CHAPTER 8.5

Geotechnical Instrumentation

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INTRODUCTION

Geotechnical instrumentation is a fundamental component of surface and underground mining engineering. Its use extends from prefeasibility studies to mine closure. Its purpose is multifold, serving both investigative and monitoring functions that are in part a necessity to ensure the economic feasibility of the mine operations and in part due diligence to ensure safe operations.

Investigative functions include

- Providing an understanding of the ground conditions for prefeasibility and design purposes,
- Providing input values for design calculations, and
- Checking for changing ground conditions as the operations expand or as workings progress to greater depths.

Monitoring functions include

- Assessing and verifying the performance of the design;
- Calibrating models and constraining design calculations; and
- Providing a warning of a change in ground behavior, thus, enabling intervention to improve safety or to limit damage through a design change or remediation measure.

The required versatility in how instruments can be deployed (on surface, from boreholes, etc.) and what they are meant to measure (rock properties, ground movements, water pressures, etc.) has led to the development of a wide variety of devices. Instrument selection, however, is only one aspect of a comprehensive step-by-step engineering process that begins with defining the objectives of their use and ends with implementation of the data (Dunnicliff 1993). It is therefore important to ask the following series of questions prior to undertaking any mine instrumentation project: What are the objectives of the monitoring project? (If the objectives are not known, then the project should not proceed.) What parameters need to be measured, and how will these aid mine excavation, ground support measures, and assessing design performance? How might these parameters vary spatially? What are the risks due to variable or poor ground conditions? What are the magnitudes of expected movement or stress increase? What are the optimal locations for instrument installation?

Only after such a reasoning exercise has been undertaken should the project proceed. The following advice of Dunnicliff and Powderham (2001) is pertinent: "The purpose of geotechnical instrumentation is to assist with answering specific questions about ground/structure interaction. If there are no questions, there should be no instrumentation."

When choosing instruments for a particular project, the engineer must consider and balance the job-related requirements of the following:

- **Range:** Range is the maximum distance over which the measurement can be performed, with greater range usually being obtained at the expense of resolution.
- **Resolution:** The resolution is the smallest numerical change an instrument can measure.
- **Accuracy:** The degree of correctness with respect to the true value is the accuracy, and it is usually expressed as a plus-or-minus number or as a percentage.
- **Precision:** Precision is the repeatability of similar measurements with respect to a mean, usually reflected in the number of significant figures quoted for a value.
- **Conformance:** Conformance is whether the presence of the instrument affects the value being measured.
- **Robustness:** This is the ability of an instrument to function properly under harsh conditions to ensure that data accuracy and continuity are maintained.
- **Reliability:** Reliability is synonymous with confidence in the data; poor quality or inaccurate data can be misleading and is worse than no data.

Dunnicliff (1993) is an excellent text on geotechnical instrumentation for monitoring field performance. The text provides a very useful discussion on these issues. Sellers (2005) eloquently discusses the concept of accuracy and puts it into perspective in relation to instrument resolution, linearity, precision, and most importantly real-world issues such as economics, reliability, and the uncertainty and natural

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Table 8.5-1 Common borehole core orientation tools

Technique	Advantages	Disadvantages
Physical Techniques		
Weighted core barrel (clay imprint, spears, etc.)	Low cost; simple to use	Impression may require interpretation; unsuitable in boreholes inclined at shallow angles (<30°)
Ballmark	Simple to use; minimal drilling delays	Triggering mechanism may not operate in weak and fractured rock
Scribe system	Continuous scribing of core referenced to borehole orientation	Moderate to highly complex to use; difficult to interpret in weak and fractured rock
Ezy-Mark	Works in soft and broken rock; operates in most borehole orientations (uphole and downhole)	Requires an inclined borehole
Digital Techniques		
Reflex ACT electronic tool	Eliminates reliance on mechanical movement; highly accurate and consistent core orientations	Requires training in operation
Acoustic televiewer	Provides a continuous record of borehole wall (three-dimensional [3-D] virtual core); provides high accuracy and confidence in data; can be used in highly fractured rock	Requires a stable borehole; requires water or mud in borehole to operate
Optical televiewer	Provides a continuous record of borehole wall (3-D virtual core); provides high accuracy and confidence in data; can be used in highly fractured rock	Requires a stable borehole; requires air or clear water to operate

Source: Adapted from Read et al. 2009.

variability in most geotechnical projects. An important, but rarely discussed issue, is the true cost of geotechnical instrumentation, which according to McKenna (2006) should be considered with regard to the "life-cycle of the instrument—from its initial geotechnical design and procurement through drilling and installation, including reading and maintenance and data management and geotechnical analysis back in the office." This is in addition to decommissioning.

In addition to providing typical guideline costs associated with instrumentation, McKenna (2006) outlines good practices and emphasizes the care required in "all aspects of design, procurement, installation, reading, maintenance, data management, and quality assurance/quality control and analysis."

INSTRUMENTATION FOR INVESTIGATION

Geotechnical instrumentation plays an important role in the investigation of mine-site geology, geological structures (faults, jointing, etc.), rock mass properties, groundwater conditions, and in-situ stress fields. These are necessary inputs for carrying out prefeasibility studies and mine design, optimizing existing operations, and mitigating uncertainty in the mine design (but unfortunately not eliminating it). It must be recognized that rock and soil are natural earth materials, the products of many geological processes and complex interactions, and as such they are inherently variable.

Data should therefore be measured and recorded in systematic ways using standardized procedures. Furthermore, specific data may be required to make a decision on a particular aspect of mine design. Much time and effort can be wasted by collecting data that may be irrelevant or inadequate. Accordingly, the type and quality of the geotechnical data required will vary as a mine project matures. Parallels can be drawn with the Joint Ore Reserves Committee's (JORC's) code for reporting ore reserves—*inferred, probable, and proven* reserves (AusIMM 2004).

As a mining project moves from prefeasibility through to detailed mine design, the amount of data collected will increase as efforts are made to minimize uncertainty and reduce risk. The nature of the data will also become more specialized and measurement will transition from surface boreholes to the development and production levels.

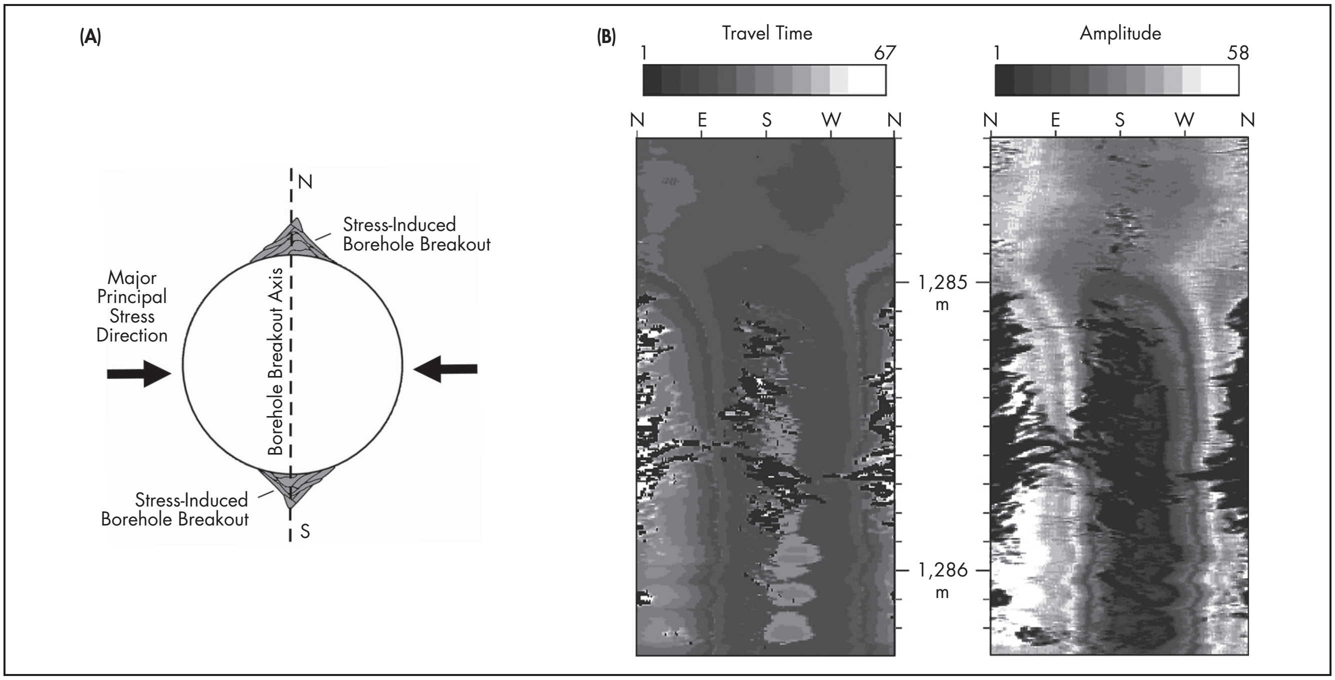
Ground Characterization: Borehole Techniques

Prefeasibility assessments and subsequent mine designs are often required to be completed prior to underground development. As a result, borehole information from drill cores and downhole geotechnical instrumentation often provide the only direct observation of the rock mass that hosts the mine in design. Core drilling is typically the most expensive phase of a mine geotechnical investigation, and therefore, every effort should be made to maximize the quality and quantity of the data collected.

Core Orientation

Discontinuities represent planes of weakness along which failure may occur. Their orientations and inclinations are key factors influencing mine design, as they may intersect each other to form potentially unstable wedges or blocks. In open-pit design, kinematic analyses using discontinuity data often controls how steep the bench, inter-ramp, and overall slope angles can be, all of which have a significant impact on the mining economics. Logging of oriented cores and borehole surveys provide a means to determine the dip and the dip direction of discontinuities intersecting the borehole. Read et al. (2009) summarizes several common core orientation tools. These may be divided into physical marking and digital imaging techniques, as shown in Table 8.5-1.

Physical marking typically involves using an orienting device during drilling to identify the top or bottom edge of the core before it is removed from the borehole. This is done by lowering the orientation device down the borehole between drill runs until it reaches the bottom, producing a mark on the top of the next piece of rock to be cored. This process is repeated so that the marks on the core from each drill run can be aligned using a reference line drawn from mark to mark. Techniques such as the downhole spear and Ezy-Mark (Table 8.5-1) are often favored for being inexpensive, quick,



Source: Adapted from Maybee et al. 2002.

Figure 8.5-1 (A) Stress-induced borehole breakout and its orientation relative to the direction of the major principal stress; (B) breakout observed in an ATV log at INCO's Totten mine. The north–south breakout is persistent for approximately 1 m along the length of the borehole.

simple, and robust. Alternatively, scribe systems (Table 8.5-1) use tungsten carbide knives differentially spaced around the core barrel to continuously mark the core as it enters the barrel. Scribe systems help to insure orientation of the core in formations with extensive fracturing.

Digital imaging techniques (e.g., acoustic and optical borehole televiewers) provide a direct, oriented, permanent, and unwrapped 360° continuous record of the borehole wall. They are used principally to map the orientation of discontinuities intersecting a borehole, detect thin beds, characterize lithology, and inspect well casings. They can also be used to provide indirect information on in-situ stress orientations through borehole breakout mapping (Figure 8.5-1A). This enhanced data output has meant that borehole televiewers are increasingly replacing conventional methods of core orientation.

