Journal of Mining Science, Vol. 46, No. 2, 2010

REVIEW OF SURFACE MINE SLOPE MONITORING TECHNIQUES

Kayode S. Osasan[a,b] and Thomas B. Afeni[a,b]

Excavation of rock initiates a reaction of movements in the rock mass. if this movement, which is a precursor to mine slope failure is timely and accurately monitored, accidents, destruction of equipment, loss of ore reserves, closure of the mine and sometimes loss of life that are the resultant effects of surface mine slope failure will be averted. Laser scanner, total station, crack meter, visual inspection, sirovision and lately monitoring radar are some of the techniques that have been developed for monitoring the displacement (i.e. movement) of mine slope. This paper reviewed the importance of slope monitoring vis-à-vis these techniques in surface mine excavations such as open pit or open cast mines. The strength and weaknesses of the techniques were also discussed. The paper concluded that a comprehensive slope monitoring program is needed in a big open pit mine with great slope stability challenges. On the other hand, a combination of two or more of the techniques is needed is shallow open cast or open pit mines, where the lifespan of the high-wall is short. In essence, each mine is peculiar and should therefore carefully analyze the nature of its stability problems before deciding on which technique or techniques to adopt.

Mine slope monitoring, displacement, open pit mine, inclinometer, piezometer, radars

INTRODUCTION

Mining activities whether by open pit or underground methods bring about volumetric as well as stress and strain changes in the rock mass around a mine opening. Once deformation exceeds the limits controlled by the rock strength, instability is created around the mining excavation [1]. The most important slope stability management tool has to do with a good laid down slope monitoring program. The work [1] also defined slope stability monitoring as the recording of the stability of the rocks making up the slopes surrounding an open pit mine. Monitoring involves periodically and automatically measuring reference points in or around an active area to determine the deformation.

Diligent monitoring and examination of slopes for warning signs is imperative for protecting workers and equipment. Geotechnical designs can be improved to increase factors of safety and proper bench designs can be improved to minimize rock fall hazards. However, even slopes with conservative slope designs may experience unexpected failure due to the presence of unknown geological structures, abnormal weather patterns or seismic shock. Unanticipated movement of any amount of rock may cause severe disruptions to mining operations, pose major safety concerns or contribute to large financial losses for companies [2].

The main reasons for monitoring the stability of slopes as stated by [1] are:

— to verify mine design. In this case slope monitoring measurements can be used as s basis for maintaining, steepening or reducing slope angles with the resultant economic and safety benefits. Slope monitoring measurements can also be used as a basis for future mine design;

— to give technical assurance to production and management officials on the stability status of the open pit min;

[a]University of the Witwatersrand, E-mail: osasankayode@gmail.com, Johannesburg, South Africa. [b]Federal University of Technology Akure, Nigeria. Original article submitted August 14, 2009.

— to serve as a warning system as to which areas of the pit are unstable;

— to give measurements of rates of movement in the unstable zone;

— to serve as a major slope stability risk management tool. Since slope failure can have serious economic consequences on an open pit mine, slope monitoring is an essential basis for making management decisions for the safety of workers and equipment e.g. not working below an unstable area, adopting special blasting precautions or evacuation.

It is stated in [3] that the three main objectives of a slope monitoring program are to: maintain safe operational practices; provide advance notice of instability; provide additional geotechnical information regarding slope behavior.

SLOPE MONITORING STEPS

Slope monitoring process normally constitutes five steps. It starts with monitoring requirements. This is to establish the objectives, need, advantages (both economic and safety advantages), researching historic problems as case studies and finally preparing a report to decision-makers motivating the need for monitoring and identifying the benefits that can be expected [4]. The second step is to establish the project requirements, which follows from the pit design and a risk assessment. The outcome of this will state the probability of failure and the variables that will most likely contribute to such failure. The third step will take account of these variables in designing the monitoring system, considering instrumentation and implementing the monitoring system [5]. The fourth step is the actual measurement and recording of field data. Measuring techniques and frequencies, accuracy, precision and personnel responsibilities are very important at this stage. Fortunately, this would have been taken care off during the design of the monitoring system.

The fifth and final step is interpretation and reporting of monitoring data. The reporting of results and documenting of events, decisions, design changes and cost-benefit analysis complete the monitoring process. A typical monitoring strategy adopted at PPRust open pit operation in South Africa is depicted in Fig. 1.

