

TECHNOLOGIES AND PRACTICES FOR REMOTELY MONITORING GROUND STABILITY IN U.S. UNDERGROUND METAL MINES

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ABSTRACT

Remotely operated or autonomous mining equipment addresses challenging mining conditions by removing workers from the mining face. A consequence, however, is the loss of human sensory data, which is important for hazard identification in mining. Therefore, the use of technologies to remotely collect and analyze geotechnical data to replace or augment human feedback will become increasingly important. In this study, a review of ground stability monitoring in underground metal mines in the U.S. was conducted to understand the current practices and barriers to implementing remote monitoring. The authors found ground control personnel preferred standalone monitoring tools, with networked instruments limited to special cases. Barriers to adopting newer ground-control technologies include: 1) understaffing, 2) limited awareness of existing tools, 3) justifying the investment in modern technology, 4) limited interoperability, and 5) inconsistent data management practices. A monitoring strategy that supports remote mining should address these barriers and could include: 1) remote imaging of the mining face, 2) ground support performance monitoring, and 3) seismic monitoring.

INTRODUCTION

As underground metal mines need to exploit deeper and more challenging resources, workers are increasingly exposed to ground instability and other environmental hazards. As a result, many mines are exploring the implementation of tele-remote and semi-autonomous mining equipment (e.g., Alexander et al. [1], Rosser [2], Mining Technology [3]), which can greatly reduce workers' exposures to hazards at the mining face. However, a complete or partial removal of underground mine workers from active mining areas will result in fewer opportunities for humans to directly identify ground control issues. Reducing these observations is a concern because miners themselves are an invaluable part of ground monitoring systems. Their reduction could result in miners' exposure to unidentified ground control risks when entering active mining areas to service or assist automated machinery. Additionally, if a piece of machinery were to become trapped by a fall of ground, recovery efforts could be complicated by an incomplete picture of the stability of the mine workings. Avoiding these scenarios will require modifications to current practices to facilitate effective remote monitoring.

Many technologies exist for the remote monitoring of various aspects of ground control in the underground environment (e.g., wireless data transmission schemes, ground deformation monitors, seismic monitoring systems, etc.). These technologies see varying levels of adoption based on their ease of use, cost, and applicability. However, these tools can be complex and difficult to integrate with other systems, discouraging their widespread use. Establishing a framework for a holistic ground stability informatics system (GSIS) is necessary to realize the potential for remote monitoring in underground mining. Informatics is "the study of the behavior and structure of any system that generates, stores, processes, and then presents information" [4]. A GSIS would have three major components, as illustrated in Figure 1:

1. the ability to integrate multiple types of geotechnical/ground stability and mining data;
2. tools for data analysis and interpretation, both for individual data types and holistic analyses; and
3. the ability to automatically monitor and alert users to changing ground conditions.

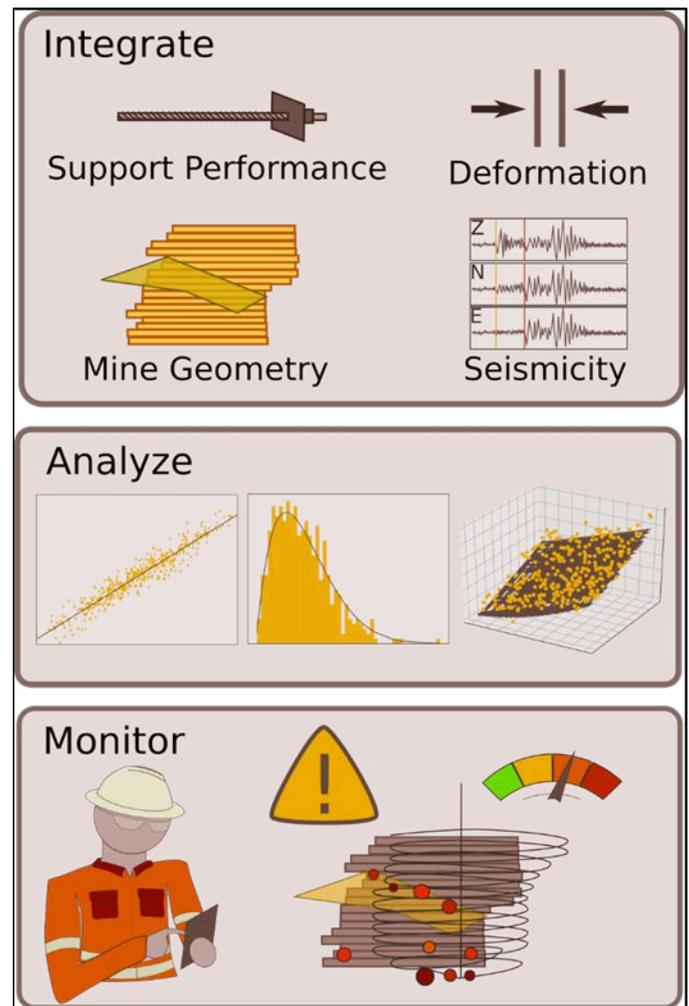


Figure 1. Diagram of the components of a GSIS.

