The use of Slope Stability Radar (SSR) in managing slope instability

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ABSTRACT

Assessing and managing instability hazards is an essential activity when working with both unstable natural slopes and engineered slopes. The 'Slope Stability Radar' (SSR) was developed to provide an improved tool to manage risk related to slope instability. The SSR is an all-weather system that remotely scans rock slopes to continuously measure surface movement with a sub-millimetre precision. The combination of near real time measurement, sub-millimetre precision and broad area coverage to quickly identify the size of developing failures provides ideal parameters for the management of slope instability hazards. It has allowed users to detect and alert personnel of rock wall movements that may result in instability. The success of using radar in monitoring slopes is verified by the rapid adoption of the technology by major mining operations throughout the world. This paper provides a brief outline of some of the slope instability risk management applications of SSR systems.

1 INTRODUCTION

The instability of engineered and natural slopes is often of high importance due to potential for loss of life and property. The Slope Stability Radar (SSR) was developed to aid in the management of risks associated with unstable slopes. This paper describes the use of the SSR system in a risk management framework for management of unstable rock slopes. Before discussion of the SSR use within a slope instability risk management framework, a brief introduction to rock slope failure, rock slope monitoring, risk management and the SSR technology is presented.

1.1 Rock slope failure

Failure of rock slopes is mostly defined by serviceability or performance criteria defined by the owners or users of the slope and is therefore difficult to define uniquely. Glastonbury and Fell (2002) used the term 'collapse' to denote the single point of sudden movement, disaggregation and associated large-scale displacement. Not all slopes showing movement will collapse, many will continue to move at a constant or decreasing rate, as the system reaches a new equilibrium. The collapse concept is however particularly relevant for many SSR monitored rock slopes that contain failure modes and geological characteristics that lead to a sudden movement and disaggregation.

1.2 Rock slope monitoring

Rock slope monitoring is required to identify precursor phenomena that occur prior to a slope failure. A number of signs may occur prior to collapse including dilation of cracks on the wall, new fracturing seen on the face, audible noise (cracking and popping), dislocation (shearing) along fractures and increased dust or rilling of loose material from the rock face. However, not all signs will be observed prior to collapse and it is difficult to predict the progression of failure towards collapse by reviewing such qualitative phenomenon. This usually results in overcautious decisions that impact on productivity, while the reverse places lives at higher risk.

A more reliable indicator of instability involves the quantitative measurement of outward movement and acceleration of material as an instability mechanism develops. There is strong evidence that small precursor movements of a rock wall occur for an extended period prior to rock slope collapse (Hoek and Bray, 1981). Development of a monitoring system, adopting acceptable slope deformation criteria coupled with warning systems and design of stabilisation or risk reduction measures if appropriate has become a standard method of dealing with slope instability (Glastonbury and Fell, 2002). Qualified personnel can interpret the pattern and history of movement to improve prediction of failure processes, and to advise appropriate and timely stabilisation or safety management actions.

1.3 Risk Management

The term 'risk' denotes exposure to the possibility of such things as economic or financial loss or gain, physical damage, injury or delay, as a consequence of pursuing or not pursuing a particular course of action. It is described and evaluated in terms of likelihood and consequences; with the likelihood a rating of the probability of an event occurring and the consequence related to the outcome of this event, which may be given as the consequence to people (e.g. single fatality) or a dollar value attached to property damage. Risk management is the process by which informed decisions are made to accept known levels of risk or to implement a set of actions to reduce unacceptable risks to acceptable levels. A simple risk management framework adopted from the Australian Risk Management Standard (AS/NZS 4360) will be used to discuss SSR applications in this paper. Before detailing specifics associated with use of the framework, overview of the main components of risk management is warranted. The activities that are required to manage risks effectively using this framework include:

1. Establishing the strategic, organizational, and risk management context in which the rest of the process will take place. This involves identifying criteria against which the risk will be evaluated. The structure of the risk analysis should be defined at this stage.
2. Identification of all risks whether or not they are under the control of the organization. What can happen? How and why can it happen?
3. Analysing risks to separate the minor acceptable risks from the major risks, and to provide data to assist in the evaluation and treatment of risks. This requires estimation of the consequence and likelihood, the product of which is the risk.
4. Risk evaluation involving comparing the level of risk found during the analysis with previously established risk criteria. The output is often a prioritised list of risks.
5. Risk treatment involving identifying the range of options for treating risk, assessing these options, preparing risk treatment plans and implementing them. Options can include: Avoid, Reduce likelihood, Reduce consequence, Transfer the risk and Retain the risk (Residual Risk).

