Measuring and monitoring to understand and reduce the fall-of-ground risk

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Keywords: rockfall, instrumentation, thermal imaging, seismicity, risk management, sounding, barring.

Abstract
Although safety in South African mines has improved dramatically over the last ten years, falls-of-ground still constitute the single largest cause of fatalities. The data show that small falls of between 4 m² and 10 m², affecting single people, are the major cause of fatalities.

The critical parameters that characterize the risk of rockfalls are: rock deformation; the rate of change of deformation; energy released in fracturing; differential change in temperature, and quantification of rock mass rating. The CSIR has developed instrumentation to measure some of the critical parameters that characterize the risk of rockfalls, including deformation; rate of change of deformation; energy released in fracturing; and differential change in temperature.

An extensive array of stationary sensors in hard rock mines does not yet present a practical solution towards early warning of rockfall hazard, although a limited number of stationary sensors has proven to be highly effective in providing warning of the onset of goafing in coal.

The sensing combination most likely to provide warning to hard-rock miners of potentially unstable rock is mobile: thermal imaging used in combination with acoustic sounding.

1. Introduction
The fatality rate in South African mines is coming down, but it is still well above that of international best practice countries such as Australia. While the percentage of fatalities caused by falls of ground has fallen, rockfalls are still the single largest uniquely identifiable cause of fatalities in South African mines.

Rockfalls are defined as an uncontrolled fall (detachment or ejection) of ground of any size that causes (or potentially causes) injury or damage (Minerals Council of Australia, 2003). Using a methodology described by Terbrugge et al. (2006) and data published by the Department of Minerals and Energy (2009), a fatal injury rate for South African miners exposed to rockfalls of worse than 10⁻³ is obtained. This is at
least ten times higher than the acceptable fatal injury rate for voluntary risk as stated by Wong (2005).

Rockfalls are particularly dangerous in South African gold and platinum mines. These mines have narrow tabular seams, and are largely mined by conventional hand-held drill and blast methods (Figure 1). The narrow stoping height has prevented widespread use of mechanization. The manual nature of the work means that a large number of miners are exposed to rockfalls, compared with more mechanized operations.

![Image](https://via.placeholder.com/150)

Figure 1. Gold and platinum in South Africa are mined in a thin tabular seam in a hard rock environment.

At present, rockfall risk is managed through best practices and through mine design. For example, best practice in entry examination has been determined and is being disseminated across the industry. In this paper, we suggest that a sensing strategy and appropriate technology can further improve the management of rockfall risk by alerting workers to changing conditions and to hidden hazards.

Three kinds of rockfalls can be identified:

- **Strong ground motion driven falls**: these occur when the working areas are shaken by nearby seismic activity, usually itself a consequence of mining. In South Africa, about half the fatalities due to falls of ground are caused by seismic activity. There is an extensive community of practice around seismic risk management in mines (Essrich, 2004), and these falls are not considered further here.

- **Large falls**: rockfalls with a mass of several tonnes or more occur in platinum mines. These falls are exclusively gravity driven, and are often associated with a particular geological environment. In the Bushveld mines, dome-shaped, low-angle thrust faults can intersect vertical mining induced fracturing leading to the fall of large blocks of rock (Figure 2).

- **Small falls**: these rockfalls are typically smaller than a few hundred kilograms, sometimes as little as 25 kg, but have the potential to injure or kill (Stacey and Gumede, 2006). The falls occur between support units, or in the unsupported area of newly exposed hangingwall within metres of the face (Brink et al., 2002). The trigger for the fall is usually gravity, but local face bursting or shakedown following a nearby seismic event may also cause the fall.
Stacey and Gumede (2007) state that at least one of three conditions must be present for a fall of ground:
- Rocks are falling where there is no support;
- Rocks are falling between support units; or
- The support system is failing.

Their approach can be summarized as attributing all falls of ground to a failure in the support system, either in its implementation or in its design. They go on to recommend a probability based approach to support design. In their paper, they mention the need for review and monitoring of support. We would go further to say that monitoring can provide improved estimates of the probability of rockfall, particularly by estimating risk factors as a function of location. Monitoring should be part of any integrated approach to rockfall risk management.

2. Method
To manage rockfall risk within an existing engineered support system, the hazard must be identified, and the risk quantified. Because the state of the rockmass in a mine is dynamic, with stresses changing constantly as the mine is excavated, the identification and risk quantification need to be undertaken in real time.

A wireless sensor networking protocol caused AziSA facilitates the solution discussed here because the in-mine environment, illustrated in Figure 1, cannot be instrumented using a wired solution. The CSIR developed the AziSA standard (Stewart et al., 2008) to allow for deployment of low cost sensors in physically challenging locations underground.

