

# Monitoring systems for warning impending failures in slopes and open pit mines

Ashkan Vaziri · Larry Moore · Hosam Ali

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**Abstract** Slope stability is a critical safety and production issue for mining. Major wall failure can occur seemingly without any visual warning, causing loss of lives, damage to equipment, and disruption to the mining process. Monitoring systems, ranging from simple piezometers and extensometers to highly sophisticated radars and global navigation satellite systems, are employed to predict impending instabilities and failure. Here, we provide a review of the available monitoring systems used in slope management and highlight their major advantages and shortcomings. We propose a simple method for evaluating the effectiveness and reliability of monitoring systems to warn of pending slope failures. The method is based on constructing monitoring reliability maps for the slope by evaluating two slope parameters: Expected deformation to failure and critical reading frequency, which depend on the slope characteristics (e.g., geology and design), service condition (e.g., rainfall, blast), and the economic impact of the failure. The reliability of a deformation monitoring system can be subsequently assessed by identifying three parameters of the system: Coverage area (large or discrete), Deformation monitoring precision, and Measurement frequency. The application of the method to most commonly used deformation monitoring systems is demonstrated. The advantages and implications of the proposed method are highlighted.

**Keywords** Mining · Slope stability · Deformation monitoring systems · Safety

## 1 Introduction

Small precursor movements of slopes can occur for an extended period ranging from weeks to months prior to instability (Hoek and Bray 1981). Monitoring systems have been used

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A. Vaziri · L. Moore · H. Ali  
FM Global, 1151 Boston-Providence Turnpike, Norwood, MA 02062, USA

A. Vaziri (✉)  
Department of Mechanical and Industrial Engineering, Northeastern University,  
Boston, MA 02115, USA  
e-mail: vaziri@coe.neu.edu

widely to monitor slope deformation and condition with the objective of predicting impending instabilities and minimizing the impact of slope failure. A detailed classification of the available slope monitoring systems is provided in Fig. 1. In this classification, four major categories are listed, depending on the parameters that are monitored by the system:

- Ground movement measurement techniques,
- Ground vibration measurement techniques,
- Groundwater measurement techniques, and
- Measurement techniques for the loads applied to supports and anchorages.

Monitoring of ground movement is the most common type of monitoring and the main focus of this study. The techniques for monitoring ground movement can be classified as Surface measurement techniques and Subsurface measurement techniques. Surface measurement techniques can be further classified to techniques that measure the displacements at discrete points (Crack width measurement techniques and Survey networks) and over large area of the slope (Scanning and Image-based techniques)—See Fig. 1. Survey networks are the most common Subsurface measurement technique in slope and open pit mines. This technique generally requires a system of local benchmarks that has to remain stable during the course of the investigation (Lang et al. 1994; Corominas et al.