The following sections describe ground support monitoring practices in the U.S. underground metal mining industry. More thorough reviews of geotechnical instrumentation can be found in Eberhardt and Stead [6], Dunclicliff [7], and Larson et al. [8]. Dawn [5] discusses instrumentation needed to monitor a block caving mine and provides explanations of different instrumentation and its advantages

and disadvantages. It is important to emphasize that ground stability challenges are not uniform between mines and depend heavily on local geology, depth of overburden, and mining method. Therefore, there is no single monitoring approach that will be adequate and cost-effective for all operations.

Table 1. Ground stability factors that are within mine operators' control. An example of such a system is described for block cave monitoring in Dawn [5]. This review examines the available monitoring technologies, current practices, and barriers to the adoption of modern remote monitoring solutions for U.S. underground metal mines. Information on these topics were gathered from three sources: 1) literature review, 2) informal conversations with ground control professionals, mine workers, and equipment vendors, and 3) the firsthand experiences of the authors of this paper. The paper also lays out important considerations and requirements for a pragmatic ground stability informatics system (GSIS) that will enable effective transitions to greater autonomy in underground mines.

Table 1. Ground stability factors that are within mine operators' control.

Factor	Related Ground Stability Concerns	Applicable Monitoring
Advance rates and excavation methods	<ul style="list-style-type: none"> Squeezing/creep Rockbursting 	<ul style="list-style-type: none"> Ground deformation monitoring Seismic monitoring
Ground support design and component selection	<ul style="list-style-type: none"> Squeezing/creep Rockbursting (damage mitigation) Sloughing Ground falls (rib, face, roof) 	<ul style="list-style-type: none"> Ground deformation monitoring Ground control performance monitoring Ground support quality control Rehabilitation/damage risk mapping
Ground support quality control	<ul style="list-style-type: none"> Support capacity 	<ul style="list-style-type: none"> Ground support installation monitoring
Ground control performance	<ul style="list-style-type: none"> Support performance Support degradation 	<ul style="list-style-type: none"> Ground support installation monitoring Rehabilitation/damage risk mapping

GEOTECHNICAL MONITORING TECHNOLOGIES

There are two categories of factors that affect the stability of underground excavations: 1) those that are within the mine's control (design and implementation) and 2) those that are not (rock mass and stress related). Tables 1 and 2 list these factors, the associated stability concerns, and applicable monitoring approaches.

Table 2. Ground stability factors that are beyond mine operators' control.

Factor	Related Ground Stability Concerns	Applicable Monitoring
Rock type and geochemistry	<ul style="list-style-type: none"> Support degradation 	<ul style="list-style-type: none"> Geotechnical mapping Corrosion mapping/geochemical analysis
Rock mass quality	<ul style="list-style-type: none"> Squeezing/creep Rockbursting Sloughing Support performance 	<ul style="list-style-type: none"> Geotechnical mapping Rock mass characterization
Geologic structure	<ul style="list-style-type: none"> Rockbursting Squeezing/creep Support performance 	<ul style="list-style-type: none"> Geotechnical mapping Ground deformation monitoring
Hydrology	<ul style="list-style-type: none"> Movement along structures Support degradation 	<ul style="list-style-type: none"> Groundwater monitoring Ground deformation monitoring Ground control performance monitoring Rehabilitation risk mapping
In-situ stress	<ul style="list-style-type: none"> Sloughing Rockbursting Squeezing/creep 	<ul style="list-style-type: none"> Stress measurement Seismic monitoring Ground deformation monitoring

Geotechnical Mapping and Rock Mass Characterization

Two of the most common methods for geotechnical mapping are line mapping and window mapping, which are described in Sun [9]. Notes and maps are typically made by hand, though some mines are adopting more high-tech solutions. For example, Barrick and Maptek

developed a tablet-based geotechnical mapping workflow that interfaces directly with Maptek's Vulcan¹ to reduce the data entry that must be done at a later time [10]. Although less proven, companies are developing drones for mapping inaccessible workings. Researchers are evaluating the use of these drones in conjunction with photogrammetry to remotely map structure and evaluate the rock quality [11-13]. As the data gathered during geotechnical mapping, (rock type, strength, and discontinuities) are collected, they are entered in the mine's planning software and used to update mining plans and ground control management plans (GCMPs).

