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Slope performance monitoring: system design, implementation and quality assurance

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Abstract

A comprehensive and robust performance monitoring system is an essential component of the slope management program in an open pit mining operation. Local conditions and experience should drive the planning and implementation of the monitoring program, and development of an early warning system. Knowledge of the capabilities and limitations of the instrumentation selected to ensure the monitoring system is and remains effective and reliable is emphasised. Another important consideration includes the appropriate skill sets of the geotechnical personnel who are responsible for maintenance of the monitoring system and for implementing standard procedures required to ensure operational safety.

With the increasing volume of data generated by modern electronic slope monitoring equipment and with an increasing variety of sensors, there is a growing need to combine and integrate the data in efficient, effective, and innovative ways. It is important that geotechnical staff do not spend their time wading through continuously mounting data but instead focus on data interpretation, reliable results reporting, and addressing urgent actions as needed. A slope monitoring system must be capable of treating all data from different sensors in a collective unified way to facilitate rapid compilation, data cross-validation, analysis, and timely reporting of results. A mining operation must address the adequacy of its performance monitoring program through its risk management process.

This paper describes the requirements of a slope monitoring system to achieve performance reliability and data quality assurance, and in this context includes an introduction to the large open pit project's 'Guidelines for Slope Performance Monitoring', which is in development. This upcoming book provides a description of the process involved in establishing and operating a reliable slope monitoring system; describes the fundamentals of pit slope monitoring methods; application; data acquisition, management, analysis; and, utilisation and communication of monitoring results.

Keywords*: geodetic monitoring, line-of-sight monitoring, data validation, data reliability*

1 Introduction

Requirements of an effective and reliable monitoring system include:

- Early detection of potential incipient instability.
- Communication of alarm exceedance.
- Analytical functionality in assessing current conditions and estimation of forecast predictions.
- Confirming physical characteristics (e.g. deformation, pore pressures, etc.) are within the expected or required performance and serviceable range.
- Identifying, for the purpose of data reliability, the critical elements that will ensure the success of the monitoring program.

The design of a monitoring system is based at least partially on an understanding or estimation of the potential failure mechanism where the data generated is used to assist interpretation of the mechanism, track movements and other features that could influence stability, and alert personnel in the event of incipient failure.

Considerations for monitoring system design include the following features:

- Monitoring instruments that take measurements and transmit data in real-time are appropriate for alarming in moderate to critical risk situations.
- Monitoring instruments that are not real-time are often necessary for identifying and understanding failure mechanisms, as well as assessing the nature of long-term trends.
- Instruments such as radar, laser scanners, and photogrammetry can monitor large areas and provide an overall understanding of the movement of a failure mass.
- Geodetic and line-of-sight monitoring instruments can provide critical information necessary to validate data from other instrumentation.
- Visual inspections assist the interpretation, validation, and reporting on monitoring data from instrumentation, and visual inspections are an important component of the risk management process that ensures the monitoring system is working as designed.

The discussion that follows highlights an approach for the development of an effective slope performance monitoring system that generally follows from relevant sections of the large open pit project (LOP) 'Guidelines for Slope Performance Monitoring'. Topics explored include considerations for monitoring instrument selection, monitoring system design and operational considerations that include instrumentation selection requirements, equipment protection and reliability, monitoring rockfall and small-scale instability, risk-based approaches to system design, and program staffing and organisation. This is followed by a discussion on data communications, data validation, reliability, quality assurance, system availability and data redundancy. Following communication and related subjects is a discussion on data analysis and utilisation, which includes relevant topics of integrated monitoring, the importance of confirming data reliability, and the contribution from numerical models. Utilisation of data for early warning detection, alarm management and response, and for effective and reliable processing and presentation of monitoring results is also examined. The discussion ends with considerations for the future relevant to slope monitoring in the mining environment. Additional details regarding these and other related topics on slope performance monitoring, including case studies and examples, are presented in the LOP project's upcoming publication.

2 Monitoring system design and operational considerations

2.1 Instrumentation selection requirements

Several basic factors that affect monitoring instrument selection must be considered that involve an appreciation for site-specific conditions in the mining environment. For development of a reliable and practical monitoring system, the slope engineer must consider and balance the instrument specifications relative to the monitoring requirements, which include:

- **Range:** the maximum distance over which the measurement can be reliably made, with a greater range usually being obtained at the expense of resolution.
- **Resolution:** the smallest numerical change an instrument can measure.
- **Accuracy:** the degree of correctness with respect to the true value.
- **Precision:** the repeatability of similar measurements with respect to a mean value.
- **Conformance:** whether the instrument is properly fixed to the ground it is meant to be measuring or if the presence of the instrument affects the value being measured.
- **Robustness:** the ability of an instrument to function properly under harsh environmental conditions to ensure data accuracy and continuity are maintained.
- **Reliability:** synonymous with confidence in the data; poor quality or inaccurate data can be misleading and may be worse than having no data.

2.2 Equipment protection for performance reliability

Slope monitoring systems must be designed to work reliably and on a continuous basis in extreme environments. Open pit mines are located in some of the driest, wettest, hottest and coldest regions on earth, while others are exposed to large night-to-day temperature changes, especially in high-altitude environments. Extreme wind environments produce unique challenges in some regions, such as near continental divides. Monitoring equipment must be rugged enough to survive and function for months under harsh working conditions such as in regions with significant winter snow accumulation, since there may be no access for long periods. Also, slope monitoring measurements are affected by snowpack, falling snow and rain, fog, dust, and other impacts of changing atmospheric conditions that require data corrections. The primary benefit of a reliable monitoring system is not simply to minimise maintenance, but the value of being able to continue mining because the stability state is being tracked and understood, versus having to stop production while the slope engineer lacks supporting data.

Most instrumentation utilised for surface deformation monitoring is designed to operate where exposed to the expected range of weather and climatic conditions, temperature, moisture, and dust at a particular mine site, and others require shelter and other means of protection from the elements. For some instruments, enclosures are designed and utilised to ensure maximum reliable performance, to extend service life, and to minimise maintenance. Enclosures utilised effectively by the mining industry vary from simple home-built wooden shacks to roomy and robust heating, ventilation, and air conditioning equipped sea containers. Instrument enclosures are routinely used to protect remote total stations and, more recently, for laser scanners, some ground-based radar units, and for other purposes. Enclosures provide not only climate control but are also designed for lightning protection, reliable power supply and effective data transmission. Equipment protection and reliability also depend on routine preventative maintenance schedules, including scheduled instrument calibration and service in accordance with the manufacturer's specifications.

2.3 Rockfall and small-scale instability

Rockfall hazards can represent the most significant geotechnical risks to the workforce in open pit mines. Operational activities which reduce rockfall risk, such as bench face scaling, catch bench clean-up, and perimeter blasthole drilling creates significant exposure of mine personnel and smaller equipment to these hazards. Rockfall risk potential to shovel and haul truck operators can be largely mitigated by machinery design which places the operator cabins high and back from the face, outside of the rockfall trajectory envelope. Dozers and other large equipment have various forms of rockfall protection, such as thick steel canopies. Remote-controlled equipment can eliminate operator exposure in cases where rockfall potential is considered to be an unacceptable risk.