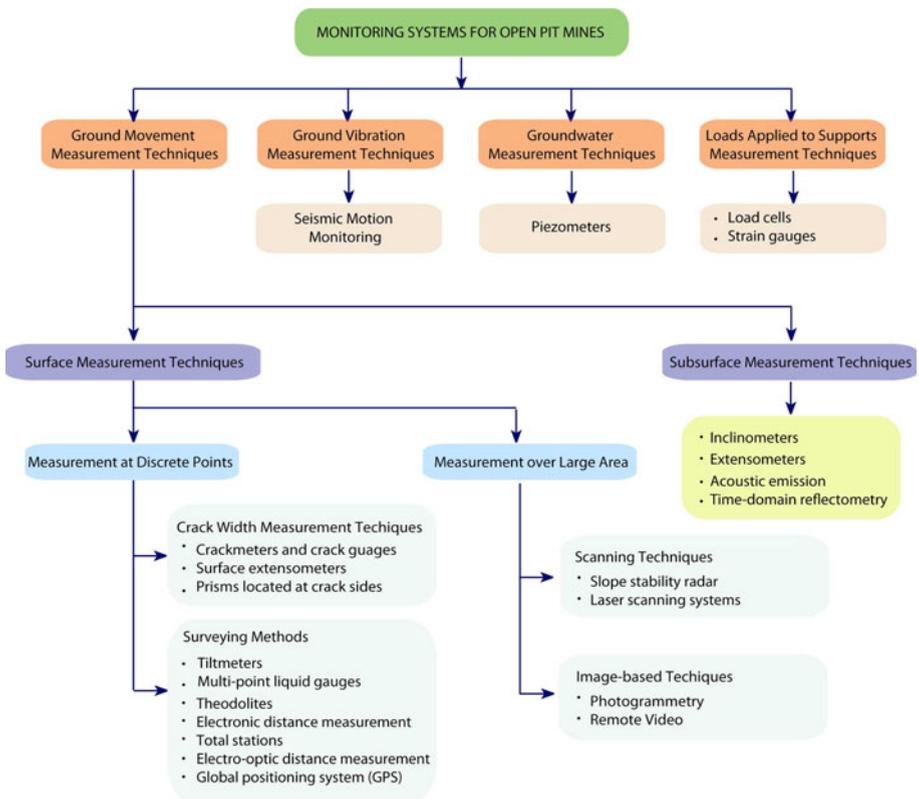


Fig. 1 Common slope monitoring systems

2000). In principle, survey techniques are limited by two main drawbacks. First, they all require access to the monitoring surface for installation and maintenance of instruments. Second, these techniques sample a few discrete points on a monitoring surface, thus, fail to provide spatial information required to assess the behavior of the whole mine wall (Lichti et al. 2000). Recent advancements in development of precise displacement measurement techniques have yielded robust and sophisticated devices for slope monitoring and mine management. An example is radar systems that progressively scan along the slope or pit wall taking measurements with a beam at each point. In these systems, data resolution is a function of the radar operation frequency and the radar distance from the target. The closer the radar is to the wall, the smaller the beam size (or pixel size) of the area being measured. In general, these systems are capable of continuous monitoring movement with high accuracy (0.1–0.2 mm) over medium to large areas in real time without the need for mounted reflectors or equipment on the slope. Furthermore, the measurement is minimally affected by rain, dust, or smoke (Reeves et al. 2001; McHugh et al. 2006; Hutchison and Widelski 2007). The most common devices and methods of Subsurface displacement measurement are inclinometers, extensometers, acoustic emission, and time-domain reflectometry. It is noteworthy that some of the techniques mentioned above, such as time-domain reflectometry, can be used for both surface and subsurface deformation measurements and are listed in Fig. 1 in view of their most common application.

Measurement of groundwater pressure, anchorage stresses, and seismic motion can provide valuable information for detecting impending failures and should be utilized when appropriate. Piezometers are often used for groundwater pressure monitoring. The most common types of piezometers are standpipe piezometers, vibrating wire piezometers, pneumatic piezometers, and multi-point piezometers. In mines located in seismically active areas, microseismic monitoring is used to detect zones of seismic activity, which can cause rockbursts and earthquakes, therefore triggering slope failure.

According to Call and Savely (Call and Savely 1990), the most important purpose of a slope monitoring program is to:

1. Maintain safe operational practices,
2. Provide advance notice of instability, so action can be taken to minimize the impact of slope displacement, and
3. Provide additional geotechnical information regarding slope behavior.

The selection of a monitoring system should be carried out in view of its reliability and capabilities, as well as the importance of the slope and its failure impact. This requires thorough understanding of displacement patterns that result from generally occurring mechanisms of failure (Lang et al. 1993; Pothitos and Li 2007; Pothitos et al. 2006; Wilkins et al. 2003). Environmental conditions (e.g., local onshore wind, high temperature variation, rainfall, insolation and tidal conditions, storm frequency and seismic regions) should be also rigorously considered when selecting systems for slope monitoring to ensure their reliability for warning of impending failures.

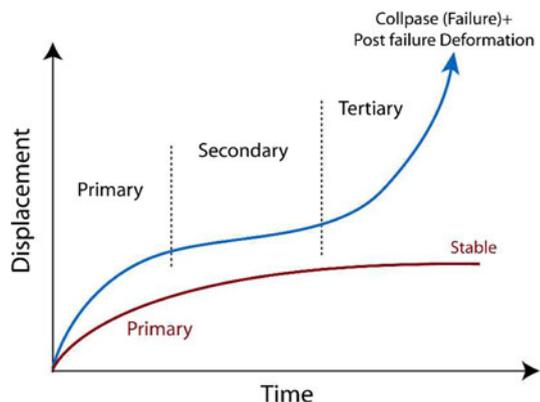
In this work, we will develop an objective method for evaluating the reliability of the deformation monitoring systems used in mines and slope management. Section 2 provides a brief review of the slope displacement patterns and common failure mechanisms. The key parameters that determine the accuracy and reliability of slope displacement monitoring systems are discussed in Sect. 3. In Sect. 4, a reliability map for slope monitoring systems is proposed in view of the key factors discussed in Sect. 3. Section 5 provides a conclusive summary of the findings of this study.