Ground Deformation Monitoring

Ground deformation is ubiquitous in underground mines and manifests in many ways, including convergence, movement along geologic structures, or sloughing. Consequently, ground control engineers at nearly every underground mine monitor deformation. There are three monitoring objectives for deploying ground movement instrumentation, according to Sandbak and Rai [14]:

1. tracking movements in the rock mass associated with excavation,
2. evaluating the effects of ground control measures, and
3. creating a database of information for modeling and prediction of ground movement.

Most deformation monitoring instruments are some variation of an extensometer, which may be installed in a borehole or stretched across an opening. String potentiometers, crackmeters, inclinometers, and cruder tools, such as a line of spray paint across a fault, are also used. Data collection methods depend on the impact of deformation and the expected life of the excavation. Monitoring near the mining face, for example, is typically measured by hand using a tape or laser extensometer. Temporary instrumentation, such as ground movement monitors, may be installed in problem areas or other areas of interest over a short term. Permanent instruments, such as borehole extensometers, are usually reserved for critical infrastructure (e.g., shops, shafts, and shacks) or problem areas.

Data collection from ground deformation instrumentation ranges from recording measurements in a notebook to streaming digital measurements over the mine network. Data-logger-enabled instrumentation eliminates transcription errors and can provide data in real-time, but these instruments are used sparingly due to telemetry challenges and cost. Data from manually-read instrumentation are typically collected infrequently (monthly or quarterly), though collection frequency may be temporarily increased (up to a per-shift basis) in areas of interest.

Data processing for ground deformation monitoring generally involves examining the magnitude and rate of movement. If either exceeds a predetermined threshold, corrective action is taken. Analysis is usually performed in a spreadsheet on a monthly or quarterly bases, though data may be collected more frequently.

Stress Measurement

In-situ stress is one of the most difficult geotechnical parameters to measure but is important to understand for mine design. The most informative instrumentation is usually complex, expensive, and time consuming to install. Additionally, these instruments have a high rate of failure and measurement variability. Consequently, stress measurements are often limited to research and consulting efforts. One of the simplest stress-measuring instruments to install is a uniaxial borehole stressmeter (doorstopper), which is affordable and relatively easy to install but only provides relative stress changes and is difficult to orient. Additional instruments for measuring in-situ stress include biaxial stressmeters, earth pressure cells, and hollow inclusion (HI) cells, among others.

In practice, estimates of stress are obtained indirectly by combining geotechnical observations and strain measurements with numerical modeling.

¹ www.maptek.com/products/vulcan/

Seismic Monitoring

Seismic monitoring is among the most sophisticated, and highest maintenance, ground-monitoring methods routinely used in underground mining. Deep metal mines have employed seismic monitoring to manage rockburst risks for decades [15], and other mines are also starting to adopt the technology [16]. A unique benefit of seismic monitoring is that it can provide remote sensing coverage over the entire volume affected by mining, provided adequate signals (seismic events, ambient noise) exist. Figure 2 shows a simplified workflow of a traditional seismic monitoring system, which is an example of a narrowly focused GSIS. Because of the large volume of data collected by seismic monitoring systems, data collection and much of the initial data processing is automated.