Mining a highwall induces stress changes and it may take time for the soil or rock mass to come to equilibrium. Where the soil or rock mass is weak or highly fractured, the bench face could unravel or fail, particularly during the initial 24 hours after the face is excavated. Failure of the bench face could impact one or more benches above the freshly excavated ground, thus inducing a rockfall condition that may impact more than a single bench. The occurrence of a small-scale rockfall event can occur quickly and without warning. Since rockfall and bench-scale instability can occur suddenly, utilisation of instrumentation to detect small-scale movement in time for the mine operators to avoid the incipient hazard can be challenging. Mining companies are starting to study time-dependent behaviours of rock masses, such as chemical degradation, which may lead to revived rockfall even over short operating lifetimes.

Mining operations manage rockfall risk with procedures directed at limiting personnel access to the hazard that are often referred to as standard operating procedures (SOP). Although the equipment used to doze and excavate blasted material provides operators with protection from exposure to rockfall hazards, there are limits to the degree of protection that mine equipment provides. In areas exposed to rockfall hazards and/or having potential for a bench face failure, the slope monitoring aspects of the SOP may include the utilisation of spotters, lights for excavation at night, barricaded exclusion zones, daylight mining only, increased frequency of inspections that may include drones or specialised surveys, and performance monitoring instrumentation for safety-critical monitoring. Techniques that utilise photogrammetry, laser scanners, and radar have been developed for the detection of small-scale movement in real-time that can be effective but must be implemented with extreme caution due to equipment vulnerabilities and the speed with which rockfall can initiate. Limitations of such equipment include sensitivity to dust, rain, snowfall, changes in atmospheric conditions, and deployment of instrumentation in strategic locations where they can be effective and not intrusive to the mining operation. The utilisation of instrumentation for the detection of rockfall and small-scale instability can present a risk by creating a false sense of security for the mine operators who trust the instrumentation to warn them in time to clear the area before the rockfall or failure event occurs. Rockfall protection is not designed for large rock blocks, such as room-sized boulders that can develop substantial momentum. Where the dislocation of large rockfall particles are observed, or are possible, special precautions should be taken to ensure potential impacts to equipment or personnel are mitigated.

Addressing the following considerations can improve the SOP for scaling and clean-up at the highwall toe for the purpose of mitigating the potential for rockfall incidents involving personnel and mobile equipment:

- Recognition of potentially hazardous ground that requires a specific SOP for mine development.
- Increased utilisation of drones for survey of as-built benches and bench faces, and rigorous search and detection of incipient cracks and other obvious and exceptional deformations.
- Utilisation of light plants, where needed, to improve visibility at night.
- Utilisation of spotters in areas determined to be potentially hazardous and where spotting can provide adequate warning.
- Recognition of the spotter's attention span to ensure that spotters are effectively utilised.
- Inspections and sign-off by a qualified person before scaling and clean-up is approved.
- Experimentation with instrumentation that can potentially be used to detect small-scale incipient deformation and rockfall potential (e.g. photogrammetry, laser scanners, radar).

It is important to recognise the limitations of instrumentation used for the detection of sudden small-scale and potentially dangerous occurrences of rockfall and bench-scale slope failure events. It is also important to understand that once adverse hazardous blocks dislocate and start to slide, even in small amounts, the instrument used for detecting incipient early movement has done its job of warning, and subsequent movement warning times may be too short to react in time for effective evacuation. Small-scale instability risks may not be reliably or adequately mitigated by the current state-of-the-art in monitoring technology. Practical remedies for these cases are not necessarily robust but have included:

- Recognition and barricading of known hazard zones for special mining treatment, such as adequately sized and protected excavators and remote-controlled equipment.
- Close examination of precisely located (relative to operating equipment) individual radar pixel changes from scan to scan (instead of relying on trigger limits), coupled with direct immediate instructions to move operating equipment away from impact zones at a moment's notice.
- Use of specifically trained spotters to warn of signs and indications of early movement.
- Frequent or continuous real-time inspections by experienced slope engineers who are aware and knowledgeable of local ground conditions.

2.4 Risk-based monitoring

Risk-based approaches applied to slope monitoring system design and to performance assessment require a thorough understanding of local ground behaviour, including relevant experience, mechanism, frequency, location, size, and runout distance. Various performance monitoring methods and an array of instrumentation must be used to gather reliable information and apply results into meaningful risk or decision analysis. Risk-based monitoring enables the geotechnical engineer to calibrate monitoring zones for reliable alarming, create failure mode models, and develop robust safety procedures suited to specific monitoring conditions. Improvements in instrumentation and automation of monitoring systems that make it possible to monitor and report information almost anywhere in real-time have added considerable value to risk-based monitoring capability. However, having that capacity also makes it easier to become complacent about systems that may or may not always perform as expected, and may lead the mine operator to become over-confident that all is well.

Local experience in ground movement behaviour should always be considered of high value in the design of a slope performance monitoring system. Experience should drive the selection and deployment of instrumentation, development of a performance monitoring program, and development of an early warning system.

The importance of validating deformation behaviour and calibration of line-of-sight movement from radar and laser scanning systems to total vector displacement available from geodetic survey systems (e.g. total station, RTS, GPS/GNSS) should never be discounted or underestimated. Not having a clear appreciation of the limitations of line-of-sight movement monitoring, no matter how precise the measurements are, can present a fatal flaw of the monitoring system. Utilisation of both ground-based and satellite-based radar can help improve the interpretation of real movement where the line-of-sight vectors to the targeted area of interest are significantly different. The provision of redundancy in the monitoring program, using different types of instrumentation, is required to ensure the ability to verify changing stability conditions.

Calibrating radar sensitivity for a large excavated slope can be more difficult than intuition might suggest. Zonation of a slope into regions of similar behaviour and geometry for purposes of line-of-sight calibration is recommended. For example, from the point of view of the position of the ground-based radar, the direction of movement near the crest of the monitored slope might be well aligned to the line-of-sight. However, movement at the toe of a developing instability on the same slope may be perpendicular to the line-of-sight. In the event that slope failure initiates at the toe of the unstable section, the radar may not detect movement until it is too late for the mine operator to react to an emergency situation. This risk is relatively high for slopes excavated in hard rock masses where acceleration to failure can occur rapidly.

Slope designs in mature operations often employ an empirical approach that may supersede a conventional deterministic approach supported by design criteria specifying a minimum safety factor. Such designs may be justified from site-specific experience and where performance monitoring instrumentation is well-suited to the task including utilisation of redundant systems for data validation and results reliability. Another important consideration includes the appropriate skill sets of geotechnical personnel who are responsible for the maintenance of site-specific monitoring systems and standard procedures required to ensure operational safety. Depending on risk potential and the operation's tolerance for managing a slope instability event, instrumentation that only measures displacement along the line-of-sight may be insufficient to adequately support a risk-based slope design. The operation must address the adequacy of their performance monitoring program through their risk assessment process. From a strategic perspective, risk-based monitoring may enable the user to calibrate monitoring zones, create failure mode models, and develop robust safety procedures under specific monitoring conditions.

