Use of a 3-D scanning laser to quantify drift geometry and overbreak due to blast damage in underground manned entries

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ABSTRACT: Case-study data from a series of three-dimensional scanning laser tests conducted at the Stillwater Mining Company's, Stillwater Mine in Nye, Montana, USA is presented. A series of blast rounds in two underground development drifts were scanned using a Leica HDS 3000 Scanning Laser. Detailed digital surveys from the scans were used to supplement basic blast audit data including location and orientation of drill holes, comparison of "as-designed" versus "as-built" and calculations of overbreak and underbreak. Operational considerations and feasibility of using the system as a research tool to quantify blast damage are discussed as well as the safety implications of improving blast designs.

1 INTRODUCTION

1.1 *NIOSH Mine Safety Research*

The National Institute for Occupational Safety and Health (NIOSH) is currently performing blasting research to help mine operators minimize the amount of loose or damaged rock surrounding a blasted opening. The goal of the research is to show that better perimeter control in underground excavations will decrease the number of accidents associated with ground fall injuries as well as decrease the exposure to hazards associated with scaling and installation of ground support. One component of the project is to develop standardized methods for quantitatively assessing improvements in blast designs. This paper highlights preliminary results from a case study of several drift development rounds at the Stillwater Mining Company's (SMC) Stillwater Mine, Nye, Montana.

1.2 *Quantification of blast damage*

The primary objective of designing an underground blast round is to fracture the rock mass of a desired excavation according to specific design criteria (e.g., size distribution, muck pile placement, round dimensions, etc.). However, in doing so, the rock adjacent to the opening is commonly fractured and weakened. The damaged ground must be secured before further advancement of the working face can occur. This task involves scaling of loose material, either mechanically or by hand, and the installation of various ground support systems. Both tasks are highly hazardous to the miners that perform them. A reduction in the peripheral damage produced from a blast would minimize the amount of scaling and ground support needed, thus reducing a miner's exposure to these hazardous tasks.

Damage and overbreak have many definitions as reported in the literature:

1. "Overbreak can be defined as the excessive breakage of rock beyond the desired excavation limit." (Fletcher et al., 1989).
2. "Blast damage refers to the type of damage beyond the breakage zone immediately around the boreholes." (Yu & Vongpaisal 1996).
3. "Damage to a rock mass is considered to be the reduction in its integrity or quality." (Scoble et al. 1997). The authors made a distinction between inherent rock mass damage, which arises from natural processes during its evolution, and mining-induced damage, which is inflicted by the mining process itself. Mining-induced damage may relate to blasting, mechanical excavation, or the redistribution of ground stressed by the excavation process.
4. "Damage is a change in the rock mass properties which degrades its performance and behavior" (Singh 1992).

For the purposes of this project, NIOSH defines blast damage as the unintended collateral damage and weakening of the rock mass around the periphery of an underground excavation due to explosives use. References to overbreak in this paper refer to that portion of the blast damage between the intended design perimeter and final excavation perimeter as shown in figure 1.

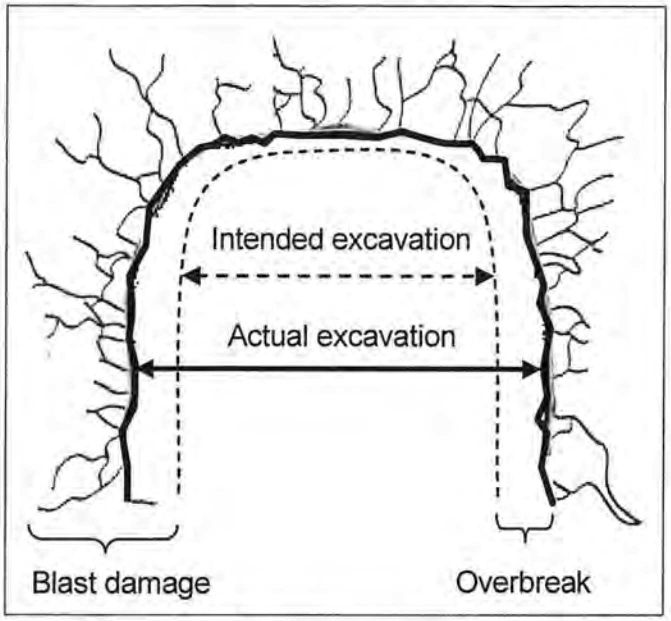

Figure 1. Comparison of "as-designed" vs. "as-built" showing overbreak and blast damage.

While the definitions of blast damage are plentiful, methods for quantifying the extent of the damage are much less accessible. This was reiterated by Scoble et al. (1997) who stated, "There is no straightforward and systematic method for adequately measuring blast damage in on-going mining operations."

The purpose of the field studies conducted by NIOSH was to investigate the feasibility of using scanning lasers coupled with digital photography and field mapping techniques to quantify the results of several blast rounds with respect to the final perimeter of the underground excavation. Information about collar locations, drill hole orientations, charge weights, explosive performance, vibration data, geological and geotechnical data and other information was also collected as part of this study.