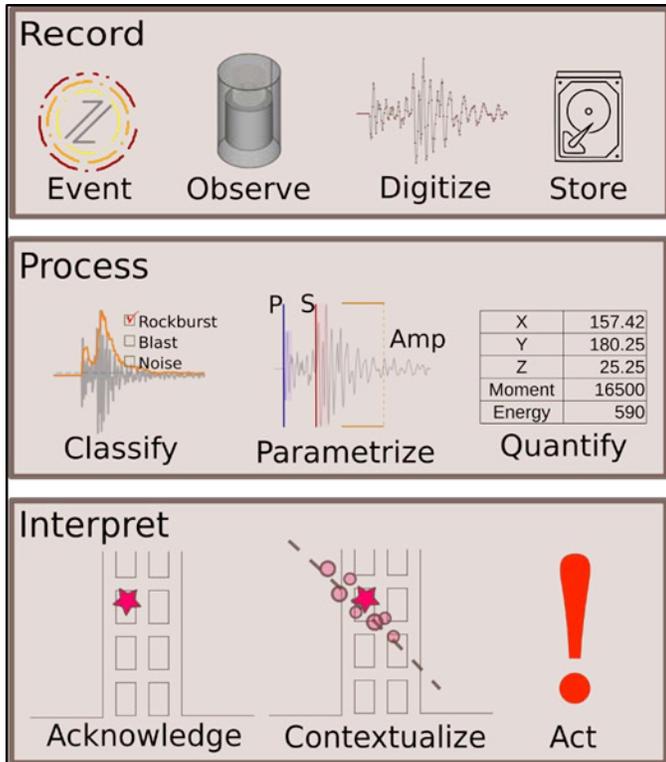


Figure 2. Diagram of data flow through a seismic monitoring system.

Seismic networks consist of time-synchronized instruments that record ground motions throughout the mine. These instruments are generally a mix of geophones and accelerometers and are installed in and around areas of interest. Continuous analog data are sampled at rates of 100-10,000 Hz per channel. The digitized data are then stored on media near the sensor or transmitted to a central server.

Seismic data analysis can be divided into two parts: the processing of the raw time-series data and the analysis and interpretation of seismic events. During the initial processing, event triggers are detected from the continuous data and classified. Various parameters are extracted from the waveform data, which are used to locate the event and calculate source characteristics (e.g. magnitude, energy, moment tensor). This initial classification and parameter extraction is usually automated and later reviewed and refined by a human analyst.

In the second phase of data analysis and interpretation, the events and their associated characteristics are contextualized with other seismic data, geology, and mine workings to ascertain something about the rock mass' structure or its reaction to mining. Tools for conducting this analysis range from software designed specifically for seismic hazard analysis (e.g., mXrap²) to simply visualizing events in

mine planning software. In many cases, the data may not be closely examined unless an event exceeds a certain magnitude or there are sudden changes patterns.

Ground Support Installation Monitoring

Ensuring ground support is adequate to sustain mine openings is among the most critical components of a mine's GCMP. To this end, geotechnical staff collect a variety of data for quality assurance/quality control (QA/QC) of various ground support elements. For rockbolts, this data includes systematic pull testing and torque testing and information reported from the bolting machines (e.g., inflation time and pressure for inflatable bolts). For shotcrete and backfill, this data includes information about mixes and strength testing. More general QA/QC data includes observations from support installation, notes about the types and amounts of support installed in given areas, and routine heading inspections.

QA/QC data is largely used for record-keeping/regulatory purposes. Data are often recorded in a field book or on inspection cards. Some of this data might be transferred to a spreadsheet or word processing file and some if it may be stored in databases. A few mining companies are implementing web interfaces for uniform data entry to enable easier searching and more robust backups [2]. Little is done to interpret this information, other than noting the location of potential problems and adjusting GCMPs as needed. This information is used for documentation for the quarterly inspections by the Mine Safety and Health Administration and must be well maintained.

Ground Control Performance Monitoring

Verification that ground support is performing at its rated capacity is essential over the lifetime of a mine opening. Many mines far exceed their initially planned mine life and new development can occur in areas with old ground support. Therefore, it is becoming increasingly important to understand whether older ground support retains enough integrity to adequately support the mine openings. Most ground control performance monitoring data are collected through visual inspection of active areas and physical testing of installed support elements (i.e., rockbolts).

A commonly applied method for ground control performance monitoring is rehabilitation risk mapping, described in Sandbak and Sandbak [17]. Workers manually inspect zones of the mine for characteristics such as corrosion, cracking in rock or shotcrete, bagging in the mesh, and changes in drift profiles. These factors are reduced to a numerical value from a risk matrix and noted by hand onto maps underground. These maps are later scanned for archival purposes, the data are entered into spreadsheets, and the matrix values are mapped onto the workings in mine planning software. Color-coded maps are created to identify areas that need immediate rehabilitation. A recent example of damage mapping in international mines is presented by Cumming-Potvin et al. [18], in which tablet-based software is used to capture ground support information and the damage due to rockburst events.

Limited instrumentation exists for monitoring ground support element performance and is largely used on a research basis. Examples of such instrumentation include:

- instrumented bolts to measure strain and provide alerts when the rated capacity is exceeded,
- environmental sensors may be installed to monitor the corrosive potential of the rock mass on support elements [19], and
- extensometers and stressmeters may be installed to monitor the closure of backfill [20].

Borehole scopes may also be used to inspect hollow bolts for corrosion or shearing. Application of this instrumentation is uncommon and often reserved for research due to maintenance and telemetry challenges.