Borehole Televiewers

Acoustic televiewers (ATVs) work by emitting an ultrasonic pulse-echo and measuring the return time and amplitude of the acoustic signal that is reflected back from the lithological and structural features present in the borehole wall. Optical televiewers (OTVs) illuminate the borehole wall and use a charge coupled device camera to record a direct image. They can operate in a wide range of borehole diameters and produce very high-resolution 24-bit RGB (red-green-blue) images with a vertical resolution of the order of 1 mm and a commercially available horizontal/circular resolution of up to 1,440 pixels. Both ATVs and OTVs are oriented using axial magnetometers and accelerometers contained within the instrument.

Some of the added advantages of ATVs and OTVs include the availability of sophisticated software for interpreting and displaying image logs. Manual or automatic highlighting of fractures and the determination of dip and azimuth from the logs can be undertaken. Data can be presented on image logs using tadpole and stick plots, stereographic projections, and frequency plots. Commercially available software allows for powerful interpretation of the data from multiple logging sources. Three-dimensional (3-D) virtual cores can be produced that are very useful in comparing logs with the actual core and investigating breakouts and borehole deformation. Figure 8.5-1B shows an example of a borehole breakout in a televiewer log from INCO's Totten mine in Canada, as reported by Maybee et al. (2002). The breakout is identified by the dark vertical bands located on opposite sides of the borehole image, indicating that the major principal stress is approximately east–west (i.e., 90° to the north–south breakout direction).

Borehole Geophysics

Nonintrusive and nondestructive, borehole geophysics provide valuable subsurface information for developing mine geological and geotechnical models. Surveys may be conducted such that both the source (seismic, radar, electric, etc.) and receiver are located together on a downhole probe or spaced through different configurations of borehole and surface source and receiver groupings (Figure 8.5-2). For effective application, it is important to ensure that all aspects of a geophysical survey are properly implemented. The International Society for Rock Mechanics (ISRM) has published suggested methods for borehole geophysics (Takahashi et al. 2006).

Geophysical logs. Wireline tools involve a variety of different sensor types, including mechanical, acoustic, electric and electromagnetic, and nuclear (Table 8.5-2). Some involve passive sensors (without excitation), and others involve active sources of excitation combined with detection sensors. Each

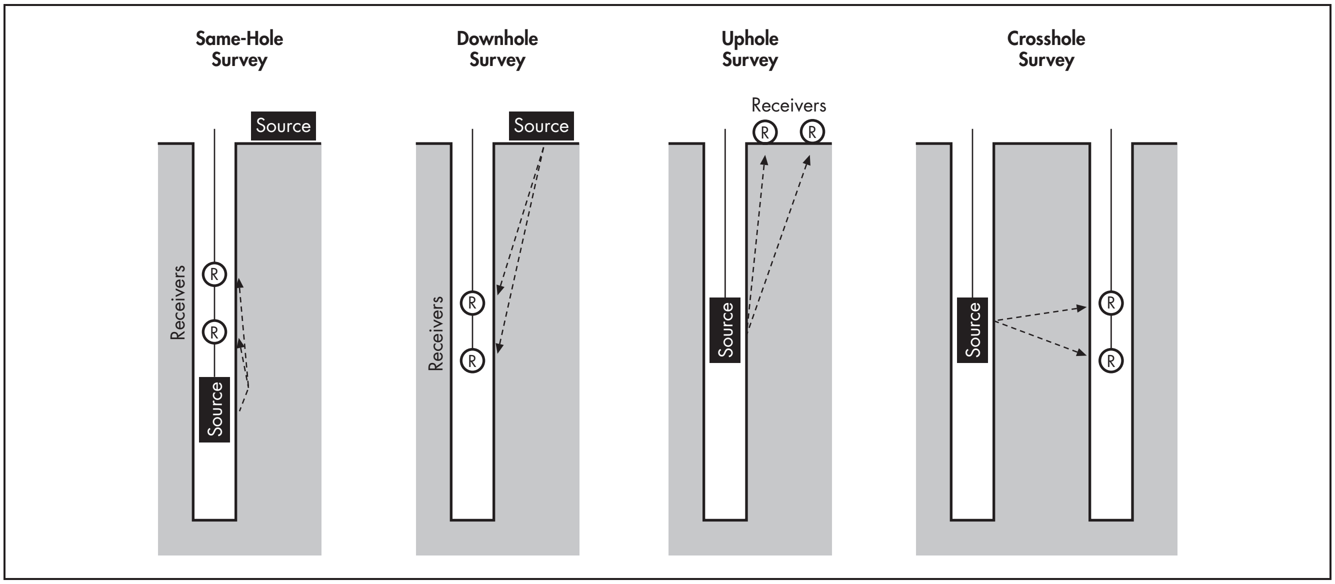


Figure 8.5-2 Example borehole and surface source and receiver configurations

Table 8.5-2 Common borehole geophysical tools used for geotechnical investigations

Source	Examples	Operation Principles and Applications
Geometry	Caliper	Measures variations in borehole diameter using spring-loaded mechanical arms that conform to borehole walls
Acoustic	Velocity; full waveform sonic; dipole shear imager	Measures P-wave or P- and S-wave velocity profiles along borehole; full waveform can be used to generate an attenuation log; provides information on rock composition, degree of fracturing/weathering, and rock properties
Electric and electromagnetic	Resistivity; spontaneous potential (SP); induction; full bore formation micro-imager	Profiles the resistivity of geological formations/fluids along a borehole; SP uses passive electric logging to measure natural electric potentials along a borehole; induction logging utilizes electromagnetic induction to profile resistivity; provides information on geological contacts, lithology, permeable formations, groundwater level, degree of weathering, and variations in clay
Nuclear	Natural gamma; spectral gamma; gamma gamma; neutron	Includes active methods (gamma gamma, neutron), which measure the formation's response to induced radiation; includes passive methods (natural gamma) that measure the natural radiation of the formation; provides information on geological contacts, lithology, clay content, structural features, density, porosity, and water content

sensor type and tool has its own advantages for identifying rock lithologies or measuring certain rock or fluid properties, either directly or indirectly through empirical relationships. For example, full wave sonic tools measure P- and S-wave velocities, for which there are empirical relationships to calculate porosity, quartz content, and clay content. When combined with density data, Poisson's ratio, shear, bulk, and Young's modulus values can be calculated. The use of multiple tools and composite plots allow comparison and validation (e.g., Figure 8.5-3).

Vertical profiling. Borehole geophysics can be combined with surface surveys to derive more information regarding the subsurface conditions. These can then be used to resolve geological features, or they can be combined with density logs to calculate the various elastic moduli along the borehole profile. There are several variations in the measurement methods, depending on source and receiver configurations split between the borehole and surface (see Figure 8.5-2). Variations include downhole, uphole, and crosshole techniques. Downhole surveys involve seismic, radar, or electric sources placed on the surface with signals measured at regular intervals down the borehole using a string of receivers or a single receiver moved incrementally up and down the hole. Uphole surveys place the receivers on the surface and place the source in the borehole. In the case of a vertical seismic profile, the P-wave arrival times for each receiver location are combined to produce travel time versus depth curves for the complete hole.

Crosshole tomography. Borehole tomography involves the measurement of seismic/radar signals between two or more boreholes to derive an image of velocity/resistivity in the intervening ground. Data are collected using one borehole for the source and additional boreholes for a string of receivers. This results in a network of overlapping ray paths that can then be used to model the velocity/resistivity profile. The resulting image is termed a *tomogram* and enables identification of anomalous velocity/resistivity zones between boreholes, as well as imaging individual velocity/resistivity layers.

Ground Characterization: Remote Sensing

The use of digital remote sensing techniques for characterizing rock mass structure in underground and surface mine environments has increased significantly in recent years. A

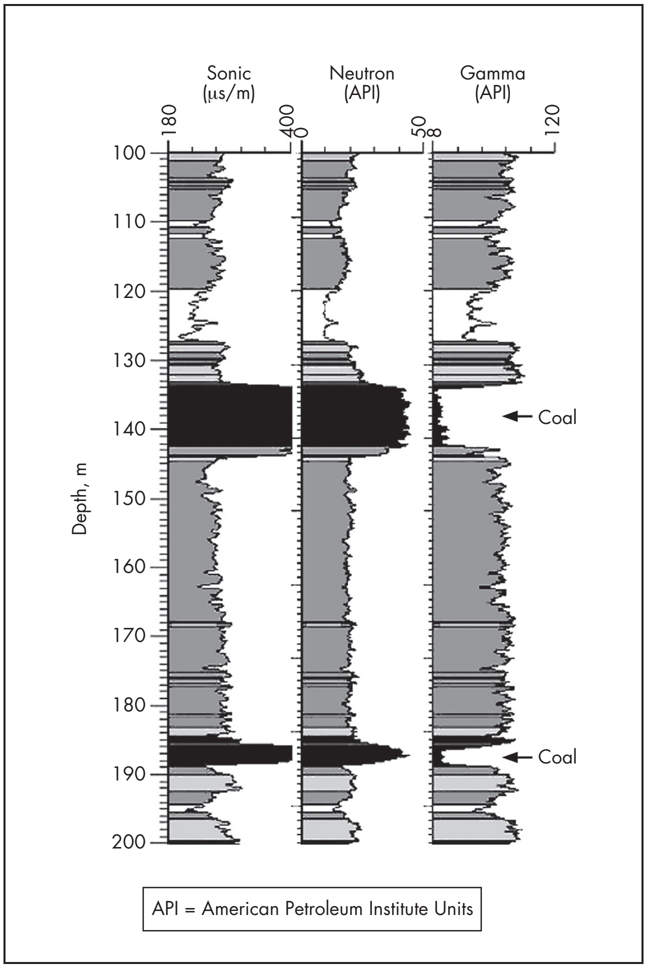


Figure 8.5-3 Example of composite geophysics log plot used to identify coal seams

major advantage of these methods is that they are able to provide data for remote and inaccessible areas, where safety concerns often preclude conventional mapping. Notwithstanding, Sturzenegger and Stead (2009a) and Lato et al. (2010) emphasize that these techniques suffer measurement bias (e.g., orientation, truncation, and censoring), which must be fully considered during processing, analysis, and interpretation of the data.

LiDAR

Light detection and ranging (LiDAR) is an optical remote sensing technique that measures properties of scattered light to determine the range of a distant target. Details on the theory of LiDAR measurement techniques are presented in Lichti et al. (2002) and in Lichti (2004). The product of a ground-based LiDAR laser scan is a 3-D point-cloud image of a pit slope or mine excavation wall, each point having x, y, and z coordinates and a pixel intensity value. The intensity may be in gray scale (Figure 8.5-4) or in color and may be draped on a photograph of the outcrop. A permanent 3-D digital image of the rock mass allows sections to be easily constructed wherever appropriate and imported into mine design and numerical modeling computer codes.

Using commercially available software (e.g., SplitFX, PolyWorks), orientation measurements of discontinuities may

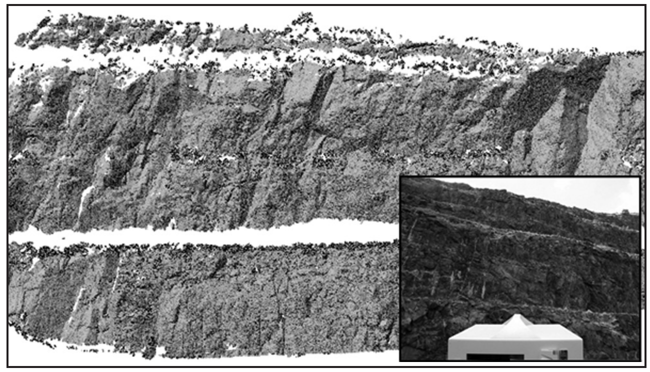


Figure 8.5-4 Three-dimensional point cloud from a LiDAR scan of open-pit benches at the Palabora mine in South Africa

be made from surfaces and traces in the point cloud, allowing for definition of discontinuity sets for future engineering analysis. The point cloud may also be used to provide data on discontinuity spatial location, persistence (trace length), and spacing (intensity). LiDAR has been used to characterize large-scale roughness and waviness; small-scale roughness still requires the use of conventional mapping surveys, as does the assessment of other parameters such as aperture and discontinuity infill. Comprehensive works on the use of LiDAR in rock mass characterization include Tonon and Kottenstette (2007), Kemeny and Turner (2008), Stead et al. (2009), and Sturzenegger and Stead (2009a). The use of LiDAR underground is less common than that on the surface, although excellent results can be obtained, as illustrated by Warneke et al. (2007).