## 2 Slope displacement patterns and failure

The movements that occur prior to collapse can result from multiple phenomena including elasto-plastic deformation, softening and failure of the rock mass (Sullivan 2007). Zavodni and Broadbent (1978) showed that almost all large-scale failures occur gradually, with the exception of slides initiated by earthquake. Serious slope instabilities are usually accompanied by the gradual development of tension cracks behind the slope crest and measurable displacements. Figure 2 shows typical slope displacement histories resulting from creep as proposed by Fell et al. (2000). The creep response of the slope is differentiated into Primary (with decreasing strain rate), Secondary (with constant strain rate), and Tertiary (with increasing strain rate). Tertiary creep is generally followed by failure and collapse of the slope. During primary creep, the strain rate usually decreases as a power law of the time. The strain rate during secondary creep is nearly constant and strongly depends on the applied stress (Amitrano and Helmstetter 2006). Varnes (1982) showed that the secondary creep generally occurs for a short period, as in this stage both primary and tertiary creep mechanisms may occur concurrently. In fact, in some cases, a crossover between decaying primary creep and accelerating tertiary creep is observed with no clear secondary creep regime (Hamiel et al. 2004). Field measurements indicate that the final phase of failure in slopes is characterized by a hyperbolic function in the velocity–time space. Petley (2004) suggested that this behavior mirrors the nonlinear final stage of creep experienced in brittle failure. If the rate of movement decreases, the slope may have temporarily stabilized as shown in Fig. 2 by the red curve.

The three most common slope failure modes are circular failure, toppling and planar and wedge failures (Lang et al. 1993; Forward 2002; Hoek 1973; Sjöberg 1999, 2001; Turner and Schuster 1996; Dunicliff 1995; Angeli et al. 2000; Mercer 2006). Each of the failure modes has certain features, which include the direction in which considerable movements occur. Circular failure generally occurs in soil, weathered and soft rock, highly fractured rock and waste dumps. The initial step of instability is usually the opening of tension cracks along the crest of the slope, followed by slumping of the crest and lateral movement of the toe. The final failure generally happens rapidly. The failed section size can range from a few meters in height to several kilometers across. Initial large vertical displacements and small horizontal displacements, which increase with progression of the failure, are the common features of circular failures. Toppling is common in rocks with well-defined bedding planes or joints that are extended into the slope. The horizontal

**Fig. 2** Creep behavior of moving slopes (Fell et al. 2000)



movement associated with this failure mode opens up tension cracks along the crest, while the movement at the slope toe is generally negligible. Small initial vertical displacements and large horizontal displacements are the general characteristics of toppling failure. Turner and Schuster (1996) suggested that this failure mode can be further categorized into flexural toppling, block toppling, and block flexural toppling. Planar and Wedge failures are common in hard rock slopes with continuous bedding or joint planes dipping out of the slope. Since failure generally takes place on a distinct plane, the failed block will move parallel to this plane and failure is often sudden with little warning. The pattern of failure may comprise of a single discontinuity plane, two planes that intersect each other (wedge failure) or a combination of multiple discontinuities that are linked together to form more complex patterns such as slab failure and step path failure (Sjöberg 1999).

In addition to the common failure modes discussed above, undercutting or raveling of steep rock faces may also occur in slopes due to toe erosion, particularly if the slope is made of low-durability rock (Dunncliff 1995). Combined failure modes can also occur in weathered materials where the shear strength of the material may be sufficiently low to allow preferential failure through the material, rather than only along discontinuities (Lang et al. 1993). Combination of toppling failure at the toe of the failure zone, with circular or planar sliding failure in the upper part of the failure, has also been recorded. More detailed descriptions of the slope failure modes and mechanisms, their dependence on the rock characteristics and also common stages of each failure mode are provided by Sjöberg (2001).

Most of the displacement monitoring sensors can be hooked to a warning device. In such cases, the warning is activated when a prescribed amount of displacement, displacement rate, or acceleration occurs. The difficulty in this procedure is determining the thresholds, since the critical value corresponding to onset of the failure varies widely from one mine to another (Angeli et al. 2000; Mercer 2006). This means that an alarm criterion used at one mine may not be applicable for other mines. In most practical cases, the threshold velocities used for the warning device represent rates that Mine Engineering and Operations are comfortable with based on past experience. The current mining conditions and the impact and importance of a particular wall to continue mine production are also considered when deciding critical movement rates and monitoring plans. For example, security of haul road access is a prime operating safety and production requirement for many mines, and thus, the thresholds for walls associated with a haul road should be chosen with extra caution.

### 3 Key parameters for reliability of displacement monitoring systems

Three key parameters of displacement monitoring systems are identified which should be considered in assessments of the reliability of monitoring systems to warn of pending slope failures. These parameters are:

- Monitoring area (over large area or discrete points),
- Frequency of reading, and
- Device precision.

Each parameter is briefly described below.