² <https://mrxrap.com>

BARRIERS TO ADOPTING MODERN MONITORING PRACTICES

There is a wide array of modern tools (i.e., capable of streaming and processing continuous data) available to supplement or replace current monitoring methods. However, these tools have not been widely adopted by the underground mining industry, except in some specialized use cases. There are five major reasons for this:

- limited awareness of existing tools and systems,
- understaffing,
- difficulty in justifying the investment in modern technology,
- limited interoperability, and
- inconsistent data management practices.

Limited Awareness of Existing Tools and Systems

One reason why digital ground stability monitoring solutions are not widely deployed underground is a limited awareness of existing technologies and their proper application. The authors of this study spoke to personnel from multiple mines who indicated that they did not have a good appreciation of existing monitoring technologies. Additionally, one engineer acknowledged that it is not obvious when to apply geotechnical instrumentation and which kind would yield the best results. Mine staff may also implement a monitoring solution without a realistic understanding of its capabilities and subtleties, or without knowing how to interpret the resulting data. When this happens, the system inevitably falls into a state of disrepair and personnel become disenchanted with the technology.

The reduced awareness of monitoring systems has several causes. The U.S. mining industry experienced a significant contraction in the mid-1980s and 1990s, losing over one quarter of its workforce [21, 22]. During this time, reduced operating budgets may have discouraged companies from purchasing and implementing modern technology. The contraction also caused a substantial reduction in mining engineering graduates in the U.S., with the number of accredited mining programs at universities decreasing by half between 1982 and 2007 [23]. The result was a significant age gap in the mining industry [23] with fewer engineering graduates with exposure to newer technologies entering the workforce. The mining industry is still making up for this loss, particularly at smaller operations.

There is also some variation in technologies taught in engineering curricula, though most programs will provide at least some exposure to advanced technologies. After engineers reach industry, their exposure to recent technology further diminishes if companies do not invest in continuing education and encourage external collaboration (Poulton 2019, personal communication).

Understaffing

Many U.S. underground metal mines have few dedicated ground control engineers, often only one, who may or may not have assistance from technicians or interns. The ground control department is responsible for numerous duties, including:

- periodic heading inspections;
- quality assurance/quality control (QA/QC) of ground support members, including pull-testing bolts, testing shotcrete and backfill, etc.;
- evaluating short- to mid-term production and development plans for geotechnical concerns;
- dealing with logistical issues such as managing consultants and contractors, renegotiating contracts, and managing changes in ground support suppliers;
- developing and implementing rehabilitation plans;
- designing ground support plans for situations with atypical conditions (e.g., for critical infrastructure such as shops); and
- addressing additional problems as they arise.

Such a heavy workload leaves little time for ground control engineers to learn about new geotechnical monitoring instrumentation or perform data analysis. It is also difficult to retain enough electricians and other staff required to maintain instrumentation.

Justifying Investment in Modern Technology

Digital geotechnical monitoring technologies require a substantial economic investment and must be justified to mine management. McKenna [24] discusses the costs, both in terms of money and labor, of geotechnical instrumentation over its lifetime, including installation, maintenance, and data analysis requirements. In his discussion, he asserts that a single permanently installed instrument costs approximately \$15,000 over its lifetime. Furthermore, he points out that approximately 20% of instruments will need to be replaced every 10 years due to damage and degradation over time. McKenna's discussion is largely aimed at instrumentation installed on the surface. There are additional challenges associated with the underground mining environment that may compound these costs:

- maintaining line-of-sight for wireless streaming may require a significant investment in wireless nodes and other infrastructure;
- modern circuit boards are fragile and often not designed to withstand an underground environment, where they will be subjected to moisture and corrosion or impacts from blasting, mining equipment, and the installation process itself (e.g., instrumented rockbolts); and
- wireless sensors and nodes have finite battery lives and replacing these batteries is a time investment or could disrupt production, as in the case of a wireless gateway installed in the back of a haul road.

Additional costs to consider are training and support/maintenance contracts with equipment vendors.

Comparing the very tangible costs of geotechnical monitoring and ground support in general, with the theoretical savings from preventing injuries or production loss, is complicated because it is difficult to prove that an incident was prevented [25]. Moreover, many geotechnical engineers do not have the time or necessary experience to develop strong financial justifications for such equipment. As a result, digital geotechnical instrumentation is often viewed as uneconomical, and until such a time as it becomes necessary to shift to an automated approach to monitoring most mines will continue to rely primarily on human observation.