Digital Photogrammetry

Ground-based digital photogrammetry is now routinely undertaken at large open-pit and underground mines. The use of this technique was pioneered by CSIRO Australia though the development of the Sirovision and Sirojoint software programs. Today, these codes, in addition to 3DM Analyst and 3G software programs, have found widespread use in the characterization of rock masses in open pits and underground mines (e.g., Birch 2006, 2008; Poropat and Elmouttie 2006). Using off-the-shelf digital cameras, stereo images of rock slopes and underground mine walls can be constructed and used to determine the orientation of discontinuities and derive joints sets in addition to obtaining similar geometric information as was discussed for ground-based LiDAR.

The advantages of stereo photogrammetry over LiDAR include the relative low cost for the hardware (a digital camera as opposed to a laser scanner) and the current ability to obtain 3-D stereo models from greater distances when using telephoto camera lenses (e.g., Sturzenegger et al. 2009; Sturzenegger and Stead 2009b). It is possible to form 3-D photo models of an open-pit mine at varying scales using a range of focal length lenses from 20 to 400 mm. This allows rock mass structures to be investigated at different image resolutions.

Figure 8.5-5 shows a 3-D photo model of the Palabora open pit using a 20-mm focal length lens and a model of pit wall benches using a 400-mm lens taken at a distance of more than 1.5 km. Figure 8.5-6 shows a photo model of a pillar using a 20-mm lens and an AdamTech underground lighting system. Both photogrammetry and LiDAR techniques complement each other and provide very similar data in terms of a point cloud and the derived rock mass parameters.

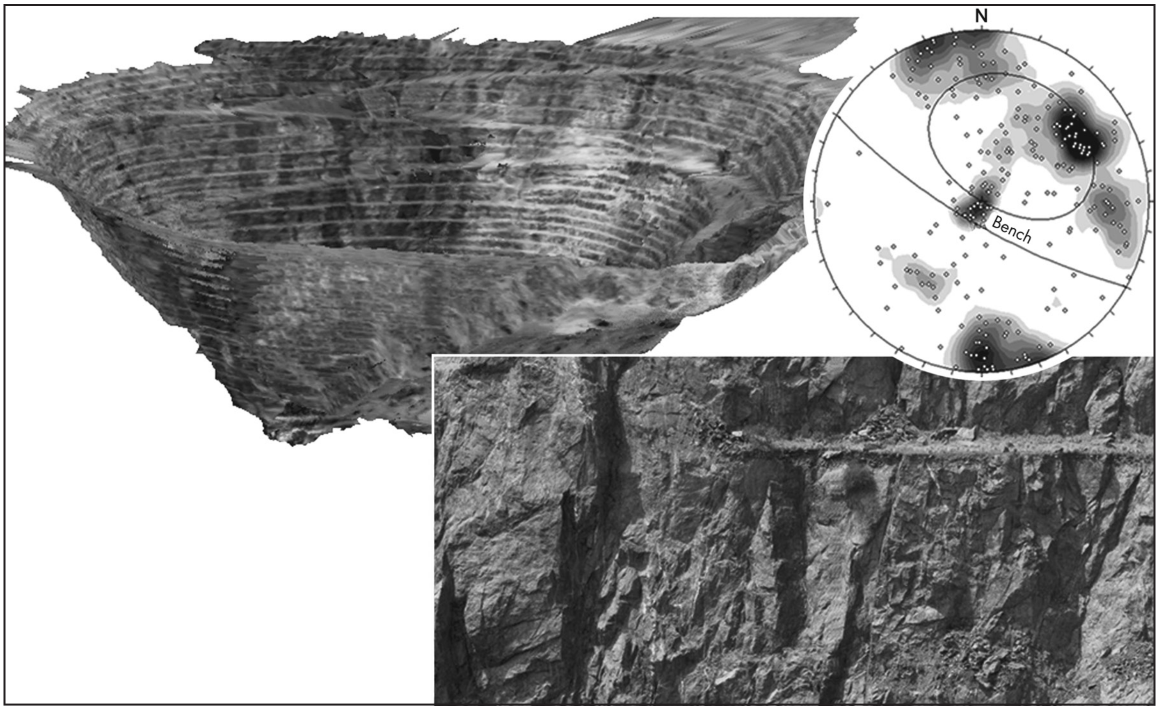


Figure 8.5-5 Three-dimensional photomodel of the Palabora open-pit mine in South Africa (20-mm lens), superimposed with a bench-scale photomodel (400-mm lens) and derived stereonet of discontinuity orientations

Surface Geophysics

Three-dimensional surveys (seismic, radar, etc.) can provide detailed information on geological contacts, faults, and other geological features important to mine design. Advantages over conventional two-dimensional (2-D) surveys include high-density data coverage, improved spatial delimitation of geologic and stratigraphic features, and the ability to visualize geologic, stratigraphic, and structural features in ways not possible with 2-D profiles.

The strength of 3-D surveys lies in their ability to establish continuity across subtle geological features. For example, Larroque et al. (2002) discuss how high-resolution 3-D seismic data were used to detect thin-layered platinum ore bodies at the Karee mine in South Africa, together with faults and other geological features that disrupted their continuity. These disturbances were of prime importance for implementing galleries, optimizing reef extraction, and positioning the shafts. Eso et al. (2006) demonstrated the application of a 3-D electrical resistivity survey to image a water-infiltrated void ahead of a mine drift in an underground potash mine. The detection of such voids is of prime importance in these mines to avoid flooding.

Ground-penetrating radar (GPR) is another surface geophysics technique that has been successfully applied in the mining industry (Pittman et al. 1982). The technique involves pulling a high-frequency radio transmitting and receiving antenna over the ground surface and recording any variations in the reflected return signal. GPR is used to map near-surface geologic conditions, including faulting and old workings that pose a hazard to miners, locating water tables, and detecting contaminant plumes. GPR can also be applied underground. White et al. (1999) provide several examples of routine use of GPR in South African mining, including ore-body delineation, mapping of faults and intrusives, and delineation of roof discontinuities.

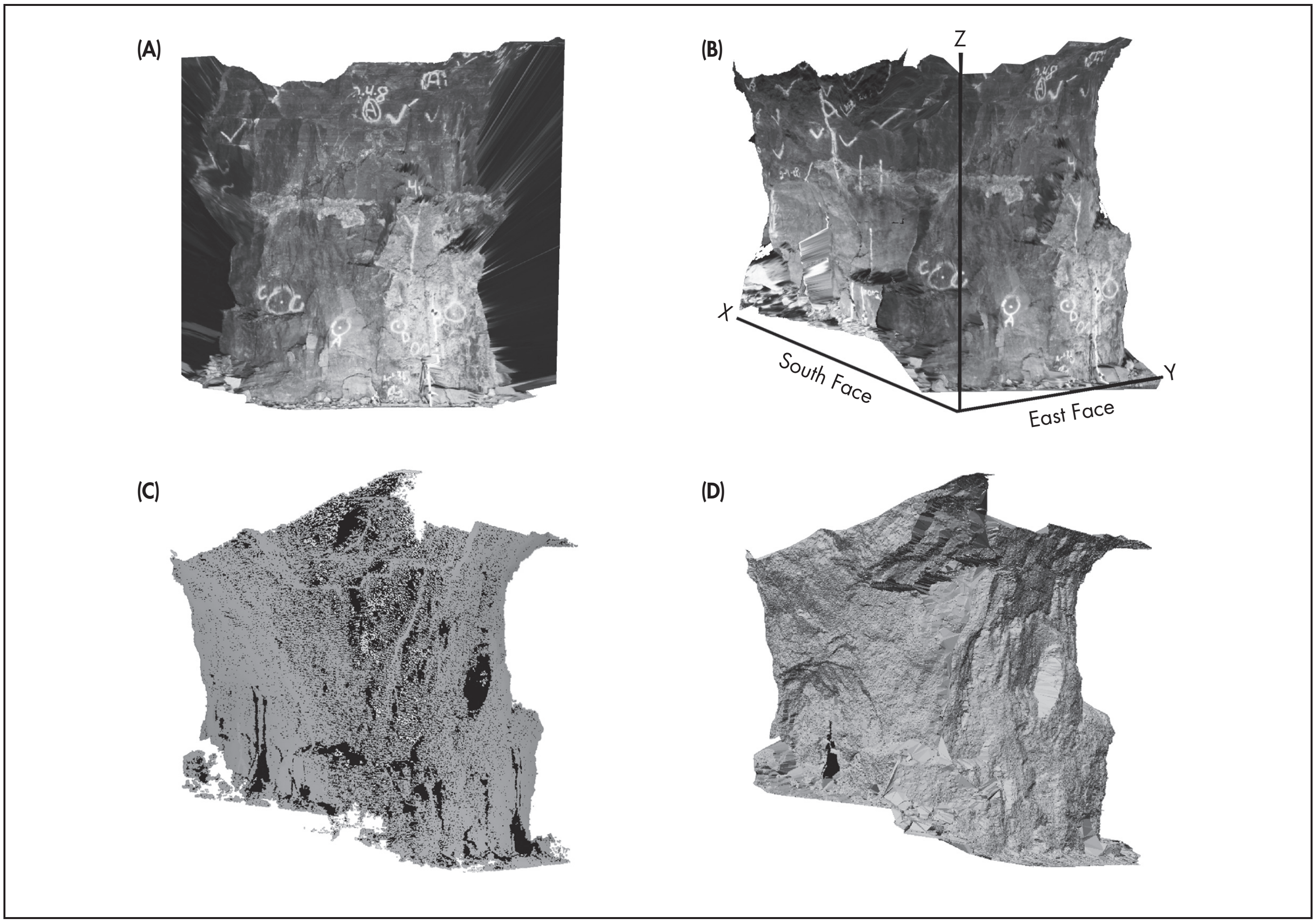
Groundwater Characterization

The determination of the water level and water pressures is an extremely important input for mine design, particularly for open-pit slopes. Pore water pressures can critically influence the stability of rock, waste rock, and soil/fill slopes. Measurement of pore water pressures is also important for monitoring the effectiveness of slope dewatering/depressurization schemes and the investigation of seepage and groundwater movements.

Piezometers

Piezometers are devices used to monitor pore and joint water pressures in boreholes. The most commonly used device is an electrical water level sensing probe that is used in combination with uncased boreholes (observation wells) to determine the depth to the water table by means of lowering the probe down the borehole. When the probe comes in contact with the water, an electrical circuit is completed, and the device makes an audible noise. Although this technique is quick and inexpensive and provides useful data in the initial stages of a project, it may be unreliable, especially in the presence of perched water tables, vertical groundwater gradients, and artesian conditions.