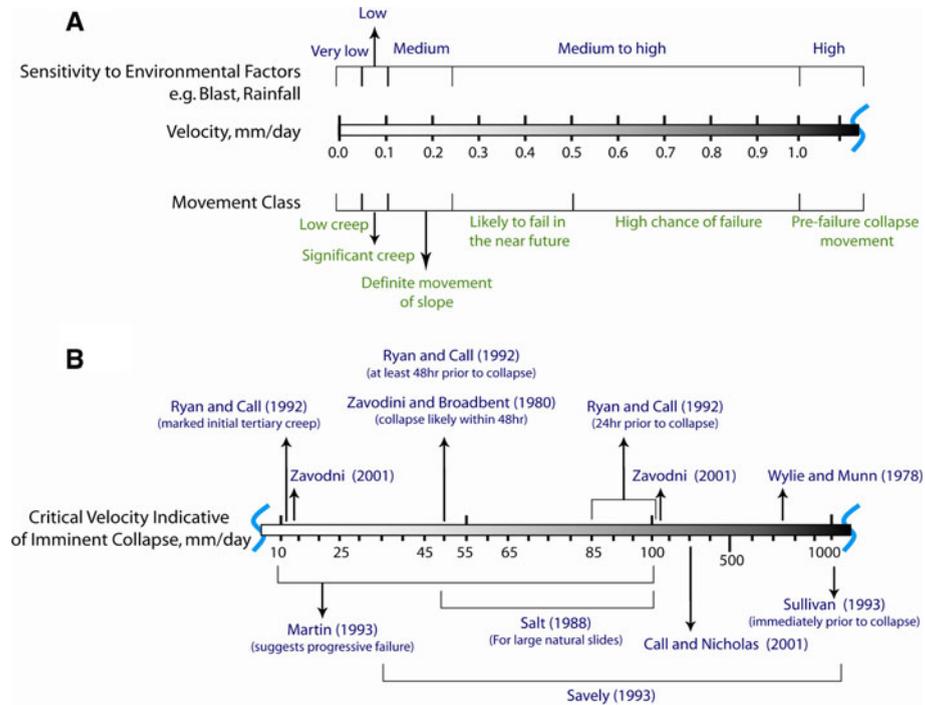
**Monitoring area:** The systems that monitor the deformation over a large area yield more useful information compared to systems designed for monitoring only at selected points, since these systems provide valuable data about the deformation pattern of the slope.

Moreover, since the deformation is monitored over a large area of the slope rather than discrete points, selected based on predefined deformation patterns and failure modes, the output of the monitoring process is less sensitive to the design uncertainties compared to discrete point measurement techniques. Monitoring the slope at discrete points is specifically problematic if new areas of instability develop that were not previously identified and, therefore, are not being surveyed. As shown in Fig. 1, Surface measurement techniques can be employed for monitoring the displacement at discrete points or over large areas of slopes. The available Subsurface measurement techniques generally monitor discrete and limited points of the slope.

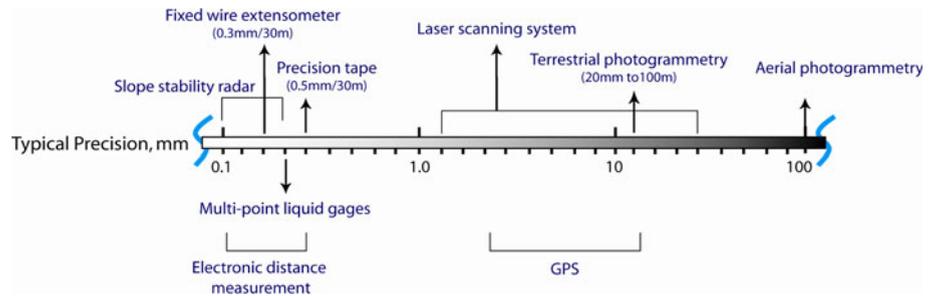
**Frequency of reading:** Systems that monitor the deformation at periods in the order of few minutes or shorter (quasi-continuously for this application) can provide a much better assessment of the slope behavior and are recommended for slope deformation monitoring. When monitoring is not continuous, it is suggested here that the maximum duration between each reading should not exceed 24 h (1 day), except for cases where the engineering analysis indicates that a longer reading period is adequate. In general, the monitoring should be performed at shorter periods when unexpected deformation patterns or high deformation rates are detected.