SLOPE MONITORING SYSTEM

Slope monitoring system can be divided into three sections, namely, visual inspection, surface/ subsurface measurements and remote monitoring technologies.

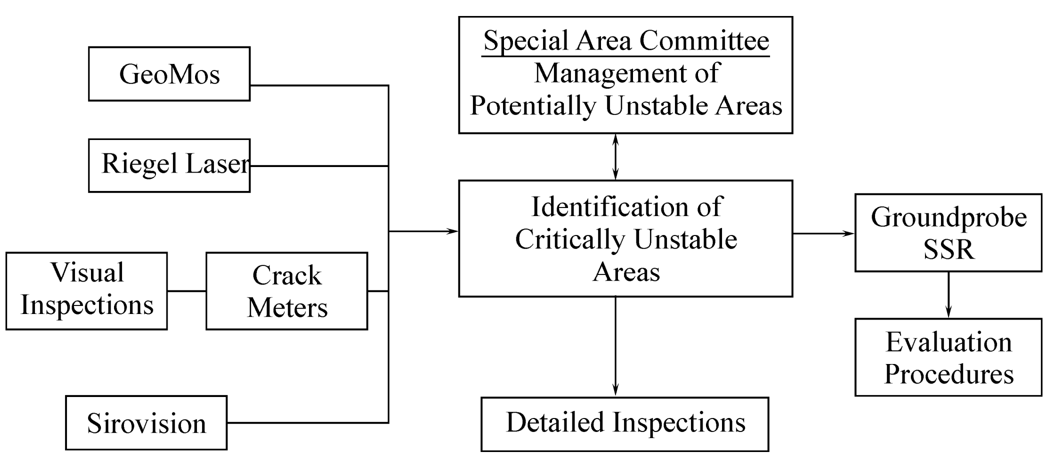

Fig. 1. Slope monitoring strategy at PPRust open pit, Limpopo, South Africa [6]

VISUAL INSPECTION

Visual slope monitoring is done by routine walkover inspections of the pit, access ways, high walls and crest that are close to potentially dangerous working areas by the Geotechnical Engineer. The Engineer compares the last visit observations with the latest one and records any deleterious slope stability changes that may have occurred. The recording of any changes that occur on the open pit slope faces by production personnel during the shift is another way of visual slope monitoring [1]. Visual observations and monitoring are at the core of any monitoring program, it's an integral part of the whole monitoring program. As a matter of fact, slope monitoring starts with visual inspection. Every morning before the commencement of mining operation, the geotechnical engineer or the geologist as it applies, should walk round the mine for any visible sign of displacement. This should subsequently be reported for detailed monitoring, if need be. Thus, every personnel involved in one activity of the other in the mine should be indirectly involved in slope monitoring.

SURFACE MEASUREMENT

The surface measurement involves some techniques among which are: survey network and tension crack mapping.

Survey Network. A survey network consists of target prisms placed on and around areas of anticipated instability on the pit slopes with one or more control points for survey stations. These stations need to be located close enough to the pit crest so that all prisms can be readily seen; the stations must also be located on completely stable ground. Electronic total station located at a monitoring station (established inside a small hut) built for such purpose, measures the angles and distances from the survey station to the prisms on a regular basis to establish a history of movement on the slope.

Data collected by the total station is transmitted by radio from the pit edge to the survey office where a computer fitted with appropriate software is located. Data come into the computer as survey coordinates of the individual prism targets. Correction for atmospheric variations is made by incorporating data collected by a combined temperature/atmospheric pressure transducer. Changes that have occurred with respect to the original position of the slope monitoring targets are calculated by the software and shown in graphical format. The Geodetic monitoring system (GEOMOS) is a typical survey network for slope monitoring that runs for 24 hours a day. The system is subdivided into three parts: data collection, date transmission, data processing and analysis [1]. Note that the optical mechanical theodolites are nowadays rarely used for slope monitoring, due to their low efficiency and the often significant atmospheric refraction errors in observed angles [5]. A major problem of the survey system of slope monitoring is the error caused by atmospheric factors such as dust and haze. Human error, damage to prism or displacement of the survey station can equally affect measurement accuracy. Errors can also be introduced by instrument or reflector set-up inaccuracies. In some locations, prism theft is another concern.