Interoperability

A significant barrier to the deployment of comprehensive ground stability monitoring systems is the lack of interoperability between hardware and software produced by different manufacturers. Proprietary systems are a common, competitive business model in the mining industry. Additionally, there may be technical challenges or liability issues involved in implementing an open system [26]. Although closed-source, proprietary systems are often simpler to use and can provide a complete "plug-and-play" solution, they have some significant disadvantages, as enumerated by Bryant and Rao [27]:

- these systems are often expensive to develop, deploy, and maintain, resulting in lower adoption rates,
- they inhibit the incorporation of recent technologies and innovations, and
- they lock customers into one system/vendor.

Specific challenges cited by mine staff the authors talked with include:

- having to duplicate communication infrastructure because some instrumentation only communicates with sanctioned wireless gateways, and
- challenges in systematically exporting data stored in proprietary systems to common aggregators.

Data Management Practices

Data collection and management standards at mining operations are often lacking or unenforced, particularly at smaller companies. Data may exist as hard copies in filing cabinets, disparate spreadsheets scattered across multiple computers, or (in more ideal cases) in a version-controlled database [28; 29]. Additionally, important metadata, such as environmental conditions or changes to sensor configuration, may not be collected or stored in an easily retrievable

manner. As a consequence, data cleaning and interpretation is a necessarily manual process and can become error-prone [28]. Furthermore, due to the ever-increasing volumes of data, mines often have insufficient personnel and financial resources devoted to data management, analysis, and interpretation [24; 28; 30]. From Hadjigeorgiou [28], poor data hygiene poses two problems:

1. the loss of valuable information needed to contextualize the data limits the analyses that can be performed, and
2. challenges in tracing the data's history to correct errors, especially when engineers maintain different copies of the data for analysis.

CONSIDERATIONS FOR A GROUND STABILITY INFORMATICS SYSTEM

Miners use three senses for monitoring ground stability conditions:

1. Vision – conducting inspections of the rock mass and support system for damage, structure mapping, and identifying loose/sloughed material or convergence;
2. Hearing – listening for changes in how the rock mass cracks and pops in response to mining; and
3. Touch – taking samples, observing how equipment interacts with the rock, and sounding it with a scaling bar or hammer to gauge its competence.

A complete remote monitoring solution should have the ability to adequately replace the information gathered from these physical senses. There are several components and technologies that are necessary for a monitoring solution to fill this need. This section discusses the technologies, data, and peripherals that constitute an effective GSIS for active mine workings, as well as some additional considerations regarding data management and analysis, as summarized in Figure 3. It is important to remember that some of these technologies require further development to be practical, and not all mining operations will have the same needs.

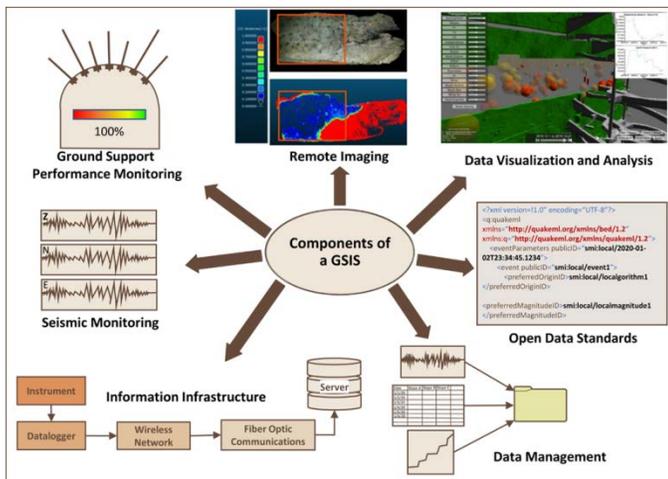


Figure 3. The seven elements and considerations for a ground stability informatics system.

Remote Imaging of the Mining Face

Drones and other camera/video feeds can provide scans of the rock mass with no human presence. Visual spectrum, LiDAR, hyperspectral, or multispectral technologies all show promise for creating point cloud representations of underground mine workings. The data from these technologies can be used for geotechnical mapping and rock mass characterization [12; 13], as well as conducting visual inspections of ground support. Furthermore, drones have been tested in applications for providing video feeds and mapping of areas that cannot be accessed (e.g., due to a fall of ground) [11; 13].

Several companies are developing drone or other vehicle-mounted systems for use in underground mining environments. These

systems are still relatively new, and much work remains to fully prepare them for use underground. However, the refinement of these technologies could enable the collection of visual information on a scale that is typically only experienced by underground workers.