2.5 Program staffing and organisation

The most important component of any slope monitoring program is the personnel who install, utilise, and manage the system. No amount of automated machinery can replace the human part of the performance monitoring equation. However, slope monitoring and management is a demanding full-time job that must overcome human limitations, including the potential for distraction, boredom with routine tasks, a limited attention span, and complacency. The qualities and capabilities of any monitoring system increase dramatically with the experience of the personnel at the mine running the system.

A monitoring system skillset matrix, such as the one shown in Table 1, is used by effective organisations to assist in developing desired skills for site personnel directly or indirectly involved in the performance monitoring program. The matrix is used to track specific tasks an individual or position is certified to perform and indicates areas where additional training may be required. The example presented matches personnel categories to the required skillsets determined by the organisation for simplicity, but it can easily be expanded to include individuals.

Table 1 Example of a monitoring system skillset matrix that defines requirements for the management of the slope performance monitoring system by members of the mine engineering and system support team

	Personnel categories						
Skillset	**Technician**	**Surveyor**	**Dispatcher**	**Engineer**	**Manager**	**IT**	**Mine ops crew**
Skill 1: System selection and layout	yellow	yellow	grey	green	yellow	grey	grey
Skill 2: System principles	yellow	yellow	grey	green	grey	grey	grey
Skill 3: System components	green	grey	grey	yellow	grey	yellow	grey
Skill 4: System deployment and/or installation	green	green	grey	red diagonal line	grey	yellow	grey
Skill 5: System setup and configuration	green	grey	grey	yellow	grey	grey	grey
Skill 6: System operation	green	grey	green	green	grey	grey	grey
Skill 7: System diagnostics and troubleshooting	red diagonal line	grey	grey	yellow	grey	grey	grey
Skill 8: Data handling and management	yellow	grey	grey	yellow	grey	green	grey
Skill 9: Data analysis and utilisation	grey	grey	grey	green	grey	grey	grey
Skill 10: Alarm thresholds	grey	grey	grey	green	grey	grey	grey
Skill 11: Communication and response protocols	green	green	green	green	green	green	green
Skill 12: Documentation and reporting	grey	grey	grey	green	green	grey	grey

Colour codes: green (full competency in skill is required), yellow (familiar with skill, but require help and guidance), grey (no experience required for skill; personnel do not perform this task), red diagonal line (a training deficiency that should be resolved).

The monitoring system skillset matrix promotes workforce flexibility and redundancy of skills availability by focusing on multi-skill tasking of onsite staff. In instances where site personnel are not available or capable of performing certain skills, consultants are often relied upon to provide qualified and experienced support. Suggestions for skillset requirements that provide definition for the skill sets listed in Table 1 are summarised in Table 2.

Table 2 Monitoring skills summary (continued next page)

Skill	Content	Implementation	Outcome
1: System selection/ layout	Types of monitoring systems, capabilities and limitations, performing geotechnical and geological assessments, performing siting/location analyses	Internal experience-sharing, information from and presentations by manufacturers, research, feedback from industry colleagues	Proficiency in determining the appropriate monitoring system/s to meet site requirements, evaluating factors that influence performance, performing location selection
2: System principles	History, physics, operating principles, applications, limitations	Manufacturer training programs, product manuals, expert guidance	Understanding of key system principles and theories
3: System components	Hardware and software components associated with the system	Manufacturer training programs, product manuals, expert guidance	Understanding of key system hardware and software components
4: System deployment/ installation	Site selection, deploying and/or installing system, geo-referencing	Manufacturer training programs, product manuals, expert guidance	Able to efficiently and effectively deploy and/or install monitoring system
5: System setup/configuration	Setup and configuration of a system from predetermined criteria, calibration, baseline testing, determining data validity	Manufacturer training programs, product manuals, expert guidance	Able to set up and configure system
6: System operation	Hardware, software, communications, and data management operation	Manufacturer training programs, product manuals, expert guidance	Understanding operation of the system components and how data is distributed and managed
7: System diagnostics/ troubleshooting	Diagnostic and troubleshooting tools and procedures, available resources, contact information	Manufacturer training programs and/or maintenance support, product manuals, expert guidance	Ability to follow basic diagnosis script and resolve expected problems, as well as the protocol for elevating to manufacturer support
8: Data handling/ management	Network communications, database management, data validation and reliability, archiving	Site-specific knowledge, internal experience sharing, product manuals, expert guidance	Ability to facilitate automatic and manual collection, transfer, validation, and backup of data at routine intervals

Skill	Content	Implementation	Outcome
9: Data analysis/utilisation	Data visualisation, analysis, trends, and interpretation; failure prediction, inverse velocity, acceleration trends, forward and back analyses	Formal education, manufacturer training programs, product manuals, expert guidance	Able to perform complex data analysis, interpretation, and decision-making
10: Alarm thresholds	Alarming methods and types, alarming theory, case history and data-based analyses, determination of data ‘noise’, level of monitoring detail, time windowing	Site-specific knowledge, internal experience sharing, formal education, manufacturer training programs, product manuals, expert guidance	Ability to determine applicable alarm types, settings, and thresholds
11: Communication/ response protocols	Distribution of alarms and notifications, responsible parties, protocols (trigger action response plans, etc.), evaluation	Site-specific training, internal experience sharing, expert guidance	Distribution of alarms to appropriate personnel for response
12: Documentation/ reporting	Periodic system/monitoring status reports, baseline configurations and change tracking logs, monitoring plans, project organisational charts, instrumentation maps, decision flowcharts, evacuation procedures, communications lists, alarm review and signoff forms, system and visual inspection forms, geotechnical reports, operational reports	Site-specific training, internal experience sharing, expert guidance	Ability to determine applicable monitoring documentation and reporting needs, and develop appropriate reporting intervals

3 Data communication

3.1 Considerations for effective data communication

A reliable communications network that transmits data collected from remote locations is an essential component of an effective risk management system. If a slope is failing and there are monitoring devices which detect the onset of instability, the system will only work if the data can be communicated reliably and quickly to decision makers.

Recent improvements in efficiency of fleet management–facilitated by the reliable and rapid collection of data from equipment and communications requirements of autonomous equipment–has encouraged miners to invest in technologies advanced for slope performance monitoring. Improvements in monitoring equipment have come with increasing demands on the communications network. For example, collecting data from a single remote telemetry station monitoring a piezometer installed on an excavated slope requires only a few bytes of information to be transmitted per hour, but collecting data from a ground-based radar or camera can require several million bytes per second.