Tension Crack Mapping. The formation of cracks at the top of a slope is an obvious sign of instability. Measurement and monitoring the changes in crack width and direction of crack propagation is required to establish the extent of the unstable area. Existing cracks should be painted or flagged so that new cracks can be easily identified on subsequent inspections. Measurements of tension cracks may be as simple as driving two stakes on either side of the crack and using a survey tape or rod to measure the separations.

Another common method for monitoring movement across tension cracks is with a **portable wire-line extensometer**. The most common setup is comprised of a wire anchored in the unstable portion of the ground, with the monitor and pulley station located on a stable portion of the ground behind the last tension crack. The wire runs over the top of a pulley and is tensioned by a weight suspended from the other end. As the unstable portion of the ground moves away from the pulley stand, the weight will move and the displacements can be recorded either electronically or manually. Long lengths of wire can lead to errors due to sag or to thermal expansion, so readjustments and corrections are often necessary. The length of the extensometer wire should be limited to approximately 60m (197ft) to keep errors due to line sag at a minimum [7].

Most of the extensometers currently in use have a digital readout. Readings can be taken manually by site personnel or can be stored in an electronic data logger and then downloaded to a personal computer. Electronic extensometers can be linked to an alarm system. When reading exceeds a certain preset limit, an alarm can be set off automatically to warn of the potential danger of pit failure. Under normal conditions, this works very well but they can be accidentally triggered by falling rocks, birds or wild animals. One other problem with monitoring cracks at the crest of a slope is that the movement has already occurred. Additional cracking will potentially weaken the entire area making the ground loose and measurements inaccurate. However, extensometer are economical to use and very effective in defining the relative movements between points either on the surface or inside a pit [5].

SUBSURFACE MEASUREMENT

This encompasses piezometers and inclinometers.

Piezometers. According to [8], the presence of ground water within the rock mass surrounding an open pit can have a detrimental effect upon the stability of the slope. Therefore, it is expedient to constantly monitor groundwater levels as well as pore pressure to assist in the assessment of slope stability [5]. Piezometers are used to measure pore pressures and also serve as valuable tools for monitoring the effectiveness of mine dewatering programs. [9] confirmed that excessive pore pressures, especially water infiltration at geologic boundaries are responsible for many slope failures. Measurement or calculation of water pressure is an important part of site investigation for stability studies. Information on water pressures is essential for designing and maintaining safe slopes.

Inclinometers. Inclinometers are used to monitor slopes and landslide to detect zones of movement and establish whether movement is constant, accelerating or responding to remedial measures. In other words, they measure the subsurface lateral displacement of soil or rock. An inclinometer consists of a casing that is placed in the ground through the area of expected movements. The end of the casing is assumed to be fixed so that the lateral profile of displacement can be calculated. The casing has grooves cut on the sides that serve as tracks for the sensing unit. The deflection of the casing and hence the surrounding rock mass are measured by determining the inclination of the sensing unit at various points along the length of the installations. [10] stated that the information collected from inclinometers can be used for the followings: 1) Locate shear zones; 2) Determine whether shearing is planar or rotational and; 3) Determine whether movement along a shear zone is constant, accelerating, or decelerating.

Remote Monitoring Technologies. These include Time Domain Reflectometry (TDR) as well as Scanners and Radars (Synthetic Aperture Radar, Slope Stability Radar, Movement and Survey Radar).

Time Domain Reflectometry (TDR). Time domain reflectometry is a new approach to monitoring slope movement [11 – 14]. Originally developed to locate breaks and faults in communication and power lines. TDR is used to locate and monitor slope failures. The technology uses coaxial cable and a cable tester. The basic principle of TDR is similar to that of radar. The cable tester sends an electrical pulse down a coaxial cable grouted in a borehole, when the pulse encounters a break or deformation in the cable, it is reflected. The reflection shows as a "spike" in the cable signature. The relative magnitude, rate of displacement and the location of the zone of deformation can be determined immediately and accurately. The size of the spike increase correlates with the magnitude of movement.

A laptop computer is connected to the tester and cable signatures are written to disk for future reference. [15] discussed the rapid increase in the use of TDR and stated its advantages over traditional inclinometers as follows:

— lower cost of installation: cable cost 2 to 38% less than inclinometer casing;

— deeper hole depth possible: Inclinometers in deep hole require special winches and cables due to the extreme weight of the equipment. All TDR monitoring equipment are at the surface;

— rapid and remote monitoring possible: TDR data can be transmitted via telecommunications, [16] and scanning coupled with recording intervals can be programmed remotely to examine zones of interest;

— immediate deformation determinations: Locations of any movement are determined immediately using TDR. Additional data reduction is generally not necessary and the cables can be used to quantify rock movement as well as distinguish shear and tension [17];

— complex monitoring situations: TDR cables have been installed in angled boreholes and have monitored deep zones below moving upper zones. Neither installation could have been done with traditional inclinometer.