There are some important limitations of remote imaging for underground monitoring. First, the volume of collected data may be overwhelming, causing data processing times to be unreasonable. A secondary hazard with the high data point density collected with these systems is that it is quite difficult to tune automated processors to ignore inconsequential movements that may cause false-positive alerts. Too many false positives undermine the confidence of end-users. The second drawback is that drone data requires stringent georeferencing, making it necessary to regularly resurvey control points if significant ground movement occurs. Finally, resolution limitations may restrict the application of these techniques. While stationary underground mapping solutions can have millimeter-scale accuracy [31; 32], drone- or vehicle-mounted-based approaches are often limited to centimeter-scale accuracy [33; 34], which may be insufficient for early detection of small-scale ground convergence. Jones et al. [35] explains some of these limitations and possible data processing solutions.

Ground Support Performance Monitoring

One area where further research is needed is a means for remotely monitoring for loose rock or damaged ground support. Surface support elements (mesh, bolt plates and heads, shotcrete, etc.) can be assessed visually; however, it is much more difficult to understand what is happening to the supports embedded in the rock mass (rockbolts). Direct remote monitoring options of this sort are limited and include instrumentation of the ground support itself (e.g., YieldPoint [36] and Mine Design Technologies [37]). Such instrumentation is not widely adopted due to cost, data transmission challenges, and sensor robustness. New sensors are being developed to make the monitoring of ground support elements more feasible on a wider scale, such as ultrasonic sensors for measuring rockbolt loading and strain conditions [38].

Ground Support Data Integration: As described earlier, a significant part of ground support monitoring involves simple record keeping, though often these records are spread among paper copies and different databases, which are not readily accessible to tech services personnel. The ability to link support installation, quantity, and quality to production maps and geotechnical models could greatly aid ground control engineers. Additionally, the operational data provided by drilling and bolting equipment might be useful to identify support issues and anomalies [39]. Emphasis should also be placed on developing more continuous monitoring of raw material feeds, plant performance, and distribution systems to aid in identifying quality issues with backfill or shotcrete to make it easier to identify potentially low-strength products.

Seismic Monitoring

Seismic monitoring is currently the one commonly employed technique that provides continuous, volumetric (as opposed to discrete or superficial) information about the rock mass response to extraction. Additionally, the data collection and processing are largely automatable, though there is room for further advances in this area. As such, it only makes sense that seismic monitoring would be a key component to a GSIS, at least in seismically active mines.

There are significant challenges associated with monitoring microseismic activity, however, including:

- sufficiently surrounding the seismogenic volume with sensors for the desired event location accuracy,
- infrastructure required to maintain adequate time synchronization between sensors, and
- substantial data analysis to achieve adequate data quality.

Because of these hurdles, seismic monitoring systems are not usually beneficial to mines that do not experience significant seismic activity.

Information Infrastructure

There is a wide variation in underground communication infrastructure in underground metal mines in the U.S. Many large mines will have fiber optic communications in much of the main development of the mine and possibly some Wi-Fi hotspots, but there are mines that have little data infrastructure other than rudimentary radio communication (e.g., leaky feeder). Other mining companies are working towards omnipresent, or “pervasive,” Wi-Fi in their underground workings [2].

For a GSIS to be practical, instrumentation with streaming data is required. Furthermore, the amount of instrumentation that may be required to monitor certain conditions may make hardwired instrumentation infeasible, particularly in the active heading, which will only be open for a few months. Therefore, additional developments will need to be made to the range and robustness of wireless data transmission technologies to make them more readily applicable to the underground metal-mining environment.

Data Management

Sophisticated analysis of geotechnical data requires appropriate data management practices. This involves maintaining a history of not only the raw data, but also the associated metadata (environmental conditions, notes about sensor outages/malfunctions, configuration changes, etc.), and processing history for all derived data. There should also be an authoritative source of truth for the data to prevent the duplication and modification of data across multiple machines. This will both reduce the time spent tracking down errors and broaden the types of analyses that may be done. A good backup strategy for the data is also essential to ensure that small-scale hardware failures do not destroy valuable information.

Although spreadsheets are a favored tool of engineers, data volumes produced by modern technologies can quickly scale beyond their capacity and may require upgrading hardware and software, as described in de La Beaujardière [40]. Open-source programming languages with a strong focus on data processing are becoming increasingly capable and accessible and will likely be part of the solution.

Open Data Standards

Proprietary solutions often hinder the integration of data by employing closed or custom data formats while failing to provide an application program interface (API) to access the data. Therefore, the introduction of open data formats or APIs is essential to maximize data integration and the value of the resulting analyses [27; 41].