To ensure reliable performance, the communications network design must be organised across all groups at a mining operation. Due to similar spectrum licensing schemes adopted worldwide, radios from different vendors for different applications will commonly use the same frequencies. The protocols for communications may be different, but there is only so much radio frequency (RF) bandwidth. Two radio networks using the same frequency will essentially be fighting with each other to reliably exchange their data packets. Ideally, radio networks for different applications will utilise different frequencies, or a single network will be built (such as Wi-Fi) to support the multiple applications. Arguably, these challenges are easier to manage during the operational phase, while resources are more readily available to implement, support, and manage these systems. During mine construction and closure, these systems are often overlooked and receive attention late in the development process or when something goes wrong. Early planning during the mine start-up, operational readiness, and pre-closure phases will ensure that the monitoring system objectives are achieved.

Due to compartmentalisation, it can be difficult to coordinate among different groups at a mine, however, a failure to do so can mean that no network operates reliably. Every mine should have a wireless oversight group and all network deployments should be coordinated through that group. This group should have RF technicians skilled in the use of spectrum and network analysers so that the wireless space may be profiled prior to the deployment of equipment, or used for troubleshooting reliability issues. If a mine is in an urban area, there will likely be numerous wireless systems nearby, including those used by wireless phones, walkie-talkies, Wi-Fi, and cellular, among others. Understanding the wireless space is critical to maintaining a reliable wireless telemetry network.

3.2 Communication: future developments

As with all technology, change is the only constant. This has been seen with communications systems. In the early days, licensed band radios were commonly required. This then gave way to unlicensed band spread spectrum technology, and the latest iteration utilises more efficient and longer distance Wi-Fi. The advantage of Wi-Fi is that multiple types of communications are supported since Transmission control protocol/internet protocol (TCP/IP) is a somewhat generic medium for the transmission of data. As more devices adopt TCP/IP support, they can leverage that single network for communications.

Further improvements to Wi-Fi technology are anticipated, including enhancements in the signal processing algorithms and receiver sensitivities to allow longer distances, lower power, higher bandwidth, and lower cost.

Cellular technologies are also continuing to improve in range and bandwidth. Data telemetry options are currently available for cell networks. However, due to limited coverage in remote areas, they find limited use in mining. This is likely to change, particularly with the release of 5G cellular technology.

4 Data validation, reliability and quality assurance

4.1 General considerations

Functionality, reliability and quality assurance of monitoring system design and performance can be defined by addressing the following basic considerations:

- Identify objectives of the monitoring program.
- Assess the risk and consequence of getting it wrong.
- Determine what parameters must be measured and to what sensitivity and frequency.
- Determine what level of redundancy (if any) is required.
- Determine the required level of technical and maintenance support.

The monitoring plan is not static and may change over time. The reliance on performance monitoring in the risk management plan may change over time due to changes in instrument response such as a trigger alarm being exceeded, or change in risk exposure during mine development. Consequently, the monitoring system must have the capacity to evolve during mine development to address the expected changing requirements over the life of the project.

The importance of data reliability must be fully recognised where poor quality or inaccurate data can be misleading and is worse than having no data. The reliability of reported instrument readings is typically described by terms that are sometimes misunderstood or improperly used interchangeably, namely accuracy, precision, resolution and full-scale. These four inherent characteristics of monitoring devices and the data they generate are materially different. Ideally, the geotechnical practitioner would like to have instrumentation that produces reliable data with a combination of high resolution, accuracy, and precision over a long measurement period. However, there is some trade-off between these attributes and the cost implications.

Sensor specifications such as these help the slope engineer to understand the effective range, reliability, and potential inherent error that will be present in resultant data. These elements must be carefully considered in selecting the appropriate monitoring device for a particular application. For many mining geotechnical applications, the relative measurement change or rate of change is a more important trigger than the precise absolute measurement at a point in time. Nevertheless, reading reliability must be aligned with the monitoring system requirements.

For example, in applications where brittle catastrophic slope failure could occur with very small displacement as a precursor to sudden collapse, very sensitive monitoring devices operating over a small base length are required whereas in other applications where substantial deformation is expected and can be tolerated, a lower resolution system with a large range of measurement may be suitable.

4.2 System availability

The full system health and component availability should be monitored and reported to stakeholders. This includes overall system health, performance of individual sensors, data communication from the field sensors written to the respective databases, and the alarm notifications to first responders.

Monitoring and reporting system health demonstrates that availability is maintained and is functioning to predefined monitoring requirements. It is important that a set of key performance indicators are tracked and reported on a regular basis. Not only will this provide confidence to stakeholders that monitoring systems are operational and effective, but it will also assist to identify trends and weaknesses in the system.

Some of the parameters that should be reported to track the performance of the monitoring device and alarming include:

- Availability of sensors and monitoring devices over the reporting period (maintain record keeping of downtime and corrective remedial actions implemented). This can be achieved with forms including daily radar check sheets and weekly summary status dashboard reports devised for various types of instrumentation (see Figure 1 for an example for multiple radars).
- Assurance of data transmission (ensure instrumentation is functional and data has been posted to the database).
- Alarm testing and evacuation trials (periodically ensure that alarm levels are relevant and ensure people know what to do in the event of an emergency).

Radar Status

`	Brockman 2 SSR067	West Angelas MSR047	Tom Price MSR048	West Angelas MSR076	Hope Downs 1 MSR077
Area monitored	BS2 Sth Wall	CEPN Sth wall	SEP north wall	CEPN Nth wall	NE3
Monitoring type*	Diagnostic	Critical	Critical	Critical	Critical
Alarming enabled	OC	OC	OC	OC	OC
Sensitive to mine plan**	Yes	Yes	Yes	Yes	Yes
Red Alarms	0	1	0	0	0
Orange Alarms	0	6	0	0	0
Grey Alerts	0	0	0	4	0
Weekly Availability	50	100	100	100	100
Use of availability (%)	100	99	100	100	96
Georeferenced	Yes	Yes	Yes	Yes	Yes
Weekly Checklist received	Yes	Yes	Yes	Yes	Yes
Next maintenance	TBA	19/01/2015	21/01/2015	19/01/2015	20/01/2015

*Critical: No mining without radar; *Diagnostic: Radar not a monitoring pre-requisite, *Background: Normal baseline monitoring	** Downtime can affect mining plan during the next week

- SSR067: Availability down as the radar was decommissioned during the week.
- MSR047: 6 Orange alarms due to weather events.
- MSR048:
- MSR076: 4 Grey alarms due to stabilisation and generator running too long events.
- MSR077: UoA down to 96% and Geotech alarms were due to stabilisation events.

Figure 1 Example of a weekly summary status dashboard for multiple radars (Source: Fanie Wessels)

4.3 Data redundancy

Data redundancy is an important additional control or backup on the monitoring system. Basic benefits of redundancy include the ability to verify or corroborate monitoring trends and to provide a backup source of data should one system fail.

Ideally data redundancy should be provided from different types of instruments. If data from prism, radar, and wireline extensometer responses show similar spatial displacements, the collective data would strongly indicate that real displacement is occurring. The hierarchical layered approach to monitoring described by de Graaf & Wessels (2013) can be used to develop a monitoring program aligned with the risk to be managed, as summarised in Figure 2. This also provides a basis for selecting which systems may require additional redundancy. However, redundancy comes at a cost with additional hardware, installations, maintenance, and importantly, substantial increase in data generated which needs to be managed and analysed.