A number of indicators can be used to detect indicators for potential rockfall risk:
1. A widely used indicator of risk is the measure of deformation, and particularly the rate of closure of the mining area in highly stressed environments such as the deep Witwatersrand gold mines. See, for example, Malan (2003, 2010).
2. As rock fractures, it releases seismic energy. This has been widely used to understand mine seismicity, but can also be used to measure gravity-driven failures. The energy release and its rate can be measured.
3. The temperature differential can be observed due to the coupling of the visible rock with the rock mass behind it.

4. The rock mass rating (RMR) can be determined as a measure of rockfall risk, and change in the RMR can also be monitored.

5. The structure of the rockmass can be investigated using Ground Penetrating Radar (GPR) or other geophysical techniques to determine planes of weakness in the rock.

A number of sensors have been tested to measure the first three characteristics. The fourth is not easily amenable to automatic sensing, although the capability is rapidly becoming viable because of improvements in computer vision technology (Gaich and Pütsch, 2008). The fifth method is practical, and is in use on some mines, but cannot yet be automated, because it requires a sensor to be moved along the hangingwall in all parts of the mine.

Two approaches can be followed for risk management:
- Early warning; or
- Probabilistic risk assessment.

Early warning can be used when the failure process takes long enough that its onset can be detected and a warning issued before the failure is complete. As a historical example, in 1976 a earthquake with a magnitude of 5.2 struck the town of Welkom in South Africa. The caretaker of the Tempesthof block of flats noticed cracks starting to develop in the building, and started an evacuation. Less than an hour later, the block collapsed, but no-one was injured.

In the case of Tempesthof, early warning saved the flat occupants: the caretaker noticed the onset of failure, and managed to evacuate the building prior to the completion of the failure process.

It is difficult to provide early warning for small rockfalls; because the rocks themselves are small direct monitoring of every potentially risky block is not feasible. Also, the energy involved is small and the time from the measurement of failure precursors to rockfall may be less than a second.

Therefore, the approach followed here is to monitor extensively, in order to better understand the likelihood of failure, and thereby to quantify the risk of rockfall in a specific area. The vision is to produce a risk map analogous to a weather map, of the hangingwall in the working area.

In Figure 3, the working face is on the left of the figure, with two gullies coming in from the right. The distance between the gullies is about 30 m, and the map of risk extends about 5 m back from the face. Colour in the risk map indicates the likelihood of a rockfall in that area in the next 24 hours. Underneath the coloured risk map is a map of the sensors on which the risk map is based. The primary fixed sensors are closure meters, but a local micro-seismic sensor is also monitoring the area through a single axis geophone.
In addition to the fixed instruments, two mobile instruments are also deployed: a thermal camera and an electronic sounding device. In the future, these will provide data via wireless into the risk assessment, and their location will be available to them via a beacon system operating in the working area (Vogt et al., 2009).

3. Results and discussion

3.1. Stationary monitoring – closure

In Figure 4, a schematic of a test site at Hlanganani Mine shows the locations of four closure meters, (67D4E, 995CB, 995BB & 67CBE); a FogWarn (6007) and a class 2 unit. The class 2 is a wireless data aggregator that collects data from the sensors and makes it available within the AziSA network.

Malan et al., (2003) and Roberts et al., (2006) reported extensively on the application of closure measurements in mines. They correlated the rate of steady-state closure (RSSC) with observed rockmass conditions and showed that in general a higher RSSC correlates with poor rockmass conditions.
Figure 5 shows the output from closure meter 995BB over a one-week period, and agrees closely in form with Roberts et al. (2006). Over the week a closure of 10 mm was observed. The arrows indicate seismic events in the area, and show how some are linked with increased closure. The largest event recorded had a magnitude of 1, with the rest below 0. On the 5th of February the seismic event occurred during the blast.

![Closure meter output over one week](image)

Figure 5. Closure meter output over one week (4 Feb - 11 Feb) at Hlanganani level 46-18 panel 8W.

Although there is clearly information in the closure meter output, at this stage the respective measurements cannot be correlated with rockfall risk, largely because it is not possible to link the closure meter results to records of actual rockfall. In future, closure meters will be deployed in areas that have additional sensors to detect when rockfalls occur, in order to generate a correlation.

There is also information in the relative closure at different locations in the working place that is not currently being used to assign rockfall risk. Again, this will be done when the measurements can be correlated with actual rockfalls.

3.2. Stationary monitoring – local micro-seismic events

Figure 4 also shows the location of a single microseismic sensor (6007), known in-house as a FogWarn. It is a single component geophone sensing the fracturing process in the immediate hanging/roof. The FogWarn has been proven in early warning of goafing in coal. The goaf occurs when the unsupported roof in the back area collapses. Unlike a rockfall, a goaf is deliberate, although the time at which it will occur is not known. Figure 6 shows a typical cluster of micro-seismicity immediately prior to the onset of a large goaf in a longwall coalmine.