A consortium of mining companies, original equipment manufacturers, academics, and regulators has identified interoperability as an important milestone for improving mine safety and productivity [42]. Although these standards focus on facilitating the adoption of automated equipment, their guidelines can be adapted to ground stability monitoring systems as follows:

1. **Data:** Actionable data should be easily and programmatically extractable. This requires that the system only use open (published) data formats, or that the system provides an API through which programs can request and receive data.
2. **Control:** External programs should be able to control the system. In the context of ground monitoring systems, this could mean that other programs can perform intermediate processing, such as estimating the location of a seismic event, and “push” data back into the system. The provenance, or history, of these changes should be tracked and version controlled.
3. **Security and Governance:** The system’s interface layers should implement modern security features as well as governance controls. This could be handled on the user account/file permissions level or through user authentication via secure API.
4. **Integrity:** Interoperability should not overwrite or jeopardize safety features or core functionality of the system.

Some companies, particularly those who are moving toward developing comprehensive analysis and visualization tools, are making strides in adopting these practices.

Data Analysis and Interpretation

Widespread adoption of remote monitoring will increase both the types and quantities of data being collected. Therefore, technologies for automating analysis and simplifying data interpretation will be essential to highlight the most relevant information. In addition to domain-specific analyses, there are general technologies that may be useful for combining diverse types of data. These technologies include machine learning for data mining and reduction, numerical modeling for system calibration, and data presentation and reporting.

Data Presentation: Geotechnical data collected in an underground environment is difficult to conceptualize for several reasons:

- only a small portion of the rock mass is accessible to mine workers,
- mines often span multiple levels, resulting in data loss in 2D “map view” representations, and
- the many different data types and sources can be overwhelming.

Therefore, a platform for visualizing multiple sources of geotechnical data and providing alerts is required. Maybee et al. [43] and Goulet et al. [41] demonstrate the benefits of a 3D, integrated approach to interpreting geotechnical data. Taking this a step further, Kaiser et al. [44], Kaiser et al. [45], and Tibbett et al. [46] illustrate the utility of virtual reality (VR) and stereoscopic visualization for geotechnical data. These studies cite the importance of depth perception for understanding true spatial relationships, immersing oneself in the data, and performing queries. Relatively portable VR systems are available for under \$1,000 [47], making such visualizations more practical than ever.

Data Aggregators: A class of software systems commonly known as data aggregators have emerged in the last several years that meet, at least in part, the definition of a GSIS given in the introduction of this paper. The focus of these systems is to integrate data from a variety of sources. Data aggregators have been employed in many surface mines in the U.S., where line-of-sight between instruments facilitates radio telemetry. Some U.S. underground mines have also implemented them [48]; however, adoption has been limited to date because they are difficult to deploy and are still relatively new and unproven. There are several examples of these systems in use in international underground mines and in the tunneling industry [49; 50].

Data aggregators and other GSIS software face the significant challenge of simultaneously capturing both the spatial and temporal nature of geotechnical information. Existing solutions can overlay a map of data onto a 3D model or plot a time history of a small number of data points. However, more development is necessary to meaningfully interpret the complex relationships among different geotechnical data sources.

SUMMARY

Automated or tele-operated mining machines are becoming more prevalent in the underground mining industry. The decrease in human presence that results, however, also reduces human observation underground, which could expose mine personnel to additional hazards. To compensate, a shift in data paradigms and practices will be needed to implement effective remote monitoring solutions that enable the operation of safe, productive mines. For example, U.S. underground metal mines rely primarily on manual methods for tracking ground conditions, whether through visual inspection, taking measurements by hand, or physically collecting data from installed sensors. Instruments capable of transmitting digitized streams of data to the mine office are reserved for special cases or problem areas due to cost, maintenance, telemetry, and interoperability concerns. It is necessary to overcome these hurdles to achieve pragmatic remote ground stability monitoring.

A GIS capable of supplementing or replacing human feedback in areas that are unfrequented by mine personnel should have the following components:

- remote imaging of the mining face for geotechnical mapping and inspections;
- technologies for ground support performance monitoring;
- seismic monitoring for remote sensing of fracturing in the rock mass and understanding of rockburst risk (if applicable);
- open data standards to facilitate interoperability among technologies for geotechnical monitoring;
- improved wireless telemetry for underground environments; and
- a data analysis and interpretation platform that selectively presents data to mine personnel to enable decision-making about ground stability concerns.

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DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of company names or products does not constitute endorsement by NIOSH.

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