Risks and the effectiveness of control measures need to be monitored to ensure that changing circumstances do not alter risk priorities (few risks remain static). Review and regular repeat of the risk management cycle is an integral part of the risk management process. Finally, effective communication is important at all stages of the process to ensure that those responsible for implementing risk management, and those with a vested interest understand the basis on which decisions are made and why particular actions are taken.

1.4 Slope Stability Radar (SSR) technology

The GroundProbe Slope Stability Radar is a new technique for monitoring mine walls and general slopes. The concept is based on differential interferometry (see Noon, 2003 for further details). The system scans a region of the wall and compares the phase measurement in each footprint (pixel) with the first scan to determine the amount of movement of the slope. An advantage of radar over other slope monitoring techniques is that it provides full area coverage of a rock slope without the need for reflectors mounted on the rock face. The system offers sub-millimetre precision of wall movements without being adversely affected by rain, fog, dust, smoke, and haze, although reduced precision occurs in pixels where there is low phase correlation between scans (e.g. vegetation on the slope). The system is housed in a self contained trailer that can be easily and quickly moved around the site. It can be placed in the excavation, or on top of a wall or on a bench to maximize slope coverage whilst not interfering with operations. The radar electronics and computer module are located on the tripod. The tripod detaches from the trailer during deployment so that vibrations from the trailer and generator do not degrade reliability and performance. The two-axis mount can scan the dish through 320 degrees in azimuth, and from - 60 to + 60 degrees vertically from the horizon level. The scan area is set manually using a digital camera image.

The display and interface module contains a keyboard, touchpad and display that are all weatherproof. Power is provided by a Remote Area Power Supply, which consists of a battery pack that is automatically charged during a 3.5 hour period each day by a 12 V diesel generator. The system provides immediate monitoring of slope movement without calibration and prior history. Scan times are typically every 1-10 minutes. Data is uploaded to the office via a dedicated radio link. Custom software enables the user to set movement thresholds to warn of unstable conditions. Data from the SSR is usually presented in two formats. Firstly, a colour “rainbow” plot of the slope representing total movement quickly enables the user to determine the extent of the failure and the area where the greatest movement is occurring (see Figure 1). Secondly, time/displacement graphs can be selected at any locations to evaluate displacement rates. Additional software can also be installed to allow the data to be viewed at locations remote to the SSR site.