Open standpipe piezometers (Casagrande piezometers) involve cased boreholes, perforated at the depth of interest, in combination with a polyvinyl chloride (PVC) standpipe with a sealed-off porous filter element attached at the end. A sand filter zone is placed in the annulus around the filter tip up to the top of the filter zone with the remaining borehole backfilled with a bentonite grout to prevent any flow of water into the filter from other horizons. An electrical sensing probe can then be used to measure the water level corresponding to the groundwater pressure for the monitored interval. Combined standpipe/inclinometer installations are possible and are commonly used at surface mining operations.



Adapted from Styles et al. 2010.

Figure 8.5-6 (A, B) Three-dimensional photomodel of a pillar using photos of the four faces, and the corresponding (C) triangular mesh and (D) point-cloud representations developed from the photomodel

Although more complex, piezometers are also commercially available that provide a direct, reliable, and accurate reading of the pore water pressure at a specific depth in a borehole. They have rapid response times and the ability to be automatically logged. In rock masses, the correct location of these devices with respect to permeable fracture zones is very important. The principal differences between the various types of piezometers include the following:

- Single-point or multipoint measurements
- Vibrating wire, pneumatic, fiber-optic, strain gauge, or micro-electromechanical system- (MEMS-) based sensors (see the "Instrumentation for Monitoring" section of this chapter for a general description of instrument sensor types)
- Conventional installation or push-in types for soft ground

There has recently been considerable discussion as to the preferred method of piezometer installation. Many authors recommend fully grouted installations that have excellent zone isolation and rapid response to pore pressure changes. The reader is referred to Dunnicliff (1993), McKenna (1995), Contreras et al. (2008), Weber (2009), and Read and Stacey (2009) for further information on piezometer completions.

Multipoint piezometers offer the advantage of monitoring pore water pressures at selected intervals along the borehole. Several commercial varieties exist that vary principally on the method of measurement and isolation. Strings of piezometers can be connected on a single cable and fully grouted within the borehole. Installations include those for conventional vertical boreholes as well as horizontal boreholes in open-pit slope walls as part of a horizontal drain drilling program (Read et al. 2009).

Another popular multipoint system is the Westbay MP system, which comprises a modular casing system that allows for a large number of monitoring zones to be established in a single borehole. Access to individual zones is provided through port couplings with a filter on the outside and a spring-loaded check valve on the inside. Seals between monitoring zones are provided by either grout backfill or hydraulically inflated packers. Wireline tools and instruments are then used to operate the monitoring system by accessing the ports. Measurement ports not only allow pore water pressures to be monitored at any number of monitoring zones, but they also provide locations for fluid sampling. Pumping ports also provide the capability to undertake hydraulic-conductivity testing.

Table 8.5-3 In-situ stress measurement methods and key issues related to their applicability

Method	Advantages	Limitations	Suitability
Overcoring	Most developed technique in both theory and practice; three-dimensional (3-D)	Scattering due to small rock volume tested; requires drill rig	Measurement depths to 1,000 m
Doorstopper	Works in jointed and high-stressed rocks	Only two-dimensional (2-D); requires drill rig	For weak or high stressed rocks
Undercoring	Simple measurements; low cost; can utilize existing underground excavation	Requires measured local stresses to be related to far-field in-situ stresses; rock may be disturbed	During excavation
Hydraulic fracturing	Can utilize existing boreholes; tests large rock volume; low scattering in the results; quick	Only 2-D; theoretical limitations in the evaluation of maximum horizontal stress (σ_H)	Shallow to deep measurements
Hydraulic testing of preexisting fractures	Can utilize existing boreholes; 3-D; can be applied when high stresses exist and overcoring and hydraulic fracturing fail	Time-consuming; requires existing fractures in the hole with varying strikes and dips	Where both overcoring and hydraulic fracturing fail
ASR, DSCA, and RACOS*	Usable for great depths	Complicated measurements on the micro-scale; sensitive to several factors	Estimation of stress state at great depth
Acoustic emissions (Kaiser effect)	Simple measurements	Relatively low reliability; requires further research	Rough estimations
Focal mechanisms	For great depths; existing information from earthquake occurrence	Information only from great depths	Seismically active areas
Core discing	Existing information obtained from borehole drilling	Only qualitative estimation	Estimation of stress at early stage
Borehole breakouts	Existing information obtained at an early stage; relatively quick	Restricted to information on orientation; theory needs to be further developed to infer stress magnitudes	Deep boreholes or around deep excavations
Back analysis	High certainty due to large rock volume	Theoretically, not a unique solution	During excavation
Geological indicators	Low cost; 2-D/3-D	Very rough estimation; low reliability	At early stage of project

Source: Adapted from Ljunggren et al. 2003.
*ASR = anelastic strain recovery; DSCA = differential strain curve analysis; RACOS = rock anisotropy characterization on samples.

Groundwater Flow Testing

The collection of data on groundwater flow is an important area of geotechnical instrumentation, particularly in large open-pit design where slope depressurization may be critical to slope stability. Beale (2009) and Read and Stacey (2009) provide detailed descriptions of the importance of developing an adequate hydrogeological model and the requirements of slope depressurization programs. The characterization of groundwater response in fractured rock masses involves the use of drill-stem injection testing, falling or rising head tests (slug tests), packer testing, and pumping tests. Read and Stacey (2009, Appendix 1) provide an excellent summary.

In-Situ Stress Measurement

In-situ stress measurement provides an important boundary condition and input for mine design, including the selection of mining method, assessment of short- and long-term performance of underground openings, design of rock support and ground improvement (e.g., grouting), and assessment of rock burst potential. Hudson et al. (2003) discuss strategies for rock stress estimation, and Amadei and Stephansson (1997) and Ljunggren et al. (2003) provide comprehensive reviews of in-situ stress measurement methods. These may be classified according to methods that involve direct measurements, for example, the rock mass's response to hydraulic fracturing or induced strains from overcoring and those that involve indirect observations (indicator methods). The second category includes borehole breakouts, core disking, acoustic emissions (Kaiser effect), strain recovery methods, earthquake focal mechanisms, geological observational methods, and statistical treatment of databases. The advantages and limitations of these techniques are summarized in Table 8.5-3.

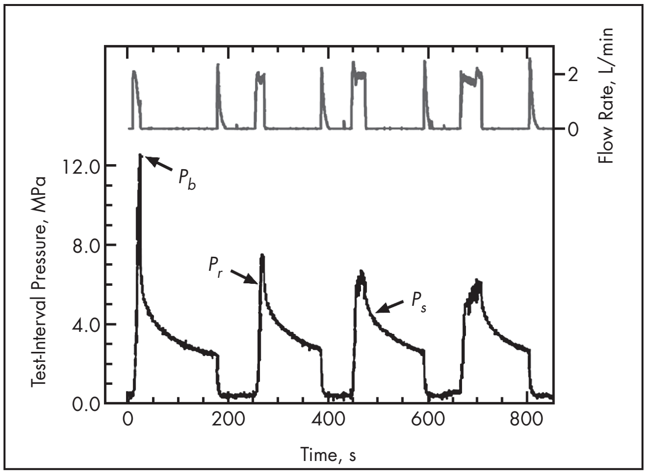
Overcoring

Overcoring is a stress-relief method that involves isolating a rock sample from the stress field that surrounds it and monitoring the strain response. As such, the measured stresses are not related to applied pressures but are inferred from strains generated by the unloading process.

Suggested methods for overcoring stress measurements are provided by Sjöberg et al. (2003). The method involves first drilling a large-diameter borehole followed by a smaller pilot hole in which a strain measuring device is inserted and fastened. The large-diameter hole is then resumed, relieving stresses and strains in the hollow rock cylinder that is formed. Changes in strain are recorded with the instrumented device as the overcoring proceeds past the plane of measurement. The in-situ stresses are calculated from the measured strains with knowledge of the elastic properties of the rock. Hence, overcoring requires the assumption of continuous, homogeneous, isotropic, and linear-elastic rock behavior. Sjöberg et al. (2003) noted that errors are introduced because these conditions are seldom encountered in rock masses. Even when seemingly ideal conditions apply, some scattering of the results always occurs.

Hydraulic Fracturing

Haimson and Cornet (2003) describe in detail the two main hydraulic methods used for rock stress estimation: hydraulic fracturing (HF) and hydraulic testing of preexisting fractures (HTPFs). For the HF method, a borehole interval devoid of natural fractures is sealed off and pressurized with water pumped under a constant flow rate until a fracture initiates in the rock. The following pressure measurements are then made: the water pressure at which the fracture occurred (the breakdown pressure), the subsequent pressure after pumping



Source: Adapted from Haimson and Cornet 2003.

Figure 8.5-7 Example of a hydraulic fracturing test showing the breakdown pressure (P_b), shut-in pressure (P_s), and reopening pressure (P_r)

is stopped and the fracture closes (the shut-in pressure), and the pressure required to later reopen the same fracture (the reopening pressure). These cycles may be repeated to provide redundant readings. A typical HF record is shown in Figure 8.5-7.

In a vertical borehole, the shut-in pressure, P_s, is assumed to be equal to the minimum horizontal stress, σ_h. The direction of σ_h is obtained directly from the orientation of the hydraulic fracture; vertical HFs propagate perpendicular to σ_h. The maximum horizontal stress, σ_H, is calculated based on the breakdown pressure, P_b. In this calculation, the breakdown pressure has to overcome the minimum horizontal principal stress (concentrated three times by the presence of the borehole) and the in-situ tensile strength of the rock, such that in the absence of pore fluid pressure the maximum horizontal stress, σ_H, is as follows:

$$\sigma_H = T + 3\sigma_h - P_b$$

The orientation of σ_H is taken to be perpendicular to the σ_h direction (i.e., the direction of fracture propagation). Other assumptions include that of homogeneous, isotropic, linear elastic behavior of the rock surrounding the borehole, and impermeability of the host rock so that pumped water has not significantly penetrated the rock and affected the stress distribution. Also, classical interpretation of an HF test is possible only if the borehole axis is parallel to one of the principal stresses and is contained in the induced fracture plane (Haimson and Cornet 2003).

The HTPF method follows a similar procedure of sealing off a borehole interval, but it involves reopening an existing fracture of known orientation. By using a low fluid-injection rate, the fluid pressure, which balances exactly the normal stress across the fracture, is measured. The method is then repeated for other nonparallel fractures of known orientation. By determining the normal stresses acting across several nonparallel fractures and knowing their orientation, a system of equations can be created to determine the six in-situ stress components without making any assumptions with regard to the orientation of the principal stresses.

Table 8.5-4 Systematic approach to planning a monitoring program

Step	Description
1	Define the project conditions.
2	Predict mechanisms that control behavior.
3	Define the geotechnical questions that need to be answered.
4	Define the purpose of the instrumentation.
5	Select the parameters to be monitored.
6	Predict the magnitudes of change.
7	Devise remedial action.
8	Assign tasks for design, construction, and operation phases.
9	Select the instruments.
10	Select instrument locations.
11	Plan recording of factors that may influence measured data.
12	Establish procedures for ensuring reading correctness.
13	List the specific purpose of each instrument.
14	Prepare the budget.
15	Write the instrument procurement specifications.
16	Plan the installation.
17	Plan regular calibration and maintenance.
18	Plan data collection, processing, presentation, interpretation, reporting, and implementation.
19	Write contractual arrangements for field instrumentation services.
20	Update the budget.

Source: Adapted from Dunnicliff 1993.

INSTRUMENTATION FOR MONITORING

Predictive monitoring systems are best implemented after a period of investigative monitoring. Monitoring information must be assessed in the context of the physical setting and the conclusions of the investigation phase. Planning of a monitoring program should be logical and comprehensive because the measurement problem may require a number of different instrument types collecting information across a range of varying scales. Furthermore, because of physical limitations and economic constraints, all parameters cannot be measured with equal ease and success. To assist with these challenges, Dunnicliff (1993) proposed a detailed systematic approach to planning a geotechnical instrumentation program, which is outlined in Table 8.5-4.