Scanners and Radars. Point by point monitoring of every potential failure block on a mine slope is not practical, but a new generation of scanning laser rangefinders has partially addressed this under-sampling problem by detecting movement over large areas. Scanners generate digital models of mine slopes without reflector prisms. The work [18] explained how displacement can be detected by comparing successive scan. The laser scanner is an active self-contained measurement technology. It generates its own light for measurement process.

A modern scanner called SiteMonitor (Fig. 2) was developed by 3D Laser Mapping Ltd, UK initially for monitoring slope stability on old coal mine waste tips in South Wales, UK. Recently, the system is being adopted more widely in the mining industry. It records movements in the slope surface as small as 10mm with a distance range of up to 1000m. It records and analyses up to 8,000 measurements per second to create a detailed, accurate and continuous record of the slope profile**.**

AngloPlatinum, the world largest producer of platinum has adopted the SiteMonitor for slope monitoring at some of its mines. The system is specifically designed for automatic and manual long range profiling of surfaces, operating at distances up to 2,500 meters with accuracy of 50 millimeters. The systems perform continuous, remote scanning for 24 hours at locations determined by the company's Geotechnical team, collecting hundreds of point measurement daily. The point cloud data collected by the laser scanners is automatically analyzed using Site Monitor software from 3D Laser Mapping Ltd. The software can detect surface movement or slope deformation by comparing readings against base measurements. The new laser scanning technology is also helping South Africa's Kumba Iron Ore to improve the safety of iron ore extraction. SiteMonitor is equally used at De Beers Kimberley diamond mine in South Africa to capture highly accurate slope measurements and to help identify potential failures within the pit wall.

Laser scanning records changes in rock structure that would be difficult and time consuming to detect using surveying techniques. The advantages of laser scanning over the survey method of slope monitoring are: 1) it doesn't require the use of prism as commonly use in surveys; 2) there is no problem of prism getting lost during blasting operations; 3) there is no safety risk during prism installation; 4) thousand of points are monitored rapidly rather than single prism location; 5) no need for fixed installation; 6) the system can be moved into areas of limited access because of its portability; 7) it covers up to 2500 m range.

Fig. 2. Riegel LPM-2K SiteMonitor by 3-D Laser Mapping Ltd U.K.

Synthetic Aperture Radar. Synthetic aperture radar (SAR) is a type of ground-mapping radar originally designed to be used from aircraft and satellites. Exploration geologists have benefited from SAR imagery since the 1970's [19]. SAR can be used to generate terrain maps, to produce high quality digital elevation models (DEM) and to detect surface disturbances or changes in surface moisture

SAR produces all weather, day and night, high resolution images of the Earth's surface providing useful information about the physical characteristics of the ground and of the vegetation canopy, such as surface roughness, soil moisture, tree height and bio-mass estimates. By combining two or more SAR images of the same area, it is also possible to generate elevation maps and surface change maps with unprecedented precision and resolution. This technique is called *Interferometry Synthetic Aperture Radar (IFSAR or INSAR)*. With the advent of spaceborne radars, IFSAR has been applied to the study of a number of natural processes including earthquakes, volcanoes, glacier flow, landslides, ground subsidence and structural stability. A very recent application of IFSAR is in the monitoring of unstable slopes in surface mines.

The advantages of IFSAR over other types of monitoring systems are its ability to work in all weather conditions; IFSAR can acquire imagery through fog, mist, rain, haze or cloud cover and can operate day and night [9]. It also has the ability to sample a large area for ground displacement, this is a big advantage over other monitoring systems such as survey networks, surface extensometers that sample movement at a few select points.