Initial experience with FogWarns in a hard rock environment shows similar promise as a short-term early warning sensor. Further experiments underground are in progress to quantify the value of FogWarn as a short-term warning device and as a longer-term stationary sensor for quantifying the background risk of rockfalls.
Figure 6. An example of the precursive clustering of micro-seismicity immediately prior to the onset of a large goaf in a coal mine.

The output of the FogWarn deployed at Hlanganani is shown in Figure 7 for seven days from 17 March to 24 March. The FogWarn event triggers are plotted as an accumulated number of events with about 20,000 events recorded over the 7 days. There was no blasting on the weekend and the following Monday. Five small events (largest event being 0.6 Magnitude at 11:41 on 18 March) were recorded on the mine seismic system and shown at the arrow positions. The FogWarn is programmed to issue an alarm should the short-term average of event rate exceed the long-term average by a factor of 10. Alarms A to C were issued at the onset of the blasts, whilst Alarm D is difficult to explain. As explained above, it is not possible to correlate the alarms with actual rockfalls, due to the lack of a reliable record of when rockfalls occur.

Figure 7. The output of FogWarn over a 7 day period, showing accumulated event count, short term/long term event rate and a number of alarms.

3.3. Mobile sensing – electronic sounding of the hangingwall
While fixed sensors have a role to play in determining the risk of rockfall, perhaps mobile sensors can make the most direct impact. In particular, the process of making
safe a working place is known to be both dangerous and poorly undertaken (Peake and Ashworth, 1996). Technology can provide assistance in scanning a working place in order to determine loose rock that may be a rockfall hazard. The CSIR has been involved in two technologies – thermal scanning and electronic sounding.

Electronic sounding involved replicating the process employed by an experienced mining in sounding, or tapping the hangingwall. A microphone picks up the sound that the miners hear, and a trained neural network classifies the sound as being characteristic of firmly attached or potentially loose rock. The device then provides feedback to the miners, who can use that feedback as confirmation of their decisions. The device has been described in Teleka at al (2011), and is not discussed further here.

3.4. Mobile sensing – thermal scanning

In principle, (Figure 8), loose rock is not as well thermally connected to the host rock as the rest of the rock surface. In South African mines, where the host rock is generally at a higher temperature than the ventilation air, the loose rock is cooled more quickly than the rest of the rock surface.

In South African, Oldroyd (2005) undertook initial tests to show that thermal imaging can potentially determine which rocks are loose underground. He concluded that although the technique was viable, the equipment available at the time was insufficiently robust. Since then, CSIR has been developing processes using newer thermal cameras, and is currently developing a sensor specifically for detecting loose rock in the hangingwall.

One issue that has emerged is the role of the topography of the hangingwall in the thermal imaging: a piece of rock may be cooler because it is loose, or because it is hanging more prominently into the ventilation air. While an operator with a thermal camera will quickly see the difference, any system that must automatically scan will require the ability to map the hangingwall in 3D and consider topography when producing a risk map.

CSIR has developed an automated scanner, shown on the left of Figure 9 and described in Dickens and Price (2012). Visible on the photo of the sensor is the thermal infrared sensor, top left, and the three sensors of an X-Box Kinect 3D sensor along the bottom of the front panel of the sensor. Within the box is an inertial guidance system that senses the direction of the sensor platform. Below the sensor head is a pan-tilt mounting that allows the sensor to be automatically scanned.
Software uses the 3D sensor data and the inertial data to stitch together a 3D view of the surroundings, on to which is overlaid the thermal data. On the right in Figure 9, the sensor has taken an image of a mock-up stope. The hangingwall is clearly visible at the top of the picture, and shows a clear region that is cooler than its surroundings. Also visible are a number of timber support units. The face is not visible in the picture, and the image is created from a virtual point below where the floor of the stope would normally be.

Now that the sensor can quickly collect large quantities of 3D and thermal data, it will be used to investigate the reliability of thermal imaging for detecting loose rock. It will ultimately be combined in a single tool with the electronic sounding device.

4. Conclusion
Rockfall remains a significant risk underground. That risk can be better managed by sensing. Fixed sensors for measuring closure and local seismicity show promise that they may be used in the future to quantify the risk of rockfalls, but more confirming data is required to show a correlation. Electronic sounding has been proven and is currently being commercialized. Thermal scanning is developing rapidly. It has shown good correlation with loose rock, but still needs extensive testing to determine its false positive and false negative rates.

The tool most likely to provide short-term benefit is a thermal scanner coupled to an electronic sounding device. For an automated system, a 3D scanner is also required to determine whether lower temperature rocks are loose or just jutting out into the ventilation air.

The greatest contribution to risk management will occur when all the various sensors discussed here can be combined into a software system that will provide situational awareness. While we are some years from seeing such a system realized, it will enable greatly improved safety in the future.
Acknowledgements
The authors thank the Mine Health and Safety Council for supporting research at the CSIR into lowering the rockburst risk.

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