The monitoring system can be viewed as connecting a transducer to a data acquisition system via a communication link. The transducer serves to convert a physical change in the parameter being measured into a corresponding output signal, which can be read manually or automatically. Reliability of the instrument is paramount; this therefore requires some understanding of the transducer housed within the instrument and its sensitivity to the surrounding environment (e.g., temperature extremes, presence of water or high humidity, dust and dirt, exposure to shock or vibrations, and erratic power supplies). Several transducer types are common to the various instrument types described in this chapter. These are summarized in Table 8.5-5 for reference.

Surface Displacements

Geodetic

Geodetic monitoring provides a means for measuring the magnitude and rate of horizontal and vertical ground movements. Methods are well established and are often entirely adequate

Table 8.5-5 Transducer types commonly used in geotechnical instruments

Sensor Type	Operation Principles
Linear variable differential transformer (LVDT)	An LVDT consists of a movable magnetic core passing through one primary and two secondary coils. An excitation voltage is applied and a voltage is induced in each secondary coil. When the core moves off center, the output voltage increases linearly in magnitude. LVDTs are commonly used in instruments to measure displacements.
Vibrating wire	This involves a high tensile strength steel wire fixed at both ends and tensioned so that it is free to vibrate at its natural frequency. The wire is magnetically plucked by an electrical coil, and its frequency is measured. When one end moves relative to the other, the tension in the wire, and therefore the measured frequency, changes. Vibrating wire transducers are commonly used in pressure cells, piezometers, and deformation gauges.
Accelerometer	This consists of a damped mass suspended in a magnetic field; under the influence of external accelerations (or motion), the mass deflects from its neutral position and the deflection is measured. Accelerometers are commonly used in tiltmeters and inclinometers.
Fiber optics	Light is emitted into and confined to a glass fiber core and propagates along the length of the fiber. Any disturbance of the fiber alters the guided light, which can then be related to the magnitude of the disturbing influence. Fiber optics is finding increased use in piezometers and deformation monitoring instruments.
Micro-electro-mechanical system (MEMS)	A MEMS is a small, integrated device that combines electrical and mechanical components on a submicrometer to submillimeter scale. This allows for transducers (e.g., accelerometers) that are much smaller, more functional, lighter, more reliable, and produced for a fraction of the cost of conventional transducers.

for performance monitoring. Measurement accuracy (and reliability) is controlled by the characteristics of reference datums and monitoring points. Checks are required to make sure these datums are located on stable ground. Geodetic survey methods represent the most commonly relied on slope and displacement monitoring system at surface mine sites. The reader is referred to Dunnicliff (1993) for a detailed coverage of survey methods for monitoring displacement.

Recent advances that are of particular importance are the incorporation of robotic total stations (RTSs) into mine monitoring networks. Cook (2006) describes an RTS as a survey instrument combining a theodolite (with automatic target recognition) and an electronic distance measurement device that can be operated remotely. The RTS monitors point by sighting prisms and tracking them as movement occurs. After the RTS has "learned" the location of the prism, it returns to redetermine the location of that prism during successive monitoring cycles; angular and distance measurements are made and the new prism locations are calculated. Many hundreds of targets can be included in the survey network. In addition to installation and operational issues and the factors controlling the accuracy of the RTS network, Cook (2006) provides a useful practical list of the advantages and disadvantages of an RTS as compared to conventional survey methods. Under optimal conditions, an accuracy of ±0.6 mm at 60 m is reported as achievable.

Little (2006) documented automatic prism monitoring at the Potgietersrus Platinum's open-pit operation in South Africa, where prisms were located on a highwall at 50 m horizontal and 45 m vertical spacing. At this mine, Leica Geosystems GeoMoS system was used and the automatic prism-monitoring network was integrated with the use of laser scanners and slope-stability radar. Cahill and Lee (2006) describe the use of an automated Leica system using more than 400 prisms at the Harmony pit at the Leinster Nickel mine in Australia. The continuity of the prism data allowed for the long-term assessment of wall movements. The geo-referenced nature of the data allowed it to be used for assessing vector movements of the pit walls and failure mechanism determination.

Brown et al. (2007) describe combining Global Navigation Satellite System (GNSS) receivers with RTS instruments to provide a stable reference frame for total stations sited in an unstable environment. Kim et al. (2003) describe a similar example for an RTS system georeferenced using GNSS/GPS at the Highland Valley copper mine in Canada. Such integration provides a fully automated, accurate, efficient, and cost-effective means for monitoring points in a large open pit where no stable location can be found to place the instrument and control points.

Global Positioning Systems

GPS surveys utilize the U.S. network of space-based global navigation satellites to provide reliable positioning of a GPS receiver. The GPS receiver calculates its position by precisely timing the signals sent by multiple satellites, computing the distances to each satellite to determine its own position (through trilateration). When paired with an antenna, automatic monitoring of pit wall movements is possible with millimeter accuracy.

GPS offers several advantages over traditional geodetic surveying techniques. In general, GPS is more efficient, highly automatic, less labor intensive, and line-of-sight is not required between stations. However, in an open pit a limiting factor for large-scale use of GPS is that, for automatic monitoring of deformations, each monitored point needs to be equipped with a receiver and antenna. This makes GPS an expensive option for slope monitoring. In addition, issues of data communication, power supply, and system control are difficult to resolve when GPS instruments are distributed at isolated points.

Another limitation of GPS involves its use with steep pit slopes. Stewart et al. (2000) describe the use of GPS to monitor more than 60 points within the Palabora pit in South Africa, generally to an accuracy of 5 mm. However, the accuracy of monitoring points deeper in the pit is less because of the limited satellite window available (i.e., satellite visibility is obstructed). This limitation can be overcome by linking a GPS receiver with multiple antennas mounted at several monitoring points, or by using pseudolites, small transceivers that transmit a local, ground-based GPS-like signal (e.g., Bond et al. 2007).

Extensometers

This group also includes crackmeters, jointmeters, strainmeters, crack gauges, convergence gauges, distometers, and sliding micrometers. Extensometers are devices used to measure the changing distance between two points. Measurement points may be located on the surface to measure ground

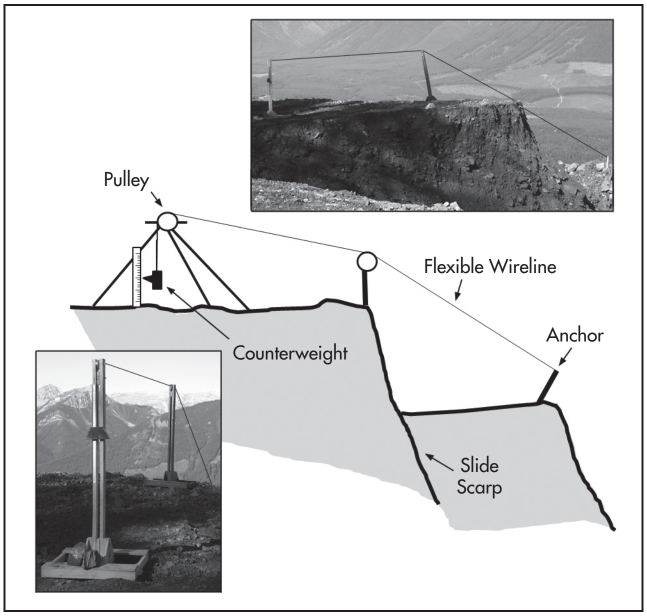


Figure 8.5-8 Schematic diagram (with inset photos) showing the use of a wireline extensometer to monitor waste dump movements at a British Columbia, Canada, coal mine

movements (e.g., spanning a tension crack to monitor its opening rate), or they may be located in a borehole to measure differential displacements along the borehole. Extensometers vary in type between those that involve manual measurements and those that are automated using vibrating wire electronics, differential transducers, or more recently fiber optics. Measurement accuracy and repeatability depend on the type of sensing device and the distance between the monitoring points. Typical accuracies range from submillimeter to millimeter over distances of less than a meter when using stiff sliding rods fixed between the monitoring points, and typical accuracies range from millimeter to centimeter over distances of meters or several tens of meters when extending a flexible tape or wire between the monitoring points.

In surface mining operations, wireline extensometers are frequently used to monitor pit slope and waste rock dump movements. These devices consist of a wire anchored in the unstable ground and tensioned across a pulley located on the stable ground behind the last tension crack using a counterweight (Figure 8.5-8). As the unstable portion of the ground moves away from the stable ground, the weight will move and the displacements can be recorded. These devices can be quickly positioned and easily moved, but care must be taken to minimize sag or thermal expansion/contraction in the wire, which can produce measurement errors. Rose and Hungr (2007) describe the use of wireline extensometer data at several mines in the United States to forecast the time of pit wall failure using an inverse velocity technique to interpret the data.

Tiltmeters

This group also includes clinometers and tilt sensors. Tiltmeters are devices used to monitor the change in inclination of a ground surface point. A detailed description is found in Dunnicliff (1993). The device consists of a gravity sensing transducer (servo-accelerometer, electrolytic tilt sensor, pendulum-actuated vibrating wire, MEMS) capable of measuring changes in inclination as small as one arc second. Tiltmeters may be uniaxial or biaxial, allowing measurement of tilt in two orthogonal directions. They are used to monitor slope movements where the landslide failure mode is expected to contain a rotational component. Advantages of using tiltmeters are their light weight, simple operation, and relatively low cost. Tiltmeters can be read manually or automated by connecting them to a data logger. They may be combined with inclinometers and extensometers in what have been termed as *integrated pit slope monitoring systems*.

Tiltmeters can be used to monitor pit-slope movements and ground subsidence above underground mines, particularly longwall and block cave operations. O'Connor et al. (2001) provides an example of a tiltmeter array used to measure the subsidence profile over an advancing longwall coal mine face. The array consisted of a series of tiltmeters connected to a central data acquisition system for automated real-time monitoring, with alarm thresholds set to warn of excessive ground deformations where the longwall panels crossed under an interstate highway.

Borehole Displacements

Probe Inclinometers

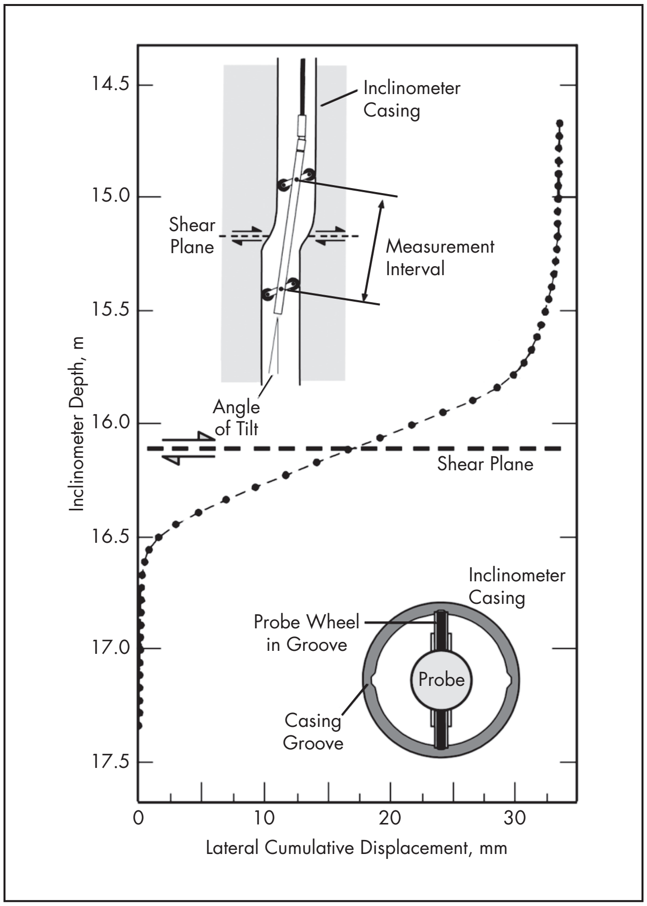
Probe inclinometers also include transverse deformation gauges and slope indicators. Inclinometers are devices used to monitor subsurface movements through a probe transducer (accelerometer, MEMS) designed to measure inclination with respect to vertical. A detailed description is found in Dunnicliff (1993). Operation involves lowering the probe down a borehole with inclinometer casing, which has two pairs of orthogonal grooves in which the probe wheels run. One pair of inclinometer casing grooves is usually oriented in the dip direction of the pit slope or in the anticipated direction of ground movement. Inclination is then measured at a number of fixed points as the probe is pulled back to the surface (Figure 8.5-9). Comparison of repeat periodic surveys provides an indication of differential displacements at depth as a function of time. Displacements are usually summed, resulting in profiles of cumulative displacement along the borehole (Figure 8.5-9).