**Device precision:** Remedial treatment is usually effective only if carried out in the earliest stages of instability. Thus, the monitoring instruments must be sufficiently sensitive to detect movements of considerably smaller magnitude than those associated with complete collapse. Slopes have considerable variations in geology, geometry, life spans, geotechnical challenges, and service conditions. Therefore, it is difficult to be prescriptive about the required level of precision for monitoring without development of a thorough understanding of the mechanics of slope deformation and slope failure modes. Figure 3a shows the typical correlation between the velocity and the expected deformation mechanism (e.g., low creep) and failure. The figure also shows the relationship between the velocity of slope movement and sensitivity of the slope behavior to environmental factors. Figure 3b shows the critical velocity, which correspond to a wide range of slope behavior (Ryan and Call 1992; Zavodni 2001; Zavodni and Broadbent 1980; Martin 1993; Salt 1988; Call 2001; Savely 1993; Sullivan 1993; Wylie and Munn 1978)—from the onset of initial tertiary creep to the critical velocity prior to collapse. For slopes with a predictable regressive failure displacement history, safe mining might be continued up to a velocity of 300 mm/day. However, a displacement rate of 50 mm/day in slopes is generally an indication of impending failure that could occur anytime within 48 h (Zavodni 2001).

For the selection of deformation monitoring equipment, Lang et al. (1993) suggested a precision of 0.1–0.5 mm and 1–2 mm when the expected range of wall movement prior to failure is 10–100 mm and 100–500 mm, respectively. Here, we suggest that the precision of the monitoring device should be at least  $1/50$  of the predicted deformation up to failure,  $\Delta$ . However, a deformation monitoring precision less than  $\Delta/200$  can provide a more precise estimate of the deformation response of the slope and is desirable. The deformation response of the slope is a function of the rock mass, the structural geology, and the slope geometry, as well as the environmental and service conditions. For the current purpose,  $\Delta$  should be provided by the slope design and mine engineers. The typical precision of common slope displacement monitoring system is provided by Gili et al. (2000) and Krauter (1988) and is summarized and expanded here in Fig. 4. It should be emphasized that these limits (i.e.,  $\Delta/50$  and  $\Delta/200$ ) are based on the authors' opinion and cannot be confirmed scientifically except by comparison with limited number of studies. Note that in Lang et al. (1993), the minimum required device precision for monitoring system is  $\Delta/20$  and  $\Delta/50$  for the expected range of wall movement of 10–100 and 100–500 mm,



**Fig. 3** a Correlation between velocity of slope movement and movement classification and sensitivity to environmental factors. The figure is generated based on the data from (Sullivan 2007). b Critical velocity indicative of imminent collapse (This set of data does not distinguish between slope geological characteristics and slope design specifications)



**Fig. 4** Typical precision of various Surface measurement techniques

respectively. For example, the suggested precision is 1–2 mm for the expected range of wall movement of 100–500 mm. The minimum required precision is 2 mm when the expected range of wall movement is 100 mm, which is equivalent to having the device precision of  $\Delta/50$ . It is conceivable that a device precision of  $\Delta/20$  is inadequate, specifically for devices that monitor discrete points on the surface or have long reading period (e.g., several hours). Thus, we suggest a minimum monitoring device precision of  $\Delta/50$ .

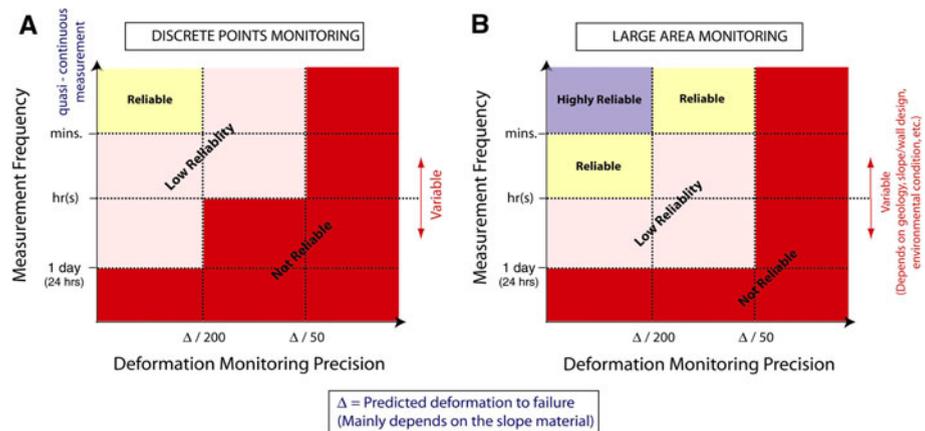
The  $\Delta/200$  limit can be found by considering the upper bound of the suggested limits. The suggested precision is 1–2 mm for the expected range of wall movement of 100–500 mm. Considering the upper bound of these limits gives device precision of  $2/500$  or equivalently  $\Delta/250$ . On the other hand, the suggested precision is 0.1–0.5 mm for the wall movement of 10–100 mm, and considering the upper bound of these limits yields device precision of  $\Delta/200$ . These two device precision limits are very close and can be considered identical for practical applications due to the uncertainties associated with estimating  $\Delta$ .