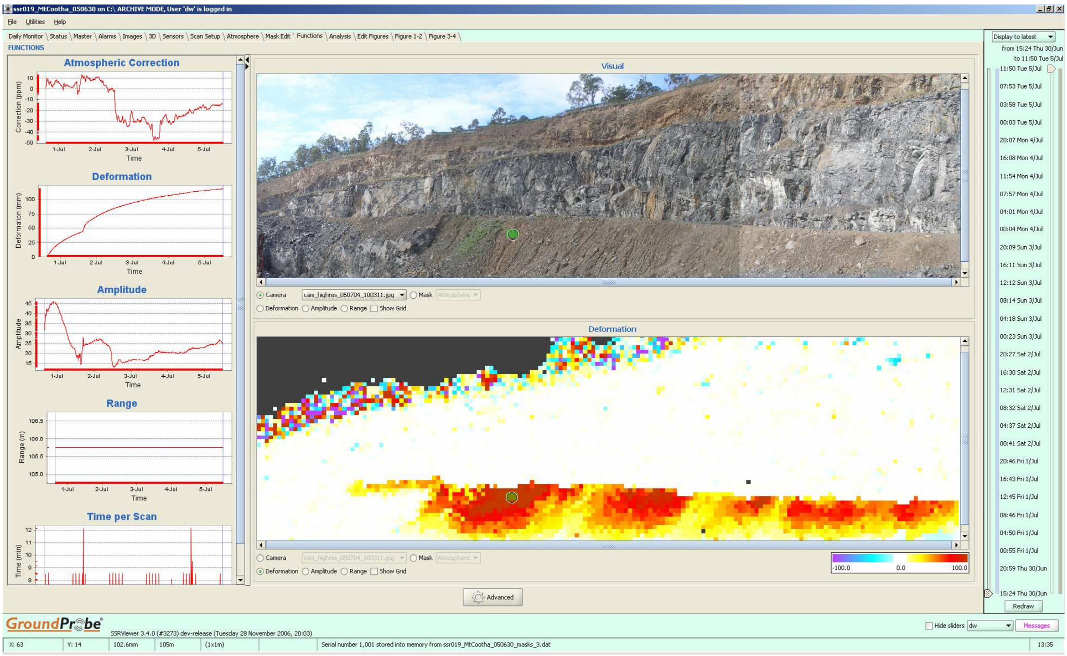

Figure 1. SSRViewer Visual and Deformation Image

2 RISK MANAGEMENT BASED ON SSR MEASUREMENTS (OR SURVEY)

Risk management frameworks for slope hazards are typically set up and administered by geologists or engineers. It would be inappropriate to suggest a generic framework as it should be developed considering the geological, environmental, operational, legal etc parameters that are likely to be distinctive for each site. Some case studies of SSR applications have been presented previously (Harries et al, 2006). This section summarizes some of the applications of the SSR in risk management obtained during a review of operations. Although not a comprehensive review, it nevertheless provides a snapshot of some of the current uses of the SSR; which will no doubt evolve, as the technology develops further and the geotechnical community becomes more educated about the system.

2.1 SSR survey in the risk management framework

It is important to define the role of the SSR system within the context of the operation. The SSR system could be equally used as a passive slope monitoring system or as an active risk management tool to increase productivity. Prior to the SSR being deployed at site, some operations have stated that they do not want to rely on the SSR system or allow the system to modify the way they operate. Other operations, in particular a number of metalliferous mining operations, heavily rely on the SSR systems and will not operate in identified areas of the pit unless they are currently being screened by a SSR system. Different operations are likely to have different view points on the SSR application, much of it based on personal preference. There is nothing wrong with this, but it is important to consider the context of the SSR in operation, which will have implications on how the technology is integrated and optimised.

2.2 Use of the SSR in identifying slope instabilities

One of the primary roles of the SSR is identifying unstable slopes. The broad area coverage and almost real time scanning means that large expanses of slope (e.g. 500,000 m^2) can be scanned and results obtained in less that 10 minutes. After a relatively short time, areas of stable slope can be identified, as well as those areas that are showing greater deformation than expected (providing they show deformation greater than a millimetre). This increased deformation may represent areas of slope instability, possible leading to collapse.

Some operations have used the SSR as a campaign monitoring tool where the portability of the system is used to scan regions of the slope for several days before moving onto the next region of the slope. The results of the slope survey are then used to target further geotechnical investigations and instrumentation. For example, additional survey prisms or wireline extensometers will then be located at areas where deformation is greater than the surrounding slope.

Another frequent application of the SSR in identifying instabilities is in monitoring highly hazardous rock walls with adverse geological structures. The SSR has seen widespread adoption in these situations because the broad area coverage and fast scan mean that such failures (providing they are above a minimum size related to distance) can be identified quickly. These small (usually wedge or planar) failures often develop rapidly with little pre-failure deformation observed prior to collapse. The time from the start of measurable deformation (approximately 1 mm) to collapse is often less than 5 hours. In the case of small bench failures (e.g. 15 m in height) in large open pits, it is prohibitive to mount survey prisms at such high densities to guarantee that the failure would be identified on survey. As a result, SSR systems are employed to provide monitoring coverage and early warning of rapid failures.