Slope Risk	Monitoring Method	Monitoring Frequency	Access Required
Low Risk	Berm inspections (crack inspections)	Increasing monitoring frequency (some can be alarmed if appropriate telemetry & alert systems are in place)	Access to berms
	Manually read crack monitors or surface extensometers		Access to berms
Moderate Risk	Laser scanners		Access to berms (install/maintenance)
	Inclinometers		Access to berms (readings)
	TDR/VWP		Access to berms (readings)/Telemetry
	Automated surface extensometers		Access to berms (readings)/Telemetry
	Manually read prisms		Initial access to berms (install targets)
High Risk	ATS Prisms (Automated Total Station)	Requires near real time telemetry and alarms (i.e. Alert, Alarm, Evacuate)	Access to berms (install/maintenance)
Critical Risk (Safety Critical Monitoring)	Radar		Remote
	Automated surface extensometers with local or remote alarms		Remote

Figure 2 Risk-based hierarchical approach to slope monitoring (from de Graaf & Wessels 2013)

A balanced, risk-based approach to monitoring program design is recommended. The number and types of instruments must be aligned with the expected modes of instability and appropriately resourced. The amount and type of redundancy requires careful consideration and must be aligned with the objectives of the monitoring program including addressing potential risk and risk tolerance.

5 Data analysis and utilisation

5.1 General considerations

The ultimate goal of the monitoring system is to obtain and use data to better understand slope behaviour and predict future performance so that decisions relevant to geotechnical risk management or optimisation of development opportunities for the operation are well informed. Unfortunately, there remain significant instances where terabytes of data are collected and not utilised to maximum potential for a variety of reasons. Often, personnel onsite either do not have the time necessary to parse and analyse the data or do not have the experience needed to make the best use of the data. In real life worst-case scenarios, damage to equipment, injury to personnel, and even fatalities could have been prevented. The only thing worse than not having data is having good data that is not utilised.

In large open pits that are well resourced, and where competent geotechnical personnel are available for data analysis, there are often exceptional practitioners who have taken an interest in understanding the output from monitoring systems. From ground-based radar technicians and geotechnical practitioners with expertise in assessing movement trends to microseismic system specialists, expertise in understanding the story that data can tell is incredibly valuable to the operation. It can mean the difference between the loss of credibility of a geotechnical department by an operation weary of false alarms or unpredicted disasters due to missed signals, and a well-executed trigger action response plan (TARP) that prevented the loss of millions of dollars of equipment or even the loss of life.

5.2 Integrated monitoring

When designing the components of a slope monitoring system, each system, sensor, or group of sensors should aim to answer at least one specific question, or one specific problem (Dunnicliff 1993). A comprehensive slope monitoring system should consist of a broad range of complementary sensors and systems that include total stations, GPS/GNSS, ground-based and satellite radars, laser scanners, photogrammetry, and subsurface geotechnical and hydrogeologic sensors. Each instrument type produces a unique set of information used to answer to a specific question. Users of slope monitoring systems must clearly understand the function of each sensor and know which question the readings for each sensor are seeking to answer.

Unfortunately, the data generated by these sensors and systems are often viewed in isolation on separate computers by different users. In the past, this has largely been the result of slope monitoring software package limitations, but a recent trend has been to integrate all monitoring data types into a single monitoring software platform. Changes in ground movement are most effectively detected through the analysis of multiple data types from varying sensors. Thus, it is important that data from these varying sensors be managed in a slope monitoring software package that has a strong emphasis on data integration.

By combining data from two different sensors such as a piezometer and a prism, the slope engineer can gain a more holistic understanding in terms of data context. For instance, a spike in pore pressure measured by a piezometer behind a pit wall in combination with a subsequent increase in rate of deformation at a nearby prism is a series of events that can be interpreted in terms of cause and effect. Data validation and reliability of the interpretation are achieved when this observation is coupled with increased velocities measured by both ground-based and satellite radar. The key is to be able to quickly and easily tie events together from the piezometer, prism, and radar.

Rapid changes to data trends for slope monitoring sensors can require time-critical responses where switching between software packages and computers for analysis is not ideal. The slope monitoring system must therefore be capable of displaying multiple sensors with varied data types side-by-side and layered one on top of another, for direct comparison and analysis. An example of 3D visualisation of multiple types of data with selected time series plots is shown in Figure 3.

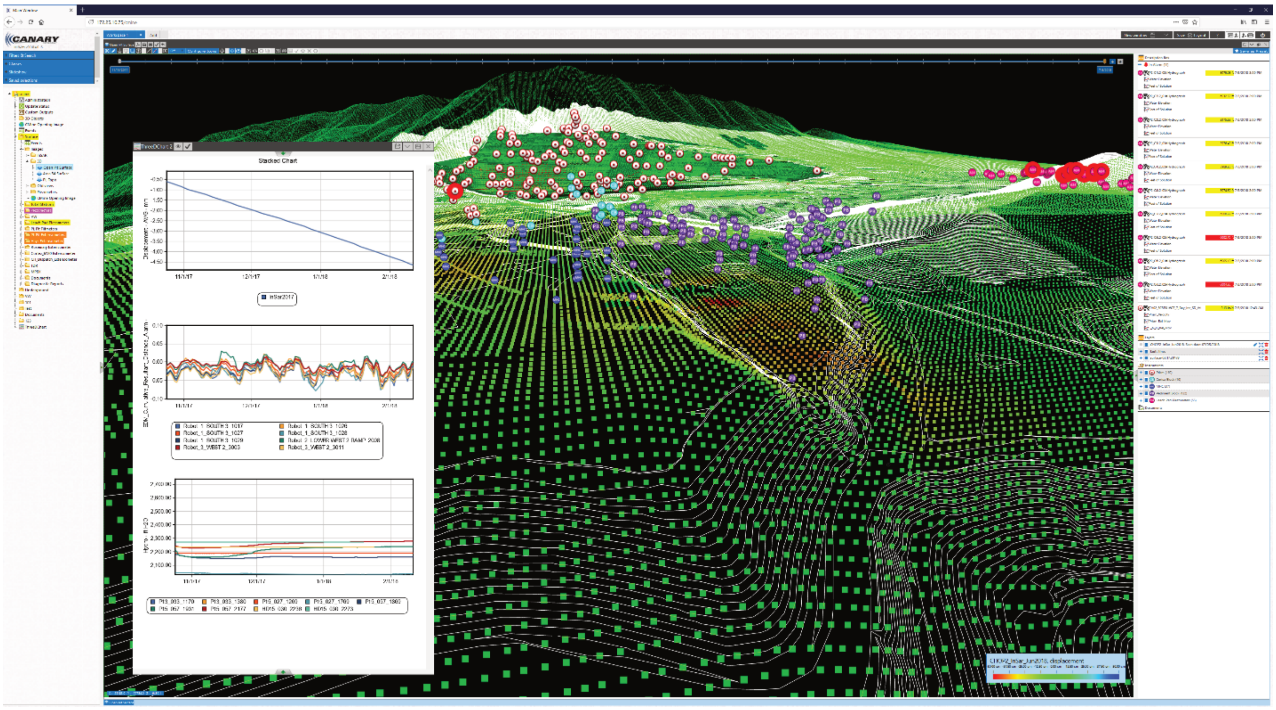

Figure 3 Example of a 3D visualisation showing inset time series results from data generated by satellite radar, remote total station (EDM), and vibrating wire piezometers (Source: Alex Neuwirt)

Another important benefit of system integration relates to the triggering and management of alarms. Having multiple systems each with their own alarm management system on separate computers is inefficient and possibly ineffective. The integration of all data types in a single location allows for the triggering and managing of alarms from a single point with embedded traceability. In this way, the overall process activating the TARP is streamlined.

