines

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PROJECT THEME: FAULTS
Alpine
Alpine Fault
Central Apennines
Chelungpu
Corinth
Crete
Dead Sea
Eger
Koyna
North Anatolian Fault
Orkney (DSeis)
Rapid Response
San Andreas Fault
Sevier Basin
Witwatersrand

http://www.icdp-online.org/projects/naturalhazards/faults/

Remaining questions:

No faults or dyke mapped on the mining level.

Does stress change abruptly at depth?

Is the fault weak? (high pressure?)

Can we drill holes into the M5.5 fault from here?
Mine 1: 2014 M5.5 rupture below the mining horizon
Normal faulting prevails on mining horizons.

>30,000 aftershocks (In-mine catalog; Fault normal view)

Initial 1-month; latest 1-year; 1-month in July 2016.

Mine 1: 2014 M5.5 rupture below the mining horizon
Slip, cm inverted by Ellsworth (Fault normal view)
Imanishi et al (JpGU 2016) found a transition in aftershock faulting mechanisms from strike (yellow) to normal slip (orange). A dashed-line rectangle shows the region of significant slip constrained by underground strainmeters (Ishida et al. 2016 JpGU).
Since February 2017, 6m x 6m x 6m drilling space had been newly excavated at Site 1 at 2.8km depth for DSeis drilling, followed by installation of anchor bolts, mesh & race, ventilation and lights.

ϕ76mm 750m full-core drilling in line with σ₁ to intersect a M5.5 seismogenic zone. Probe geological, physical, hydrological properties. Recover cores with minimal damage to see stress variation along the hole. Compare those with the main- and after-shock data.

Photo of Site 1 by H. Ogasawara 5 May 2017
Horizontal deflection has caused more difficult intersection with the M5.5 rupture.

- Planned
- 639m Surveyed
- 750m extrapolated

Apparent distance from the M5.5 rupture is mainly caused by change in Hole A trend up to 30 degrees.
- Planned
- 639m Surveyed
- 750m extrapolated
Mine 2: $M_w \sim 2$ aseismic ruptures ahead of mining fronts

- Quartzite with faults or dykes on mining horizons
  - simpler to interpret
- Targets more than 10 x smaller than the M5.5 can let us
  - probe much larger volume in much less cost,
  - discuss scale dependency,
  - conduct overcoring stress measurement, and
  - compare between ruptures exhumed by mining and recovered by drilling.
AE monitoring at Cooke 4# (led by M. Nakatani, U. Tokyo)

Aug. 17 ~ Sep. 23, more than 220,000 AEs (P pick ≥ 10, RMS residual ≤ 0.2 ms)

*AEs in front of mining face (~ 200,000 events; 90%)*

*Known fault*

*Planar AE distributions (thickness < 1~5m)*

*AEs around tunnel*
Mine 2: $M_w \sim 2$ aseismic ruptures ahead of mining fronts
The ICDP DSeis drilling offers a unique opportunity to:

- Compare the directly probed seismogenic zones and those inferred from seismic analyses;
- Investigate the relationship between violent motion and the directly-probed heterogeneity;
- Investigate scale effects and the factors that control seismic rupture;
- Investigate the relationship between seismicity, hydrology, and microbiological activity.