In addition to the parameters discussed above, the ideal monitoring system should be free of operator bias, independent of weather conditions, and operable at night. Automated equipment is generally more accurate than manual equipment since ‘human error’ factors are eliminated. Automated systems also provide added flexibility in the sampling rate and, therefore, can monitor more frequently than manual readings. For manual equipment, geotechnical specialists can interpret the pattern and history of movement to improve prediction of the failure process and to advise appropriate and timely stabilization or safety management actions. Using manual equipment is generally labor-intensive, particularly if a large area is surveyed with large numbers of prisms (Newcomen et al. 2003). In addition, using a manual system may require substantial time to process the data, resulting in delays of up to a few days before slope movement trends can be determined, leading to substantial degradation in the reliability of the system. Another distinct advantage of automated systems is their ability to trigger alarms if certain threshold limits are reached. However, these systems are generally more expensive than manual systems.

It should be noted that, in this work, we did not consider the aspects associated with the reliability of the instrument itself (e.g., failure of the system during operation).

#### 4 Reliability map of displacement monitoring systems

Based on the three parameters discussed in Sect. 3, the reliability maps for slope deformation monitoring systems shown in Fig. 5 are proposed. If the system monitors the

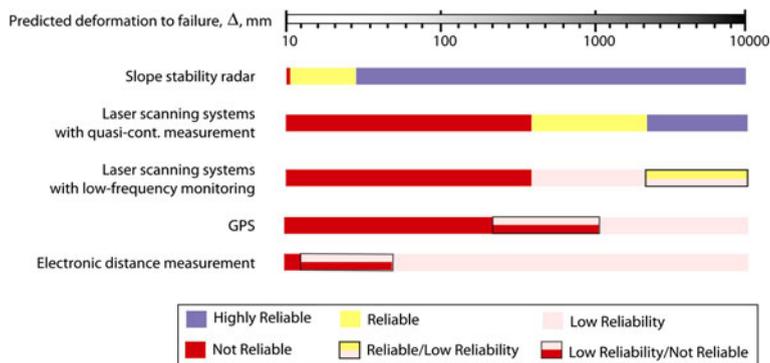


**Fig. 5** Reliability map of deformation monitoring systems. Plot **a** corresponds to systems that monitor the deformation at predefined discrete points. Plot **b** corresponds to Surface deformation measurement techniques that monitor the deformation over a large area—See Fig. 1

deformation at selected points of the slope surface, plot (A) should be used for evaluation of the system reliability. For systems that monitor the deformation over a large area, plot (B) should be used. The terms used for demonstrating the system reliability (e.g., *Not Reliable*, *Highly Reliable*) denote the qualitative capability of the monitoring system for predicting impending failures. Here, monitoring systems with a reading period longer than 1 day or precision less than 1/50 of the predicted deformation to failure are considered *Not Reliable* and should be excluded when selecting the monitoring system.

The reading frequency denoted by  $hr(s)$  in Fig. 5 is critical for evaluating the reliability and selection of monitoring systems for slopes. The value of this *critical reading frequency* should be estimated for each slope and wall of the mine by considering the timescale associated with failure and considering the geology, design, environmental conditions, and the economic impact of the failure. In general, monitoring should be performed at higher frequencies (i.e., shorter periods) if there are design uncertainties, existence of frequent rainfalls, snowfalls, high-speed winds, and harsh service condition (e.g., frequent blasting), as well as for walls with higher economic impact and importance to continue mine production. In such cases, the critical value of the reading frequency should be shifted upwards in Fig. 5. Existence of complementary measurement devices (e.g., ground water pressure monitoring) justifies having lower reading frequencies and shifting this value downwards.

Figure 6 shows the typical reliability of various common monitoring systems evaluated based on the proposed reliability maps for slopes with a wide range of predicted deformation to failure,  $\Delta$ . In the development of this figure, the typical precision of each device (from Fig. 4) was used. As an example, Slope stability radar systems (e.g., Ground Probe series) are mainly used to monitor surface displacements of slopes and walls over large areas. In most cases, the scanning speed is high and the slope monitoring can be considered quasi-continuous. The typical precision of these devices is in the range of 0.1–0.4 mm, which is much smaller than the predicted failure deformation for most slopes. Therefore, these systems are ‘*Highly Reliable*’ for most mine walls and slopes. Exceptions are cases where the predicted deformation failure is very small (<55 mm), which is not common.



**Fig. 6** Reliability of various monitoring systems. The reliability of monitoring systems in the regions denoted by ‘*Reliable/Low Reliability*’ and ‘*Low Reliability/Not Reliable*’ depends on the system frequency of reading and the critical reading frequency denoted by  $hr(s)$  in Fig. 5. If the measurement frequency is lower than the critical value, then the lower level of reliability should be selected (e.g., in the case of ‘*Reliable/Low Reliability*’, ‘*Low Reliability*’ should be selected.)