An example of a site that adopted the concept of data integration for all its slope monitoring sensors is Debswana's Jwaneng diamond mine in Botswana. Table 3 provides a summary of the variety of slope monitoring sensors utilised at the operation and the associated number of software packages originally required to visualise and analyse the data prior to integration into a single data hub. In some cases, vendor software is maintained for more instrument-specific complex analysis, as the integrated system is sometimes not permitted to reproduce vendor intellectual property.

Table 3 Example of the reduction of fragmented monitoring software following the deployment of an integrated monitoring system at Debswana's Jwaneng diamond mine

Sensors	Data acquisition	Before visualisation	After visualisation	Analysis
Ground-based radar	Vendor	Vendor	Integrating software	Vendor
3D laser	Vendor	Vendor		Vendor
Prisms	Vendor	Vendor		Integrating software
Continuous operating reference stations	Vendor	Vendor		
Precise levelling	Manual	Spreadsheet		
Tiltmeters	CSI data logger	Loggernet		
Inclinometers	CSI data logger	Loggernet		
Time domain reflectometry	CSI data logger	Loggernet		
Weather station	CSI data logger	Loggernet		
Piezometers	Specialty software	Spreadsheet		
	CSI data logger	Loggernet		
	Vendor	Loggernet		
Divers	Manual	Spreadsheet		
Dewatering boreholes	Manual	Spreadsheet		

5.3 Advantages and challenges

The development of numerous systems for monitoring geomechanics issues in mining has necessitated the development of methods for integrating these various data sources. From a general point of view, if the data can be integrated, then a more complete picture of the risks of mining can be understood. Advantages of this approach include:

- **Safe working environments:** Injuries to personnel or machinery are prohibitively expensive. Furthermore, in this age of large publicly traded mining companies, perception can be worth billions of dollars. If the public perceives a company to be operating without regard for the safety of its employees and infrastructure, the 'license to operate' will be impacted.

- **More predictable operating costs:** Operational risks may be identified prior to failure which will allow mitigation. The cost of failure has become so extreme that one significant failure could jeopardise an entire mining operation.
- **Improving monitoring return-on-investment (ROI):** Data integration provides the ability to compare disparate but related monitoring data to create or substantiate models of behaviour and risk. In other words, it is a classic example of 'the whole is greater than the sum of the parts'. Increasing ROI incentivises miners to invest more significantly in all monitoring technologies, which benefits the entire enterprise.
- **More efficient training:** Reducing the number of systems that operators must learn and use reduces the cost of training and increases the likelihood of them using the tools properly to maximise their risk management capabilities. Also, mine operators tend to move personnel among their various properties, so having a single integrated tool in use across an organisation means training investments are not lost when personnel are relocated.
- **Improving workplace attitudes:** Employees seeing the investment made by their employer to manage risk will respect their employer and often be more engaged and involved with operations. They will tend to better understand and appreciate the role they play in helping to manage the monitoring system and participate in the success of the system and the data it generates.
- **Improving stakeholder relations:** The investment marketplace can be punishing. Perceptions can cost miners millions, if not billions, of dollars. It can also delay approvals for new mines or mine expansions. Investment in technology that integrates performance monitoring data can demonstrate to stakeholders that the mine operators are managing their assets safely and as efficiently as possible.

There are numerous challenges associated with the development and management of integrated mine monitoring systems. An analogous scenario is the development of safety systems in mobile equipment, where for example, the number of safety systems in a car has increased over time through experience. Early automobiles did not have safety belts, crumple zones, safety glass, and airbags, among other features taken for granted in the modern world. Systems are continually added to automobiles to provide more protection for occupants. New safety systems do not replace old systems; they augment them. Likewise, in geotechnical applications, no single device provides complete risk management; rather, they are complementary in their ability to help manage risk.

Miners have always employed the observational method, using their eyes and ears to monitor their operations. The development of electronic technologies including instrumentation, hardware, and software, has led to automated methods to augment the miner's continued observational methods. The challenge is that–unlike the automotive industry where the manufacturer must integrate all of the safety technologies into one automobile–the mining industry is served by many industries. There are often multiple vendors for each type of monitoring product and technology being offered. All of these technologies are complementary to each other and even within the same type of technology, there are capabilities and limitations associated with each vendor's product or service. However, since they are all offered by different vendors, there is a decided lack of integration of the information produced by each type of risk management technology.

Vendors are also not incentivised to work together. On the contrary, they often use proprietary technology as leverage to discourage customers from working with other vendors. As a consequence, customers often remain bound to a single vendor. Ultimately, the limitations of mine monitoring system integration are analogous to the limitations of an automobile's safety system that is not integrated. If the electronic system designed to detect a collision is not connected to the air bags which protect the passengers in the event of a collision, then the benefit of the two systems working together will be lost.

Geographical or geo-referenced software systems (e.g. GIS) are becoming popular for collecting and managing the various types of information produced by different monitoring technologies. However, the residual challenge is integrating all of these systems into the same coordinate system. Base maps may be in one of several coordinate systems, including systems developed by the mine itself. Data from satellite and ground-based radars may associate with one coordinate system, mine drawings and plans may be in another system, and data from other sensors located on and below the ground surface may be referenced in another system altogether. Initial planning for an integrated system must include surveyors, mine planners, and all other stakeholders involved with organising information for the mine.

Automated systems work very well to create large quantities of data automatically, silently, and out of view. The challenge is that more data collection can make for more processing, analysing, and reporting work. In designing a mine monitoring system, thought must be given to the types of data to be collected and the minimum frequency of collection that can be reasonably processed and analysed. It may appear counter-intuitive but less is typically more in an automated system because more often means that the volume of data is unmanageable and hence, the value is lost.

Technology is intrinsically complicated, and complexity only increases with time. This means that personnel skills must be continually updated to reflect the increasing complexity of the systems. Mine personnel must learn basic electronics, instrumentation, communications, database systems, and software systems, not to mention acquiring the expertise required to properly process and analyse data. The competitive nature of the commodities markets also means having to continually do more with less. Technology has helped in some ways, but has also made other challenges more acute. It can become difficult for operators to make time to properly understand what the systems are doing and what the data indicates.