When installing inclinometer casing, it is important to select the appropriate diameter. Large-diameter casing is better suited to shear zones, multiple shear zones, and slope failures. Moderate- to small-diameter casing can be used for short-term installations or slopes where smaller displacements distributed along the borehole are anticipated. Correct installation of the casing is important; and in deep holes, particularly the influence of helical deformation must be considered. A digital spiral sensor probe can be used to check the spiraling of the casing.

Inclinometer monitoring is widely used at the Syncrude oil sands mine in Canada to monitor highwall performance while draglines operate above it. McKenna et al. (1994) reported that approximately 20% of the highwalls have significant potential for slope failure, requiring intensive monitoring to ensure safe operation of the draglines. From 300 to 800 inclinometers were being installed each year to monitor shear movements and the development of slide surfaces at discrete depths (Figure 8.5-9).

In-Place Inclinometers

Where the depth of localized subsurface displacement is known or can be anticipated, an in-place inclinometer system



Source: Adapted from McKenna et al. 1994.

Figure 8.5-9 Inclinometer data of shear displacements at depth recorded for a highwall at the Syncrude oil sands mine in Canada, showing basic operation principles of a probe inclinometer

may be used to monitor continuous movements across known active shear surfaces. This system may also incorporate MEMS technology. In-place inclinometers consist of one (or several) inclinometer sensors housed within a stainless-steel enclosure. Sensors are separated from one another by stainless-steel rods and wheel assemblies. Sensors are installed in zones of expected displacement allowing remote automatic monitoring of pit slope movements.

Borehole Extensometers

Another variant from those previously discussed involves the use of mechanical or electrical probes (i.e., probe extensometers) to monitor changing distances between fixed points along a borehole as determined by the probe position. Typical accuracies for probe extensometers range from submillimeter to millimeter over distances of less than a meter.

A wide variety of borehole probe extensometers are commercially available, which differ according to the following:

- Single-point or multipoint measurement
- Measurement transducer/principle (dial gauge, resistance, magnetic, sonic, fiber optics, vibrating wire, and MEMS technology)

Multipoint borehole extensometers monitor displacements in a borehole at various depths within a slope or excavation wall/floor/roof. They usually comprise up to eight rods per drill hole and have manual readout or vibrating wire transducers with a measurement range of between 25 to 100 mm and a sensitivity of between 0.01 and 0.1 mm. Magnetic extensometers consist of spider magnetic anchors positioned along a PVC tube with a stable anchor at the base of the borehole (Figure 8.5-10A). The vertical movement of the anchors can be monitored manually with a probe.

Other versions of magnetic extensometers allow for automatic monitoring. The Increx system is comprised of brass rings located at fixed intervals along the outside of the PVC borehole casing (Figure 8.5-10B). A probe is used to measure the distance between successive rings, and the result is compared to an initial survey. Surveys taken at specific time intervals provide indications of whether compressive or extensile displacements have occurred. Changes as small as 0.001 mm can be measured with an accuracy of ±0.01 mm/m. Applications of the Increx system include the monitoring of vertical and horizontal deformations around underground and surface excavations.

A variety of sonic probe extensometers are also commercially available. The Sondex system installation consists of regularly spaced steel sensing rings and a corrugated Sondex pipe installed over inclinometer casing (Figure 8.5-10C). The annulus between the borehole wall and the Sondex corrugated pipe is filled with soft grout. This couples the pipe to the surrounding ground, so that the pipe and rings move with settlement or heave. As the probe passes a ring, an audible sound emits and the depth reading is taken. Settlement and heave are calculated by comparing the current depth of each ring to the previous readings of depth. Sonic extensometers have found considerable application in monitoring roof, wall, and floor deformations at specific depths. In stratified rocks, this allows for the estimation of dilation and bed separation around the opening.

Resistance wire extensometers are comprised of a pretensioned electrical resistance wire element fixed within a 1- to 2-m-long plastic tube and a strain gauge measuring readout. The wire is attached, under mild tension, to each end of the tube. The extensometer is installed by grouting into a borehole; a number of resistance wire extensometers can be installed end to end. Significant tensile strain can be measured with high sensitivity. Resistance wire extensometers are used for the monitoring of tensile strains around underground excavations and slopes. Applications have included pillar, roof, and stope wall displacement.

Convergence Monitoring Systems

Bock (2000a, 2000b) provides a useful summary of geotechnical instrumentation used in tunneling with particular focus on performance monitoring to assist with construction control. Measurements normally required include tunnel convergence, for which there are several instruments. Tunnel-profile monitoring systems comprise a series of linked rods fixed to the tunnel wall to monitor displacement; each rod has a high-accuracy displacement meter and a tiltmeter that record changes in displacement and tilt. The Bassett convergence system uses a system of articulated arms fitted with tilt sensors to monitor the movement of reference points that are mounted

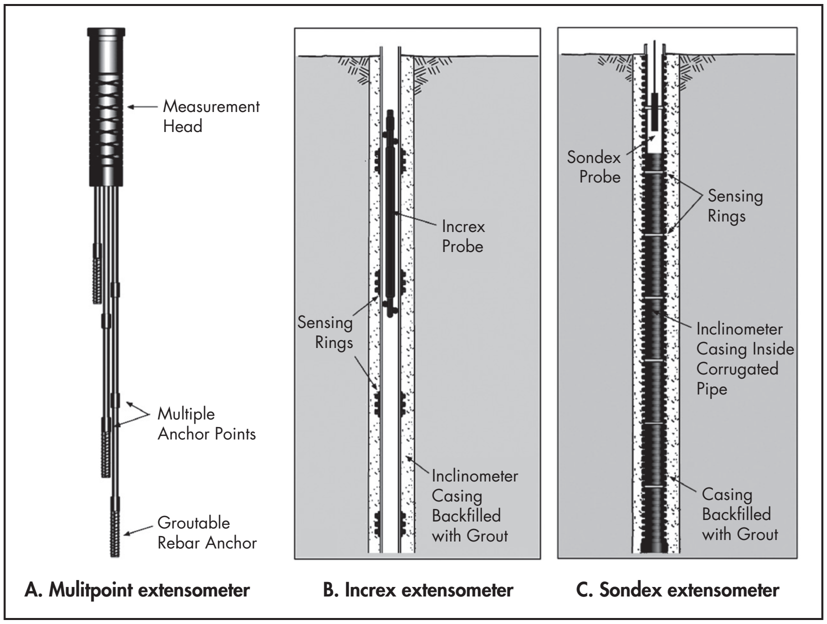


Figure 8.5-10 Types of borehole extensometers

on the tunnel wall. Metje et al. (2006) describe a new fiber-optic-based Smart Rod tunnel monitoring system to measure structural displacements and deformations. The Smart Rod system was designed as a series of short rod sections, joined at fixing positions around the circumference of the tunnel.

Shaped Accelerometers

A new, wireless, MEMS-based system recently developed for real-time deformation monitoring is described by Abdoun and Bennett (2008). This system is based on triaxial MEMS accelerometer measurements of angles relative to gravity. Three accelerometers are contained in each 30-cm-long rigid segment for measuring x, y, and z components of tilt and vibration. The segments are connected by composite joints that prevent torsion but allow flexibility in two degrees of freedom. These rigid segments and flexible joints are combined to form a sensor called a ShapeAccelArray, which is capable of measuring 3-D ground deformation from within a borehole, for example, at 30-cm intervals to a depth of 100 m (Figure 8.5-11). The arrays consist of subarrays of eight segments connected end to end. Microprocessors, one per array, collect data from the groups of sensors.

Time Domain Reflectometry

Time domain reflectometry (TDR) is a standard electrical method for locating faults in cables. TDR is finding increasing use in mining geotechnical applications. The essential principle of TDR involves the effect of cable deformation on the passage of a voltage pulse along a two-conductor coaxial metallic cable, with the pulse being partially reflected by the deformation. TDR instrumentation allows for the location of the cable deformation using the travel time of the voltage pulse and the propagation velocity of the signal in the cable. Shearing of a TDR cable grouted in a borehole in rock or soil allows the location of the shear zone through changes in geometry and impedance between the inner and outer coaxial cable conductors. The magnitude of the soil and rock deformation over time can be determined, as it is proportional to the amount of cable deformation and hence changes in amplitude of the reflected voltage signal.

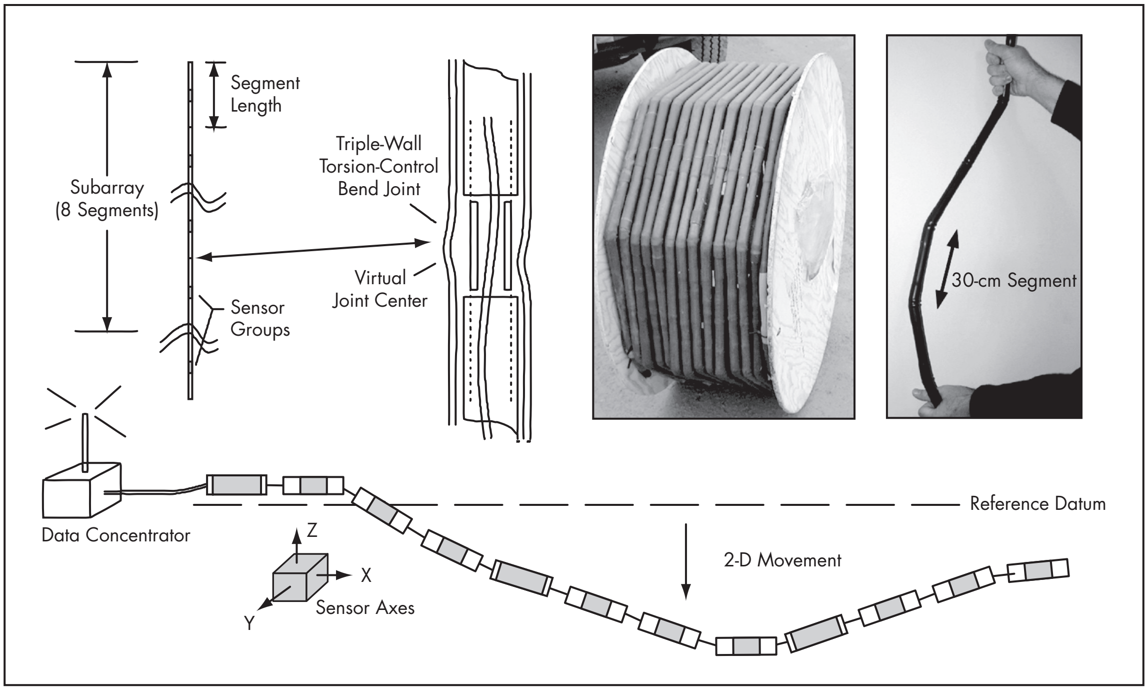
Dowding et al. (2003a, 2003b) provide a synopsis of the concept of TDR, its use in geotechnical engineering, and valuable practical experience gained in its use. Of particular interest are correlations between TDR magnitude and inclinometer displacements, the use of long (>300 m) horizontal TDR sensor cables above underground mines and parallel to both roads and slopes, monitoring at great depth (>500 m), and the use of TDR in geotechnical alarm systems (O'Connor 2008).