2.3 Use of the SSR in analysing slope instability risks

The SSR system can also provide data to aid in the analysis of risks related to slope instability. It provides data useful both for assessing the likelihood and for estimating the consequences of slope failure. In both cases, geotechnical input is required and without skilled staff reviewing the data, the value of the SSR for analysing risks is compromised.

2.3.1 Analysing the likelihood of slope failure

In determining the likelihood of slope failure the SSR monitoring record provides a useful measure of deformation rate and trend. While the rate of deformation is a clear indicator of potential failure, the trend is an even clearer measure. In environments such as open pit mining where blasting /excavation can occur at regular cycles, it is quite common to see a regressive rate of movement in the displacement of pit slopes. These are characterized by initial high velocity caused by some trigger event (usually blasting, excavation or rainfall) which reduces with time to a lower background level (often zero velocity). Stress relief of excavations can lead to such a trend. This contrasts with a progressive rate of movement that has initial lower velocity but the velocity increases with time. The likelihood of a failure is far greater when a progressive failure curve is measured.

2.3.2 Analysing the consequence of slope failure

The SSR can contribute to the determination of the consequences of failure by providing information relating to three major factors; the size of failure, mode of failure and determining the potential for evacuation. The size of failure can be critical (e.g. is it small enough to be caught by the catch bench) and the SSR is ideal to determine the areal size of the failure after a very short monitoring time (several scans). A number of operations have been unpleasantly surprised by the size of the failure developing after the SSR system has been deployed following the monitoring of several existing survey prisms.

The deformation footprint can be reviewed along with the visual image to study the characteristics of the failure. The SSR data can be Georeferenced if required, with the 3D deformation data imported into 3D CAD packages to investigate the mode of failure. This can be a particularly strong analysis technique, where a 3D geological model is also available in the same software package. The

SSR Viewer software can also be used to select multiple time-deformation figure plots from different parts of the failure, which can then help distinguish between toppling and rotational failure mechanisms etc. Knowledge of the failure mechanism can help in determining the likely consequence of the failure.

Whether an area is evacuated in time prior to a failure obviously has major implications to the resulting consequence of that failure. Although loss of access and productivity may not change, an effective evacuation should mean a slope failure without loss of life and with a minimised cost to equipment. The near wide area coverage and real-time nature of monitoring with the SSR systems has meant increasing confidence of operators to evacuate operations with a minimized loss to production. It should be noted that the monitoring of a failure using a SSR system is only a part of the chain of responses that is required to effectively evacuate an operation and all the components (many of which require human responses) need to be considered before incorporating the SSR into the consequence of failure analysis.

2.4 Use of the SSR in treating risks associated with slope instability

SSR systems have been used as an aid to effectively treat risks related to slope instability in a variety of ways. Risk treatment usually involves a combination of avoidance, reduce likelihood, reduce consequence, transfer the risk or retain the risk. Risk avoidance has been achieved in at least one occasion where an operation has ceased activity due to the deformations recorded by the SSR exceeding set triggers. Although not a normal operational situation, in scavenge mining operations or in pits towards the end of their working life such situations may arise.

2.4.1 Reducing the likelihood of slope failure

The likelihood of failure can sometimes be reduced by modifying the geometry or properties of the slope. SSR systems are often used in buttress operations during both removal and creation. During the development of slope stabilizing toe buttresses, the SSR system has been deployed to monitor the real-time velocity of a slope while material is added to the toe of the slope to stabilise it. As well as monitoring the stabilization effect of buttressing on the slope (works cease when slope velocity drops below a target level). The SSR is also used to monitor and alarm for an increase in slope velocity or disintegration of the slope, so that the construction team can be safely evacuated.