Slope Stability Radar (SSR). A scanning radar system was designed by researchers at the University of Queensland, Australia in 2002 specifically for monitoring mine slopes using differential interferometry (Fig. 3). The system, known as the Slope Stability Radar (SSR), uses real aperture 2° beam-width radar to scan a slope in both vertical (height) and horizontal (azimuth) directions. Scanning at a rate of 10°/second over a range of $\pm 60°$ vertically and 340° horizontally, the system continuously monitors the slope face for deformations. The return signal phase is recorded for each pixel in the resulting image and phase unwrapping is used to remove the 2π ambiguity [20]. The SSR is a trailer-mounted unit that features a 0.92 m diameter scanning parabolic dish antenna, controlling/data collecting computer, remote area power supply, warning siren and lights, CCD camera, communication links, and internet compatibility. Typical scan repeat time is 15 minutes. The system can operate at a range of 450 m from the target slope. Line of sight displacement can be measured to ± 0.2 mm without the use of reflectors. In operation, the system scans a region of the wall and compares the phase measurement in each region with the previous scan to determine the amount of movement of the slope. It then produces an image showing spatial deformation relative to a reference image for the entire slope scanned. The displacement history of each point in the image can be plotted.

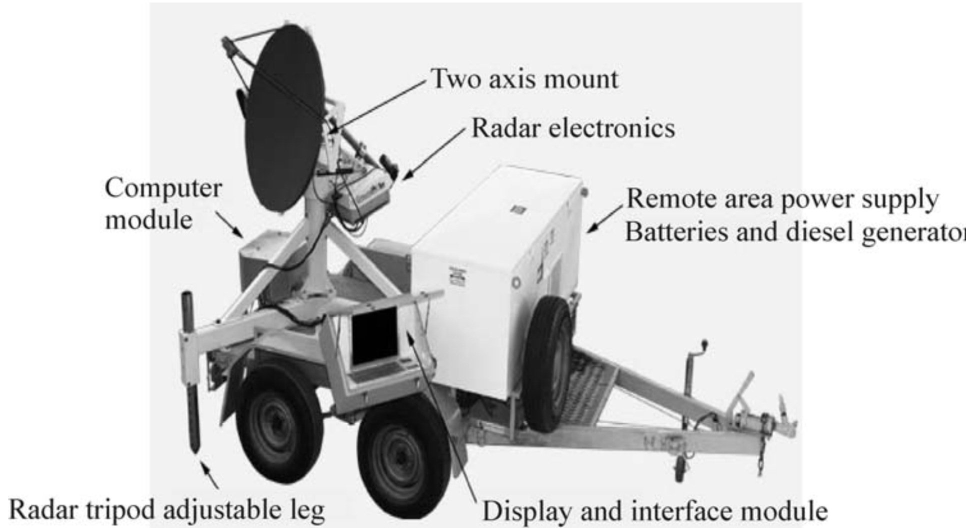

Fig. 3. Slope Stability Radar [20]

Data from the SSR is usually presented in two formats. Firstly, a color rainbow plots of the slope representing total movement which quickly enables the user to determine the extent of the failure and the area where the greatest movement is occurring. Secondly, time/displacement graphs can be selected at any locations to evaluate displacement rates [21]. Additional software is also installed to allow the data to be viewed live at locations remote to the SSR site such as offices of relevant geotechnical personnel.

The SSR systems have been deployed in many mines in Australia, Indonesia, South Africa, Zambia, Chile and the United States. Greater than 70 rock falls and waste dump failures have been monitored and on every occasion precursor “warning” movements were recorded by the SSR [22]. The work [23] reported that the SSR has been in use since 2002 at Leinster nickel mine, Australia for monitoring mine walls in areas with low confidence level on the ability of prisms and visual inspection to predict failure. Phelps Dodge Sierrita Mine, is the first mine in the United State of America to use the SSR. The SSR is the only system in the world that provides continuous sub-millimeter measurements of rock wall movements across the entire face of a wall [19].

Movement and Surveying Radar (MSR). A contemporary of the SSR called Movement and Surveying Radar (MSR 200) was introduced into the market in January, 2006 by Reutech Radar System (Pty) Ltd. South Africa. The MSR 200 (Fig. 4) works in the same manner as the SSR with all slope measurements fully geo-referenced but an additional feature separates the MSR from the SSR is that it provides fully geo-referenced surveying information thus allowing areas that are not hitherto accessible to be surveyed. This is made possible because the system incorporates a fully integrated total station which is a surveying instrument that allows the MSR 200 to be accurately geo-referenced. The survey measurement of the MSR is capable of measuring 3D information of the slope surface and can also be used to determine the amount of materials removed [24].