TDR has found application in surface mining, underground mining, and subsidence (Kniesley and Haramy 1992; Dowding and Huang 1994; Allison and de Beer 2008; Carlson and Golden 2008). Carlson and Golden (2008) describe successful use of TDR in remote monitoring of cave initiation at the Henderson mine (Colorado, United States). Allison and de Beer (2008) describe the monitoring system used to monitor the cave at the Northparkes mine (Australia), Lift 2. Displacement monitoring including TDR cables, convergence, and multipoint borehole extensometers are associated with damage mapping, borehole video, and microseismic monitoring. These authors emphasized the need to minimize the time between installation of TDR cables and the commencement of monitoring in order to reduce the possibility of cable damage.

Szwedzicki et al. (2004) clearly showed the applications and success in TDR monitoring at PT Freeport's Deep Ore Zone block cave mine (Indonesia). Results at PT Freeport from TDR cables monitored over a period of 2 years provided information on vertical progression of the cave and zones of dilation. Horizontal progression of the cave was monitored using cables installed from the undercut level. TDR at the Deep Ore Zone mine also provided information on the cave ratio (cave back height to height of draw) and the rate of progressive caving.

Fiber Optics

Fiber-optic technology (Table 8.5-5) is being increasingly used in the development of geotecthnical instrumentation.



Source: Adapted from Abdoun and Bennett 2008.

Figure 8.5-11 ShapeAccelArray subarray assembly

Commercially available fiber-optic-based instrumentation includes displacement transducers, piezometers, strain gauges, and temperature gauges. The following four main types of fiber-optic sensors exist:

1. Point sensors using Fabry-Pérot interferometric sensors
2. Multiplexed sensors using fiber Bragg grating sensors
3. Long-base sensors using interferometric SOFO sensors
4. Distributed sensors using either distributed Brillouin scattering sensors or distributed Raman scattering sensors

These sensors provide exciting new development potential for geotechnical instrumentation (e.g., Inaudi and Glisic 2007a). Of particular interest is the future potential of distributed sensors as reported by Bennett (2008) and Inaudi and Glisic (2007b). Distributed fiber-optic sensors can use a single optical fiber with a length of tens of kilometers to obtain dense information (every meter) on strain distributions across geotechnical structures or on the surface above underground mine excavations.

Remote Sensing of Ground Deformation

Satellite InSAR

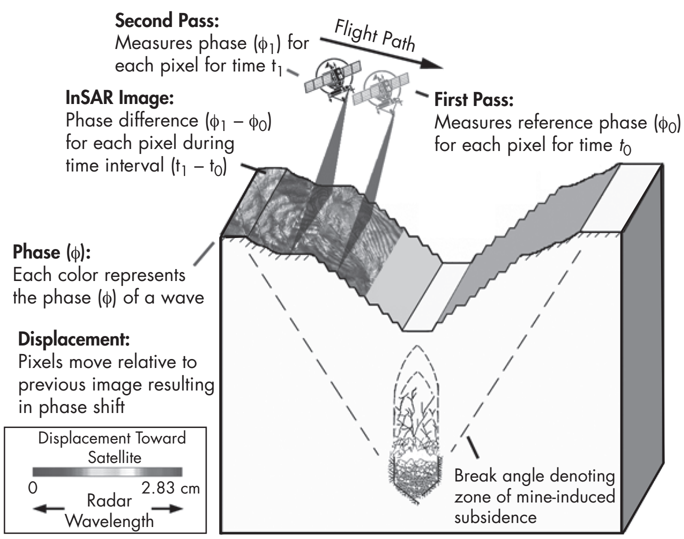
Space-borne interferometric synthetic aperture radar (InSAR) involves the use of satellite-based microwave radar to remotely monitor ground deformations. With repeated orbits and image capture (referred to as stacks), interferometric techniques can be used to resolve 3-D information of surface deformations by analyzing differences in the phase between waves being transmitted and received by the satellite (Figure 8.5-12A). Ground deformations on the scale of centimeters to millimeters can be detected for a surface area resolution of several square meters using these techniques.

Jarosz and Wanke (2003) describe the feasibility testing of InSAR for two mine sites in Western Australia. Results are provided for the Leinster Nickel mine, a sublevel caving operation beneath an open pit, for which InSAR was used to detect the extent of subsidence within the pit and active mining area. Kosar et al. (2003) used InSAR at the Island Copper Mine on Vancouver Island in western Canada to test its ability to provide adequate warning of potential failures during flooding of the pit during its decommissioning. Small ground movements along the steep pit slopes were successfully detected. This lead Kosar et al. (2003) to point to the continuous spatial coverage provided by InSAR compared to the large number of survey or GPS monuments that would have been required to cover the same area. Kosar et al. (2003) also pointed out the ability to remotely obtain data from sections of the pit that were otherwise inaccessible due to safety concerns.

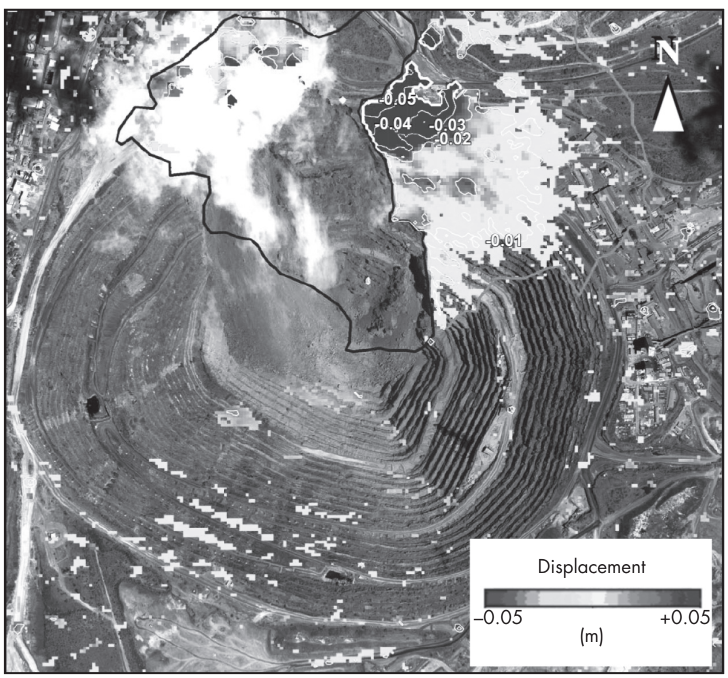
Rabus et al. (2009) describe the use of InSAR to identify and map spatial movements within and around the Palabora open-pit mine due to block-cave mining beneath the finished pit (Figure 8.5-12B). This ability is important for protecting key mine infrastructure located near the pit rim.

Surface Radar

Since about 2000, ground-based radar has become an increasingly efficient method of monitoring open-pit slope movements (e.g., N. Harries et al. 2006; de Beer 2007). These systems are able to provide accurate displacement measurements along the line of sight of a high number of targets (natural or artificial reflectors) with submillimeter precision. The slope-stability radar (SSR) system, described by Harries and Roberts (2007), uses a real aperture on a stationary platform positioned 30 to 1,400 m away from the slope. Extended-range versions are now able to obtain a maximum range of 2,800 m.



A. InSAR operating principles, showing measurement of surface displacements above a block cave operation



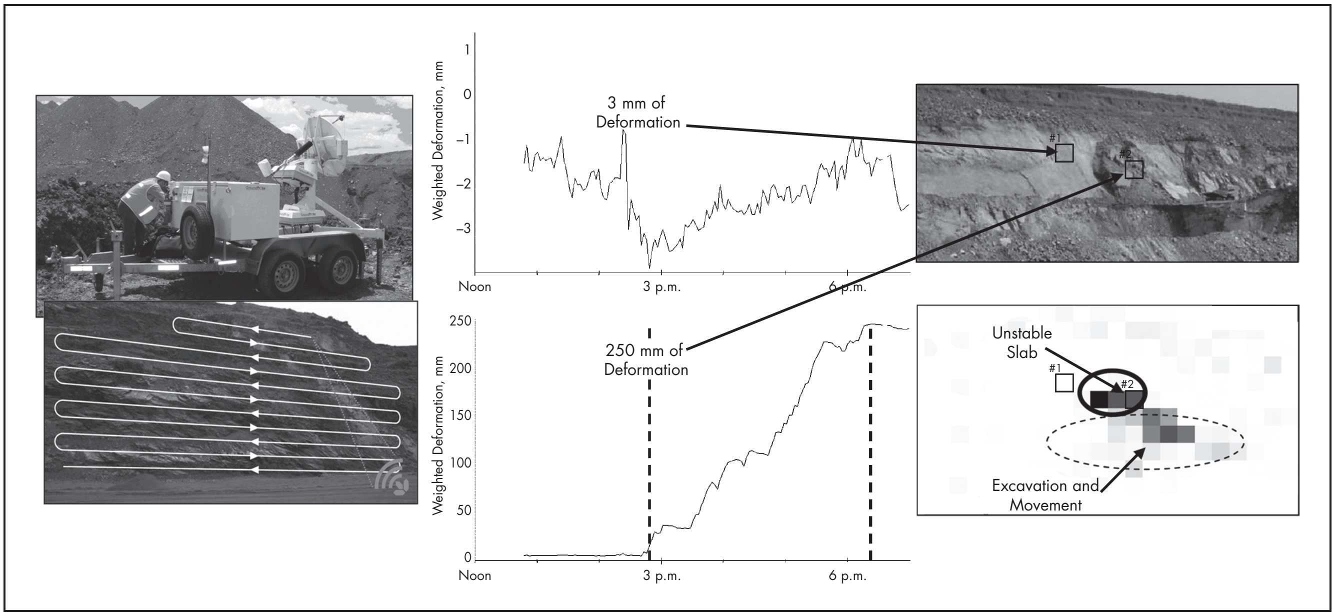
B. InSAR measurements of caving-induced subsidence and pit wall movements at the Palabora mine

Source: (A) Adapted from Rabus et al. 2009; (B) Adapted from AMEC 2006.

Figure 8.5-12 InSAR measurements

Figure 8.5-13 shows the SSR equipment, the generated data that scans a region of the pit wall, and comparisions of the phase measurement in each footprint (pixel) with a reference scan to determine the amount of movement of the slope.

Slope radar technology has revolutionized surface mine monitoring, providing full coverage of a rock slope and offering submillimeter measurements of wall movements. Adverse affects due to rain, dust, and smoke are minimized, although reduced precision occurs in pixels due to low coherence between scans, for example, due to vegetation. Harries et al. (2006, 2009) describe the application of the technology at numerous open-pit mines where it has been successfully used to monitor and provide impending warning of pit slope failures just tens of minutes to hours before failure. Cahill and Lee (2006), Joost and Cawood (2006), and Little (2006) provide well-documented examples of the benefits of this



Source: Adapted from Harries et al. 2006.