Finally, the economics of mining are highly cyclical and subject to forces that can be global, national, or local. Even when the industry is enjoying generous profits, budgets are often constrained by the need to operate more efficiently. It can be difficult to obtain approval for investing in risk management systems because the benefits to operations are often not well articulated or clearly understood. Integrating data does not directly produce a product, and ultimately resources within mining companies tend to be prioritised and focused on production. Once management understands how risk management technologies provide more stability to operations and helps mitigate expensive failures, budgets are not as challenged, even during economic downturns.

5.4 Importance of confirming data reliability

With the increasing volume of data generated by modern electronic slope monitoring systems and with an increasing variety of sensors, there is a growing need to combine and integrate these data types in efficient, effective, and innovative ways. It is important that geotechnical staff do not spend their time wading through piles of data, but instead focus on data interpretation, reliable results reporting, and addressing urgent actions as needed. A slope monitoring system must be capable of treating all data from different sensors in a collective unified way. For example, where multiple technologies and sensors are being used to measure vertical displacement data, all data from these sensors should be available in a single data hub for rapid compilation, data cross-validation, and analysis.

Users of monitoring data must be aware of the limitations and potential traps of comparing data from different sensors that have been put into service to answer different questions. However, with a good understanding of the limitations of each dataset, material value can be gained from an integrated approach to data analysis. An example of a potential trap is where ground-based radar measurements indicate movement on a highwall, but the corresponding prisms located on the same wall indicate little or no movement. This comparative observation is illustrated in Figure 4. What is actually happening in this case is that the radar is measuring ravelling of loose surface material, while the prism that is anchored a metre into the highwall is indicating that the overall mass is stable. For the complete picture of this scenario, both the radar and prism data need to be examined in unison. No single sensor can tell the complete story.

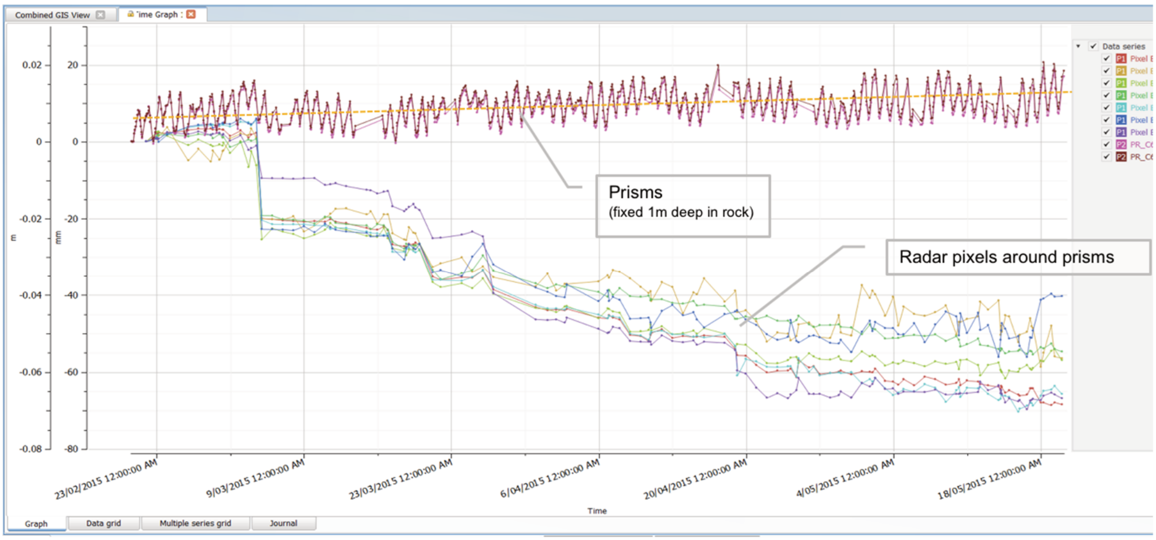

Figure 4 Comparison of prism and radar displacement, where results appear to generate conflicting information about real slope movement (Source: Sixense-Soldata)

5.5 Contribution to and from numerical models

Numerical models–capable of representing deformation behaviour and displacements as the model is cycled through mining sequences–are widely used to analyse slope stability. Pit slope monitoring data and observations are used to calibrate numerical models to the best representation of actual conditions possible, which yields higher confidence in predictive results. Instrumentation data and observed conditions that can be utilised for calibration include:

- Line-of-sight prism displacements.
- Vector data as derived from prisms, inclinometers, GNSS units, and field measurements (e.g. slickensides or striations).
- TDR (time domain reflectometry) or inclinometer shear points at depth.
- Crack development from slope deformation.
- Satellite radar images and data for spatial extents of deformation.
- Microseismic data.
- Collapse features.
- Pore pressure changes (in low permeability material).

The more that model behaviour can be matched to multiple points of actual observed behaviour and mechanisms, the higher the confidence will be in model calibration and data validation. History points that can track displacements, tilt, and pore pressure changes in the model should be fully utilised, placing them at the same locations in the model as the instruments are located in the pit slope. They should be set up to record the same information (e.g. horizontal displacement) as the instrumentation data being used for model calibration.

6 Early warning: detection and communication

6.1 Data utilisation and communication

A reliable monitoring system should record and identify incipient anomalous slope movement. Although the most obvious purpose of a monitoring system is safety related, slope deformation and performance monitoring also enhance the understanding of slope behaviour and assist in improving system design and implementation. In order for a monitoring system to be considered an effective early warning alarm, it needs to operate in real-time and should be linked to the mine's emergency communication system.

6.2 Alarming instabilities and failures

The purpose of alarming is to determine when indications from monitoring instrumentation could result in a failure that will pose a material risk to the operation. Failure of an excavated slope is defined when the rate of displacement is greater than the rate at which the failed mass can be mined safely and economically, or when movement produces unacceptable damage to a permanent facility (Zavodni 2001). Until a failure occurs, parts of a slope moving faster than the surrounding areas are often referred to as instabilities.

Alarms should be based on threshold values that exceed predetermined values and time periods. The determination of threshold values is improved from the application of relevant site-specific experience. Alarms are set so that the slope engineer, the workforce, and management are aware of slope performance issues and where the occurrence of false alarms are minimised.

Two broad approaches are typically utilised for improving the effectiveness of alarms. The first is to minimise information to the operator that is of no consequence; and the second is to improve the visibility of the alarm and ensure clear expectations for response to the most important or critical alarms. Most practitioners rely on movement data as the primary indicator of relative slope performance. Recognising excessive movement is the primary means of slope performance determination. In other words, an alarm is set to alert the slope engineer to a significant change in the movement trend.

6.3 Practical aspects of alarm management and response

A TARP defines the plans of predetermined responses for responsible individuals during the occurrence of an unwanted geotechnical event (the trigger). TARPs are usually tied to a mine site's geotechnical performance monitoring system. Monitoring inputs or triggers can vary significantly across a site and may include:

- Inspections and observations.
- Prism movement (velocity, slope distance, total vector distance).
- Rockfalls.
- Radar images indicating deformation and resulting radar alarms.
- Lack of data or lack of data collection (equipment down time).
- Bad weather (precipitation, high winds, reduced visibility, or rapid temperature changes).
- Surface or groundwater inflows.
- Increases in groundwater levels (piezometers).