According to [25], another brand MSR 300 was introduced in June, 2008 as an improvement on the MSR 200, like the SSR, the MSR 300 is capable of detecting sub-millimeter movement of the rock face. The MSR 300 offers continuous slope monitoring and surveying of rock surfaces up to a slant range of 2500 m under all weather conditions. The MSR 300 offers the capability of tracking movements of up to 300mm from scan-to-scan as well as maintaining a high level of immunity to false alarms during sudden environmental changes such as rain, dust storms or mist formations. It equally offers significant improvement in the system’s surveying capability.

Fig. 4. Movement and Surveying Radar, MSR 300 [24]

The MSR is currently utilized in Africa, South America and Australia. Specifically, it's been used by Anglogold Ashanti in its Navachab open-pit mines in Namibia, sunrise dam gold mine in Australia. Seven MSR are in use at different open cast coal mines operated by Anglocoal in South Africa, the MSR is also used to protect Andina mine in Chile. Like the SSR, the MSR is gaining popularity in managing and monitoring sub-millimeter movements in mine slopes around the world.

CONCLUSION

Apart from visual inspection, conventional monitoring equipment such as survey system theodolite and total station with reflecting prism, extensometers, inclinometers, piezometers provide information only for a single site, or at most, a small number of locations in the mine. If the monitored sites are too widely separated or if displacement occurs between sites, early indications of a pending slope failure might go unnoticed. Coupled with this is the fact that these conventional monitoring tools are difficult to install at many surface mines where steep high-walls and lack of benches limit access to areas above the working floor.

Relocating monitoring equipment from location to location is costly, time consuming and could be dangerous on unstable slopes. Disturbing signals from trucks and other mining vehicles can cause step changes in the displacement measurements, confusing the user and making automatic alarming difficult. Furthermore, Vegetation on the rock face reduces the accuracy of the displacement measurements for that location, confusing the user and reducing confidence in the rest of the measurements.

Laser scanner would have been a likely solution to the deficiencies of the conventional techniques but it equally comes with its own disadvantages. The time required in processing of the scan document is too great for effectiveness. In addition, the range and accuracy of these systems can be greatly impaired by differences in the reflectivity of the rock, the angle of the rock face, weather, vegetation and other factors.

The advantages of slope monitoring radar such as the Slope Stability Radar (SSR) and the Measurement and Surveying Radar (MSR) over other methods is their ability to cover large areas on the surface for true two- dimensional monitoring day and night in almost any weather without being affected by atmospheric dust or haze. SSR's active transmit/receive mode of operation also provides an advantage over passive optical methods that depend on solar or other illumination [26].

The slope monitoring radar invention resides in anomaly detection and correction module for a slope monitoring system comprising: an atmospheric correction module that corrects slope movement measurements for anomalies caused by atmospheric changes and a disturbance detection module that identifies disturbances that cause errors in the slope movement measurements.

The disturbance detection module suitably masks regions affected by the errors of the conventional methods. In another form, the invention of the SSR resides in a method of error handling in interferometric signal processing for a slope monitoring system including the steps of: extracting uncorrected movement data from interferometric radar measurements, correcting the movement data for changes in atmospheric conditions, identifying disturbances in the corrected movement data and displaying the corrected movement data and regions affected by the disturbance.

The slope monitoring radar is a state-of-the-art technology whose advent has completely transformed geotechnical risk management in surface mines.

RECOMMENDATION

The peculiarity of each surface mine differs, in a large and dip open pit mine with a lot of slope stability problems, a comprehensive slope monitoring should be in place. This should involve integrating all the slope monitoring techniques as shown in Fig. 1, from visual inspection to radar monitoring. In shallow surface mines like open cast coal mine, high-wall slopes are frequently mined-out, thus having a short lifespan. Slope stability problems which are basically on the high-wall and low-wall is not as challenging as a very deep surface mine, hence, monitoring techniques adopted may not be that comprehensive. A combination of two or more techniques should be adequate.