## 5 Conclusions

A relatively simple method for evaluating the reliability of slope monitoring systems is proposed, which can help in selecting effective systems for slope and mine management. The method is based on constructing monitoring system reliability maps for the slope and entails evaluating two key parameters of the slope:

- Expected displacement to failure, and
- Critical reading frequency.

These parameters depend on the geology, design, environmental and service conditions of the slope, as well as the economic impact of the slope failure. The developed map for a slope can be used to evaluate the reliability and selection of slope monitoring systems by considering:

- Coverage area of the monitoring system (discrete points or large area),
- Monitoring system reading (measurement) frequency, and
- Deformation monitoring system precision.

In general, systems that monitor the surface deformation over a large area of the slope at high frequency and are able to detect displacements much smaller than the expected displacement to failure are considered to be *Highly Reliable*. This statement assumes that the intrinsic reliability of the system to perform its intended function is verified through other means.

Once a monitoring program is adopted based on the analysis of slope and reliability consideration, the monitored displacement patterns should be continuously compared to the design displacement field. Variations between the design and actual displacement field are indication of unexpected behavior or incorrect modeling assumptions. This is particularly important for mine walls with very long service time, since significant changes in the geological and service condition of the slope could occur during the service life. For example, a weathered low-strength rock mass would be expected to behave in a more plastic or ductile manner than a fresh high-strength rock mass. Such geological change that may occur in mine walls during their service life and the associated changes in the deformation pattern manifest themselves in the measured information obtained from the monitoring system.

In general, a considerable margin of uncertainty exists in estimating the strength of the rock mass and its variation by time and environmental condition, hidden geological and hydrological details and seismic and operational loading (e.g., blast). Therefore, it is recommended to exploit several different monitoring methods together to facilitate the interpretation of instrument records and enhance the accuracy of the monitoring system (Girard and McHugh 2000). It is also recommended to incorporate some level of redundancy in the monitoring system by using multiple systems to cross-check instrument performance and eliminate errors. Redundant or overlapping measurements will also provide a backup in the case of instrument failure.

It is noteworthy that implantation of monitoring systems in conditions which limit the possibilities for contingency action or where contingency action cannot be implemented sufficiently fast does not provide any advantage for loss prevention. Thus, when designing the monitoring system, equal attention should be devoted to the development of such contingency actions.

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## References

- Amitrano D, Helmstetter A (2006) Brittle creep, damage, and time to failure in rocks. *J Geophys Res* 111:B11201
- Angeli MG, Pasuto A, Silvano S (2000) A critical review of landslide monitoring experiences. *Eng Geol* 55:133–147
- Call RD (2001) Nicholas, Monitoring and slope management, unpublished
- Call RD, Savely JP (1990) *Open pit rock mechanics, surface mining*, 2nd edn. Society for Mining, Metallurgy and Exploration, Inc, pp 860–882
- Corominas J, Moya J, Lloret A, Gili JA, Angeli MG, Pasuto A, Silvano S (2000) Measurement of landslide displacements using a wire extensometer. *Eng Geol* 55:149–166
- Dunnicliff J (1995) Monitoring and instrumentation of landslides. In: Bell DH (eds) *Proceedings of the sixth international symposium on landslides*, Christchurch. Balkema, Rotterdam, pp 1881–1896
- Fell R, Hunger O, Leroueil S, Reimer W (2000) Geotechnical engineering of the stability of natural slopes, and cuts and fills in soil. In: *Proceedings of conference geological engineering*, Melbourne, Australia
- Forward TA (2002) *Quasi-continuous GPS steep slope monitoring: a multi-antenna array approach*. PhD Thesis, Western Australian School of Mines, Department of Spatial Sciences
- Gili JA, Corominas J, Rius J (2000) Using global positioning system techniques in landslide monitoring. *Eng Geol* 55:167–192
- Girard JM, McHugh E (2000) Detecting problems with mine slope stability. In: *31st Annual Institute on Mining Health, Safety, and Research*, Roanoke, VA, Also NIOSHTIC Report-No. 10006193
- Hamiel Y, Liu Y, Lyakhovsky V, Ben-Zion Y, Lockner D (2004) A viscoelastic damage model with applications to stable and unstable fracturing. *Geophysical J Int* 159:1155–1165
- Hoek E (1973) Method for the rapid assessment of the stability of three-dimensional rock slopes. *Quart J Eng Geol* 6:243–255
- Hoek E, Bray JW (1981) *Rock slope engineering*. The Institute of Mining and Metallurgy, London
- Hutchison BJ, Widelski M (2007) Rockfall management at the Savage River Mine. In: *Slope Stability, Proceedings of 2007 international symposium on rock slope stability in open pit mining and civil engineering*, Perth, Australia, pp 379–392
- Krauter E (1988) Applicability and usefulness of field measurements on unstable slopes. In: *Proceedings of the 5th international symposium on landslides*, Lausanne, pp 367–373
- Lang AM, Swindells CF, Higham GJ (1993) Survey based open pit wall monitoring—Experience based realitie. *Geotechnical instrumentation and monitoring in open pit and underground mining*, pp 303–309
- Lang AM, Swindells CF, Higham GJ (1994) The realities of survey based open pit wall monitoring. *Aust Mining* 86:24–25
- Lichti DD, Stewart M, Tsakiri M (2000) High density spatial data collection for monitoring of steep wall movements. In: *Proceedings of the ninth international symposium on mine planning and equipment selection*, pp 327–331
- Martin DC (1993) *Time dependant deformation of rock slopes*. PhD Thesis, University of London
- McHugh EL, Long DG, Sabine C (2006) *Applications of ground-based radar to mine slope monitoring*. NIOSH Publication, No. 2006-116
- Mercer KG (2006) *Investigation into the time dependent deformation behaviour and failure mechanisms of unsupported rock slopes based on the interpretation of observed deformation behaviour*. Doctoral thesis, University of Witwatersrand, Johannesburg
- Newcomen HW, Murray C, Shwydiuk L (2003) *Monitoring pit wall deformations in real time at Highland Valley Copper*, pp 1–15 (available online)
- Petley DN (2004) The evolution of slope failures: mechanisms of rupture propagation. *Nat Hazards Earth Syst Sci* 4:147–152
- Pothitos F, Li T (2007) Slope design criteria for large open pits—case study. In: *Slope stability 2007, Proceedings of 2007 international symposium on rock slope stability in open pit mining and civil engineering*, Perth, Australia, pp 341–352
- Pothitos F, Webster S, Meagher L, Li T (2006) *Cadia extended pit instability monitoring and management*. In: *Proceedings of 2nd international seminar on strategic versus tactical approaches in mining*, Perth, Australia