Other monitoring inputs can include changes in geologic conditions with respect to design, seismic events, lack of surface drainage control, or operational issues (e.g. poor excavation practice, poor highwall blasting).

6.4 Trigger action response plan processes

When an alarm trigger occurs, the response of the workforce and implementation of the plan depends on employee 'buy-in' of the TARP and a belief that following the TARP will keep people safe. When writing a TARP, assignment of, and input from, responsible persons (RP) are required to ensure a successful TARP is executed. The process of involving RPs should be used for other critical mining documents such as the ground control management plan and the emergency preparedness and response plan.

Ownership of the TARP by the workforce and those supervising the workforce is paramount. Four key elements that are vital to the TARP process include:

- Communication of the TARP status (designed to ensure RPs act in accordance with the TARP).
- Coordination (where mine management, safety personnel, and their consultants often assist in assessing hazard exposure and development of mitigation plans); input from the site's geotechnical engineer is essential to ensure safety during incidents or events.
- Signoff of and training on TARP procedures should be regularly reviewed, updated, tracked (including record keeping).
- Personnel requirements (where consideration must be given to the level of experience, oversight, and availability of the RPs).

6.5 Effect of instrument limitations on trigger action response plans

For TARPs to be effective, the capabilities and limits of instrumentation used to determine alert levels must be considered. Since most TARPs utilise slope movement as the primary alarming criteria, the ability of instruments to measure movement should be accurate and precise enough to satisfy the alarming objectives of providing ample warning for operators to properly react to incipient slope movement. Importantly, however, the relationship between the slope distance measured by the instrument relative to total vector movement of the target needs to be clearly understood by the slope engineer.

Analysis of monitoring data should consider instrument limitations such that misinterpretation and/or a misunderstanding of information are avoided. This includes the time between reading limitations (scan times for radar and laser scanners) when using velocity as the primary alarm. Typically, misinterpretation of the data and lack of understanding of instrumentation limitations result in poor decisions being made including false alarms or, more importantly, lack of action calling for access restrictions or evacuations when needed.

As mining companies increasingly employ slope monitoring systems using radar and laser scanners, diligence with respect to observing details of the dynamics of the slope and reacting to the failure mechanism can be compromised. Because radar covers the entire slope, operators and practitioners are lulled into a false sense of security as long as the radar does not generate any alarms. Two potential traps which often occur together are:

1. Line-of-sight movement measured by radar and laser scanners may not represent the full component of the actual movement which potentially leads to the setup of thresholds that are too high (often done for minimising false alarms). This can lead to a false sense of comfort or safety with respect to the stability of the slope being monitored.
2. Coherence is a correlation measurement based on the range and amplitude between the current scan and the preceding scan. Practitioners must understand the implications when the radar signal is out of coherence or coherence is low. It may indicate that the slope being monitored is moving faster than the ability of the radar to measure the actual slope movement along the line-of-sight.

While radar and laser scanners are effective for slope monitoring, they cannot be the only tools used to manage geotechnical risk in an open pit. Without a carefully considered strategy for the application of alarms for monitoring instruments, some operations may be left exposed without appropriate documentation, processes, or adequately trained site personnel. Such a strategy should include reinforcement of line-of-sight measurements with remote total stations and/or GPS/GNSS to validate monitoring data.

Any deficiencies in training and/or documentation relating to alarm threshold justification should be recognised as significant business risks for any operation wishing to implement what should be seen as industry leading practice. Determining appropriate alarm thresholds is a key component of a site's geotechnical risk management strategy with regard to slope stability monitoring.

A thorough understanding of inherent geotechnical risk relating to a mine design is required when setting up a slope monitoring program. Additionally, the risk must be continually evaluated in the event that an unwanted geotechnical incident escalates. A process must be in place to communicate increasing risk to the appropriate level in the organisation at the right time, which is a fundamental objective of a TARP.

6.6 Processing and presentation of data

An important role of the slope engineer includes the routine interpretation of movement trends. Trends are used to demonstrate how closely, or not, observed conditions align with predicted behaviour of excavated slopes. Timely data processing should enable the slope engineer to make rapid reliable assessments of information sufficient to protect people and assets. Ideally, data should be presented in a verifiable context of potential triggers that explain trend changes resulting from events such as:

- Strong storm and rapid snow/ice melting.
- Blasting and mining activity.
- Changes in geology encountered during excavation such as lithology, alteration, and faults.
- Changes in groundwater or surface water conditions resulting from installed drains, pumping of nearby wells, or changes in the surface water diversion system.

Automating the integration of databases from various performance monitoring instruments makes putting data in context much simpler and far faster than manually manipulating spreadsheets. The slope engineer is encouraged to contract with relevant service providers that specialise in the development of automated data integration systems.

6.7 Considerations for the future

Innovation applied to the development of new instrumentation and remote monitoring, investigation, and problem solving will be driven by mine operators who seek to automate their operations and remove people from potentially hazardous conditions. Motivation for increasing automation of mining operations is driven by safety performance, economy (budgets and staffing), and risk management.

As mining operations evolve towards increasing automation, it is anticipated that geotechnical performance monitoring systems will also become increasingly automated. Data management, interpretation, and results reporting from instrumentation will also become increasingly automated. A primary goal of such a performance monitoring system will be to manage critical procedural controls in real-time that will maximise geomechanics risk management in the automated mining environment. Promising innovative geotechnical monitoring methods under development at the time of writing include:

- Utilisation of microsensors (nanosensors) for mine environmental and deformation monitoring.
- Imaging spectroscopy using remote mapping methods.
- Autonomous mapping, inspection, and analysis using fully autonomous unmanned aerial vehicles (UAV).
- Virtual reality for open pit visualisation, inspection, and monitoring.

Methods such as these will advance improvements in data storage/management and interpretation. It is noteworthy that the current priority for developing some of these innovative visualisation and monitoring tools is for underground mining applications. In time, however, the capability of such instrumentation will evolve towards open pit applications, driven by mine safety, to overcome access restrictions and to improve on existing methods for advancing geotechnical risk management.

7 Conclusion

Performance monitoring of open pit slopes is essential for ensuring safe and economic open pit development and is a critical part of a mine operation's geotechnical risk management program. This includes the importance of assessing site-specific needs required to design, implement, and maintain the slope monitoring system, to produce and manage reliable data, and to report and act confidently on results in real-time. Emphasis is also placed on the human resources required to manage the monitoring system, including the appropriate skill sets and continuing training requirements. It is important to understand monitoring program design requirements, including the essential capabilities and limitations of instrumentation that comprise the monitoring system. Opportunities for improvement are evident from continuing advances made in instrument capability, data communications, speed, and integration of data that come from improvements in computing, and the ability to acquire data using remote methods required by the mine operators.

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At the time of writing, CSIRO Publishing reported that 'Guidelines for Slope Performance Monitoring' is in press with an estimated release of June 2020. Since significant content of this paper is adapted from the guidelines manuscript, it has been requested that this paper should not be circulated outside of the conference, e.g. social media, until after the book's release.

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