Use of the SSR systems to monitor removal of a buttress is particularly common in the coal mines where failures on the high wall often occur due to coal excavation (coaling). The SSR has been utilized in known unstable areas of the high wall during coaling to safely excavate the coal rather than leaving the coal in place (which involves a significant loss of production). The amount of coal that is safely extracted will be dependent on the deformation response of the high wall during production. This requires near real time monitoring data over the expanse of the rock slope, for which the SSR is well suited.

A less direct application of the SSR in reducing the likelihood of failure involves using the data obtained in geotechnical analysis and design, which is then used to modify operational activity. For example, at one mine site the sub-millimetre response of a rock slope during blasting was monitored by the SSR for a number of different blasting trials, to select the best limit blasting procedure to reduce damage to the rock slopes. Monitoring and feedback is an essential part of the design process and the large quantities of data produced by the SSR are useful for this purpose.

2.4.2 Reducing the consequence of slope failure

The treatment of risk related to slope instability by reducing consequence of failures is possibly the most significant application of the SSR systems. This is achieved by setting alarms on the SSR systems that automatically trigger at given displacement thresholds. These displacement threshold alarms are usually measured from a nominated time or over a set time window (e.g. where displacement exceeds 20 mm over a 24 hr monitoring window). For the alarming system to work well, geotechnical input is required to ascertain the correct displacement thresholds. Multiple alarms allow a hierarchical approach of alarming, using increasing thresholds to represent increasing urgency. In this way, a minor alarm level can be used to notify geotechnical staff to review the situation, whereas a higher alarm setting can be used to notify all the people concerned to evacuate the operation. The colour graphic output of the SSR Viewer has been found to be an excellent communication tool with equipment operators, who can clearly understand the visual image produced (white – no deformation, yellow-orange-red increasing deformation) and some operations have printed daily updates of SSR plots to post in lunch rooms so that equipment operators remain involved and aware of geotechnical hazards.

2.5 Summary of the use of the SSR in the process of risk management for rock slope instabilities

Using the risk management framework introduced in Section 1.3 some of the applications of the SSR to manage risks associated with rock slope instability has now been presented. These applications are shown graphically as a summary in Figure 2.

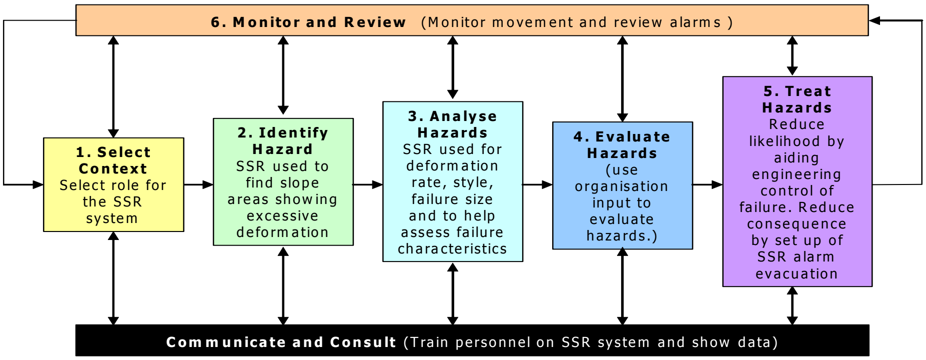

Figure 2. Summary of SSR Use for Slope Instability Hazards using a Risk Management Framework

3 CONCLUSIONS

The SSR is the state-of-the-art development for monitoring slope movement in open pit mines and non-vegetated slopes. It offers the unprecedented advantage of sub-millimetre precision and broad area coverage of wall movements through rain, dust and smoke. The real-time display of the movement of rock faces has allowed continuous management of the risk related to slope instability at a large number of mining operations and at several infrastructure projects. The SSR technology has enabled a radical change in the management of risks in open cut mining operations, which has resulted in a rapid adoption of the technology throughout the world to date. At a number of mines, the SSR is now an integral part of the mine providing major contributions to the mine's future plans. It is also believed that the SSR will contribute significantly to safety and mine design by providing accurate, reliable deformation data that may be later reviewed to further develop our understanding and analysis of failure mechanisms in open pit mines, eventually leading to improved slope design.

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