- Reeves B, Noon DA, Stickley GF, Longstaff D (2001) Slope stability radar for monitoring mine walls. In: Proceedings of SPIE, pp 57–67
- Ryan TM, Call RD (1992) Application of rock mass monitoring for stability assessment of pit slope failure. In: Proceedings of 33rd US rock mechanics symposium, pp 221–229
- Salt G (1988) Landslide mobility and remedial measures. In: Bonnard (ed) Proceedings of fifth international symposium on landslides, vol 1, Balkema, Rotterdam, pp 757–762
- Savely JP (1993) Slope management strategies for successful mining. In: Innovative mine design for the 21st Century, pp 25–34
- Sjöberg J (1999) Analyses of large scale rock slope. PhD thesis, Division of Rock Mechanics, Luleå University of Technology, Sweden
- Sjöberg J (2001) Failure mechanisms for high slopes in hard rock. Slope stability in surface mining. In: SME Proceedings, Chap. 7, pp 71–80
- Sullivan TD (2007) Hydromechanical coupling and pit slope movements. In: Slope Stability 2007, Proceedings of 2007 international symposium on rock slope stability in open pit mining and civil engineering, September, Perth, Australia, pp 3–43
- Sullivan TD (1993) Understanding pit slope movements, geotechnical instrumentation and monitoring in open pit and underground mining. In: Szwedzick (ed) Proceedings of the conference on geotechnical instrumentation and monitoring in open pit and underground mining. Balkema, pp 435–445
- Turner AK, Schuster RL (1996) Landslides—investigation and mitigation, transportation research board. National research council, special report, vol 247. National Academy Press, Washington, DC, p 673
- Varnes DJ (1982) Time-deformation relations in creep to failure of earth materials. In: Proceedings of the seventh Southeast Asian geotechnical conference, Hong Kong, pp 107–130
- Wilkins R, Bastin G, Chrzanowski A (2003) ALERT: a fully automated system for monitoring pit wall displacements. In: Proceedings, 11th FIG symposium on deformation measurements, Santorini, Greece
- Wylie DC, Munn FJ (1978) The use of movement monitoring to minimize production losses due to pit slope failures. In: Proceedings of the first international symposium on stability of coal mining, Vancouver, Miller Freeman, pp 75–94
- Zavodni ZM (2001) Time-dependant movements of open-pit slopes. Slope stability in surface mining. In: SME Proceedings, Chap. 8, pp 81–87
- Zavodni ZM, Broadbent CD (1978) Slope failure kinematics. In: Proceedings of 19th US symposium on rock mechanics, vol 2, pp 86–94
- Zavodni ZM, Broadbent CD (1980) Slope failure kinematics. CIM Bull 99:69–74