REFERENCES

1. G. Kayesa, "Prediction of slope failure at Letlhakane Mine with the Geomos Slope Monitoring System," in: *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering Situations*, Series S44, South Africa (2006).
2. J. M. Girard, "Assessing and monitoring open pit mine highwalls," in: *Proceedings of the 32nd Annual Institute of Mining Health, Safety and Research*, Roanoke (2001).
3. J. Sjoberg, *Large Scale Stability in Open Pit Mining - A Review. Technical Report*, Division of Rock Mechanics, Lulea University of Technology, Lulea, Sweden (1996).
4. F. T Cawood and T. R. Stacey, "Survey and geotechnical slope monitoring considerations," *Journal of the South African Institute of Mining and Metallurgy*, **106**, No. 7 (2006).
5. X. Ding, S. B Montgomery, and M. Tsakiri, *Integrated Monitoring Systems for Open Pit Wall Deformation*, Australian Centre for Geomechanics, MERIWA Project Report No. 186, PP4 (1998).
6. M. J. Little, "Slope monitoring strategy at PPRust open pit operations," in: *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering*, The South African Institute of Mining and Metallurgy, Symposium Series 44 (2006).
7. R. D Call and J. P. Savely, "Open pit rock mechanics," in: *Surface Mining*, 2nd Edition, Society for Mining, Metallurgy and Exploration Inc. (1990).
8. E. Hoek and J. W. Bray, *Rock Slope Engineering*, Revised Third Edition, Institute of Mining & Metallurgy (1981).
9. J. M. Girard, R. T Mayerle, and E. L. McHugh, "Advances in remote sensing techniques for monitoring rock falls and slope failures," in: *Proceedings of the 17th International Conference on Ground Control in Mining*, NIOSHTIC-2, NO 20000186 (1998).
10. C. Kliche, *Rock Slope Stability*, Society for Mining, Metallurgy and Explorations, Inc. (1999).
11. W. F. Kane and T. J. Beck, "Development of a time domain reflectometry system to monitor landslide activity," in: *Proceedings of the 45th Highway Geology Symposium*, Portland, Oregon (1994).
12. W. F. Kane and T. J. Beck, "Rapid slope monitoring in civil engineering," *American Society of Civil Engineer, New York*, No. 666 (1996).

13. W. F. Kane and T. J. Beck, "An alternative monitoring system for unstable slope," *Geotechnical News*, No. 143 (1996).
14. K. M. O'Connor and C. H. Downing, *Geomeasurements by Pulsing Time Domain Reflectometry Cables and Probes*, Boca Raton, Florida, CRC Press (1999).
15. W. F. Kane, *Time Domain Reflectometry*, KANE GeoTech, Inc. (1998). Available at: ourworld.compuserve.com/homepages/wkane/tdr.htm.
16. Campbell Scientific Inc., *Time Domain Reflectometry for Measurement of Rock Deformation, Product Brochure* (1998).
17. C. H. Downing, M. B Su, and K. M. O'Connor, "Measurement of rock mass deformation with grouted coaxial antenna cable," *Rock Mechanics and Rock Engineering*, **22** (1989).
18. E. L. Mchugh, D. Jami, D. G. Long, and C. Sabine, "Application of ground-based radar to mine slope monitoring," in: *Investigation Report 9666*, National Institute for Occupational Safety and Health (2006).
19. S. Rossignol and K. P. Corbley, "Reconnaissance by radar," *Canadian Mining Journal* (1996).
20. B. Reeves, D. Noon, G. Stickley, and D. Longstaff, "Monitoring rock slope deformation by radar interferometry," in: *Proceedings of the Workshop on Applications of Radio Science WARS'97*, A. Kulessa Edition, Australian Academy of Science (1997).
21. *The Use of Slope Stability Radar (SSR) for Managing Slope Instability Hazards, Product Brochure* (2003). Available at: www.groundprobe.com.
22. N. Harries, D. Noon, and K. Rowley, "Case studies of slope stability radar in open cut mines," in: *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering*, The South African Institute of Mining and Metallurgy, Symposium Series 44 (2006).
23. J. Cahill and M. Lee, "Ground control at Leinster Nickel Operations," in: *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering*, The South African Institute of Mining and Metallurgy, Symposium Series 44 (2006).
24. Reutech, *Slope Monitoring, New Radar System Provides Accurate Slope Survey, Reutech Newsletter* (2006). Available at: http://www.rrs.co.za./news/MSR200serieslaunched.asp.
25. Reutech, *Movement and Surveying Radar Newsletter* (2008). Available at http://www.rrs.co.za/news/documents/MSRNewsletter.pdf.
26. L. M. Edward, G. L. David, and S. Charles, "Applications of ground-based radar to mine slope monitoring," in: *Presentation at Annual Conference of American Society for Photogrammetry and Remote Sensing*, Denver (2004).