Figure 8.5-13 SSR system showing the continuous monitoring of millimeter-scale movements across the face of an unstable open-pit mine slope

technology in managing the risks due to slope instability at major open-pit mines.

LiDAR and Photogrammetry

In addition to pit slope and rock mass characterization, terrestrial LiDAR and photogrammetry can also be used for pit-slope displacement monitoring. Early use of terrestrial LiDAR monitoring focused on surface mine operations, in particular blast design and control. Coggan et al. (2001) illustrated the potential use of LiDAR in monitoring the retrogression of a mine slope failure in a china clay quarry pit. The use of ground-based LiDAR in an integrated surface mine monitoring program is described at the Potgietersrus Platinum mine (South Africa) by Little (2006), where two permanently mounted LiDAR scanners were used to scan a pit wall and help demarcate areas of slope deformation. The ground-based LiDAR at this mine was used in combination with prism surveying and also with slope-stability radar.

Terrestrial photogrammetry has an even longer history in the monitoring of surface mine slopes. Digital photogrammetry forms an excellent record of slope performance and rockfall activity. Tunnel scanners are used for profile scanning (e.g., determination of overbreak, to verify shotcrete thickness, tunnel face change detection with time, and tunnel surface deformation). Systems may be either LiDAR or photogrammetrically based. Wilson and Talu (2004) describe the use of a tunnel scanner at the Finsch mine (South Africa) for providing data on deviation of tunnel profiles from planned and actual, tunnel shape, damage, and alignment.

Photogrammetric systems may use either two digital cameras mounted on a portable fixed bar or one camera with a specialized tripod head allowing controlled repeatable multi-imaging of the tunnel. All systems provide a digital 3-D stereo image of the tunnel. Birch (2008) and Wimmer et al. (2008a, 2008b) describe the use of photogrammetry in underground blasting and fragmentation studies.

Stress Change and Pore Pressures

The change in stress associated with various stages in mining is of significant importance. This can range from monitoring pressures within pillars as adjacent rooms are excavated to the monitoring of pressures in the roof of excavations. Often the associated instruments are used in association with convergence and borehole extensometers to provide data for optimizing future mine design using numerical models and ensuring safety.

Pressure Cells

Borehole pressure cells typically have a measurement range of 0 to 70 MPa. They may be a flat jack (two steel plates welded together with hydraulic oil in between) configured to detect changes in stress perpendicular to the cell, or they may be cylindrical in design measuring the average change in pressure in the plane perpendicular to the borehole. Push-in (or spade) pressure cells are particularly useful for applications such as measuring total pressures in earthfills. These cells can be fitted with integral piezometers to allow measurement of pore water pressures and derivation of effective stresses. Push-in cells have standard ranges of operation up to 5 MPa. Shotcrete stress cells generally consist of two rectangular steel plates welded together with de-aired fluid in between. Changes in pressure in the shotcrete lining are recorded by a change in pressure in the fluid within the cell; electrical resistance or vibrating wire technology is used to record this change in pressure. Standard measurement ranges from 2 to 35 MPa are common.

Direct measurement of stresses in tunnel linings can also be undertaken using the slot-relief or flat-jack compensation method. This involves locating measurement points positioned adjacent to a future diamond saw cut, cutting a narrow slot and measuring the convergence across it due to stress relief between the measurement points, and inserting a flat jack and inflating it until the convergence of the points is fully reversed. This value is termed the *compensation pressure* and approximates the value of stress in the shotcrete.

Variations in pore water pressure during the lifetime of a mining project are likewise an important component of geotechnical instrumentation and design. Piezometric instrumentation was described previously in the "Groundwater Characterization" section. Ongoing monitoring of pore water pressures can be compared with deformation measurements used to provide an indication of groundwater conditions ahead of the mining front, used to provide information for remediation measures, and used as an input for numerical modeling.

Microseismicity

Microseismic monitoring provides mining and rock mechanics engineers with information on the stress conditions in the rock mass and how the ground is responding to induced stresses due to changing mine excavation geometries. The location of seismic events and their characteristics provides valuable information, both in terms of improved mine safety, and optimization of mine design and sequencing. Commercial microseismic monitoring systems have been in use since the 1970s and were originally used in underground rock-burst-prone mines (see Blake and Hedley 2004). The systems are now increasingly being used in both underground and surface mines.

Numerous companies provide state-of-the-art 24-bit digital seismic recorder systems that integrate into local area networks (LANs) or wireless networks. Hudyma and Brummer (2007) address the key questions in the design of a seismic monitoring system, mainly the optimal number, type, and location of the sensors. Seismic sensor arrays are usually composed of uniaxial and triaxial sensors. Triaxial sensors can provide seismic source parameters (energy, seismic moment, and magnitude), whereas uniaxial sensors primarily provide accurate seismic locations.

The sensitivity of a seismic array is directly proportional to the number of sensors used. The source location accuracy is also proportional to the number of sensors in the seismic array. Hudyma and Brummer (2007) present a guideline that the system source location should be approximately 5% to 10% of the intersensor spacing. Where possible, the seismic array should surround the rock mass of interest, but if this is not practical, the array should be spread geometrically in three dimensions. If there are an insufficient number of triaxial sensors, the seismic parameters may be influenced by attenuation or by seismic-event energy radiation patterns.

The reader is encouraged to consult Hudyma and Brummer (2007) for further useful discussion of the practical aspects of seismic array design in underground mines, including design for future mining stages, sensor installation, automatic source location reliability, system calibration and maintenance, seismic data analysis, and ensuring optimal performance from seismic systems. These authors emphasize that microseismic monitoring in underground mining can be optimized through good system design, frequent data analysis, and routine auditing of the system. Delgado and Mercer (2006) provide an interesting description of one of the largest mine microseismic systems in the world at the Campbell mine in Red Lake, northern Ontario, Canada. Also discussed are some of the issues faced.

Recent years have seen an increase in the successful use of microseismic systems in open-pit mines, spurred on by the ever-increasing depths of large open pits and the presence of underground mines beneath open-pit slopes. Lynch and Malovichko (2006) describe how microseismic monitoring in open-pit slopes has been routinely practiced since 2002 at mines in Namibia, South Africa, and Australia. They report that monitoring had been conducted for more than 25 open-pit slopes, all of which showed signs of brittle fracturing, in one case at a slope height of only 80 m. They emphasize that for reliable event locations, the seismic sensors array should surround the volume of rock being monitored, which in an open-pit mine means that they must be located near to the surface as well as at the bottom of the monitored volume.

In practice, potentially unstable slopes are monitored rather than the entire pit. Typical sensor separations are in the order of 100 to 200 m. The system described by Lynch and Malovichko (2006) involved near-surface sensors installed in short (i.e., 10 m) vertical boreholes using 4.5-Hz geophones, and in long inclined holes (i.e., 100 to 300 m) using 14-Hz omnidirectional geophones. These authors show correlations between microseismic activity and mining at the base of the slope, removal of broken rock, and the location of seismically active structures behind the pit wall.

Wesseloo and Sweby (2008) emphasize the increasing role that microseismic monitoring will be required to play as open pits increase in depth with a consequent increase in stress and a greater uncertainty in the pit slope deformation mechanisms. These authors provide an overview of microseismicity in rock slopes and in mine slopes in particular. They also provide an excellent account of microseisimic response to mining, event size (energy), and S-wave to P-wave ratios. An informative case study of microseismicity at an Australian open pit is presented by Wesseloo and Sweby demonstrating the future potential of this monitoring technique in open-pit environments.

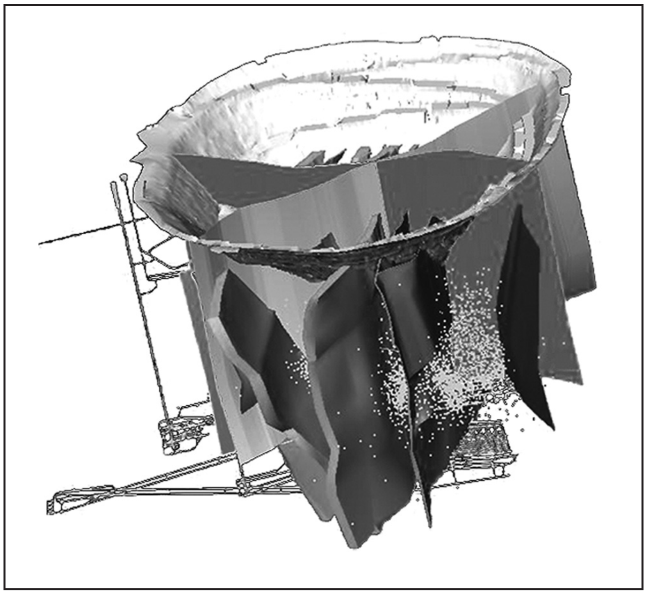
DATA AQUISITION AND PRESENTATION

Data reliability is of primary importance, requiring mine personnel to have confidence in the performance of an instrument. This can be gained, in part, through the performance of routine calibration checks, instrument inspections, and maintenance. Data integration and data management are also key issues. Important new elements such as Web geographic information system (GIS) services can be integrated into the operational resources of decision makers. These services are linked to early warning systems through wireless data acquisition and transmission technologies, which enable real-time data from multiple remote monitoring sites to be accessed and viewed by mine geotechnical staff, both on- and off-site, by means of the Internet. This is proving to be a highly valuable resource where an unstable pit slope threatens production and/or worker safety. Spatially and temporally distributed measurements should be combined with a knowledge engine and an evolving rule base to form the hub of a decision-support system (Hutchinson et al. 2007).

Wireless Data Transmission

Wireless technology enables continuous real-time monitoring of production activities and rock mass response to mining throughout an operation. Although automatic data-acquisition systems cannot replace engineering judgment, when combined with wireless data transmission, the following advantages can be gained (Dunnicliff 1993):

- More frequent readings
- Retrieval of data from remote/inaccessible locations



Source: Adapted from Woo et al. 2010.

Figure 8.5-14 Integrated mine-data model combining surface and underground mine plans, geology, and microseismic data

- Instantaneous transmittal of data over long distances
- Measurement of rapid changes/fluctuations in monitored parameter
- Increased reading sensitivity
- Reduction of measurement and recording errors
- Increased flexibility in selecting, managing, and storing data

From a system's operation perspective, automated wireless systems increase safety and lower costs. The fundamentals of a communication system include a transmitter, a receiver, and a surge arrestor, which allows reliable communication over distances of a few kilometers. The advantages of these systems over satellite or cell phone communication include lower costs and ease of use. The disadvantages include the requirement to use repeaters if a line of sight over long distances is not possible. It is vital that the network be reliable and always available, even in difficult terrain and harsh weather conditions.

Data Immersion and Visualization

The acquisition of geotechnical mine data can lead to the generation of massive volumes of data from in-situ surveys and mine operations, making managing, storing, and utilizing the data difficult. Improved computer performance and new software developments are changing this situation. Easy-to-use integrated geotechnical data-management systems with 3-D visualization and data immersion can be envisaged, linking monitoring, analysis, prediction, and remediation.

These attempts at data "fusion" are moving toward the adoption of virtual reality technology, where the identification of hidden relationships, the discovery and explanation of complex data interdependencies and the means to compare and resolve differing interpretations, can be facilitated (Kaiser et al. 2002). Spatial databases can be developed to integrate the different data sets being used for mine design and geotechnical analyses (geological, geotechnical, operational, etc.) into an interactive 3-D visualization and virtual reality environment (Figure 8.5-14).

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