Related project work is being done by NIOSH and cooperating researchers to quantify the extent of damage that extends beyond the perimeter of the final opening. The focus of this paper is to highlight the operational logistics and feasibility of using a three-dimensional scanning laser to quantify drift geometry and overbreak as well as to aid in collection of blasthole data. Detailed digital surveys of several development drift rounds were made using a three-dimensional scanning laser. Results were used to compare "as-designed" versus "as-built" dimensions of the drifts and to calculate overbreak percentages. Information was also collected to assess the drilling accuracy.

2 EQUIPMENT AND DATA COLLECTION METHODS

2.1 *Equipment Selection Considerations*

One of the most important components of NIOSH's initial blast audit was the measurement of the overbreak and underbreak in the underground openings. Several methods have been used in the past to measure overbreak and underbreak in underground excavations. These methods include manual measurements, standard surveying, laser surveying with reflectors, photographic sectioning, and light sectioning methods. The limitations of some of these previously used methods are that they are subjective, manually intensive, time-consuming, and often provide detailed information only for a select number of points instead of for the entire scene.

In order for an instrument to be of any practical value, the necessary data must be easily attainable while minimizing disruption to the production cycle. Maerz et al. (1996) developed the following criteria for an instrument to measure tunnel profiles successfully in a working environment:

1. Speed: measurements should not interfere with operations, and results must be available from one round before drilling begins on the next round.
2. Accuracy and precision: measurements must be reproducible, and of sufficient accuracy.
3. Simplicity: the method must be easy to implement by available personnel.
4. Cost: purchase, operation, and maintenance of the equipment must be within a specified budget.
5. Reliability: equipment must function under a large range of conditions, including high temperature, humidity and levels of dust.
6. Versatility: the method must be operational for different shapes and sizes of tunnels, shafts, and inclines.
7. Clarity of results: the output data must be immediately usable; in practice this refers to both graphical and numerical output.

As much as possible, NIOSH's field equipment selection and data collection methodology was based upon these criteria while also ensuring the instrumentation was capable of collecting the required research data.

2.2 *Field equipment used*

For the field tests NIOSH selected Leica Geosystems' HDS-3000, which is a pulsed, high-speed laser scanner with survey-grade accuracy, range, and field of view (Leica GeoSystems

HDS3000 (Leica, 2006)). The instrument supports standard surveying procedures, such as instrument setup over known or assumed survey points, height-of-instrument measurements, and instrument orientations for automated geo-referencing of scan data to local coordinate systems. The instrument is also capable of taking digital images of the scan area. Table 1 provides an overview of the system performance and capabilities of the instrument.

Table 1. Overview of Leica HDS 3000 scanner specifications

Instrument type	Pulsed, high-speed laser scanner, with survey-grade accuracy, range, and field-of-view
User interface	Notebook or Tablet PC
Scanner drive	Servo motor
Camera	Integrated high-resolution digital camera
System Performance	
Accuracy of single measurement	
Position*	6 mm
Distance*	4 mm
Angle	60 microradians
Modeled surface precision/noise	2 mm
Target acquisition**	2 mm std. deviation
Laser Scanning System	
Type	Pulsed: proprietary microchip
Color	Green
Laser class	3R (IEC 60825-1)
Range	300 m @ 90%; 134 m @ 18% albedo
Scan rate	Up to 4,000 points/sec.
Scan resolution	
Spot size	From 0-50m : 4 mm (FWHH - based); 6 mm (Gaussian - based)
Selectable resolution	Independently, fully selectable vertical and horizontal point to point measurement spacing
Point Spacing	Fully selectable horizontal and vertical; 1.2 mm minimum spacing
Maximum sample density	1.2 mm
Scan row (horizontal)	Max 20,000 points/row
Scan column (vertical)	Max 5,000 points/column
Field -of-view (per scan)	
Horizontal	360 degrees (maximum)
Vertical	270 degrees (maximum)

* At 1m-50 m range, one sigma

** Algorithmic fit to planar HDS targets

Use of the scanning laser made it possible for the researchers to collect detailed digital surveys of the underground openings without a major disruption to the production cycle and to analyze the point clouds from the scanner in terms of overbreak, underbreak, and drift geometry.

Additional blast data was collected using Instantel Minimate® Plus vibration monitors and triaxial geophones mounted along the ribs at varying distances away from the blast. Loading and timing information was provided by the miners working at the face. NIOSH personnel and contractors from the University of British Columbia's Geomechanics Group working in cooperation with Stillwater's rock mechanics and geology departments extensively mapped the geology and structural information in the test drifts. Geotechnical, geological, and blast vibration data coupled with blast performance measures and laser scan data provided a wealth of information that will be reported elsewhere. The primary focus of this paper is a discussion of the data collection methodology, field considerations, and results from the laser scanner.

2.3 *Data collection procedures*

The initial round of field tests were conducted in two separate development headings on the 4400W Footwall Lateral (44W FWL) and the 4700W Footwall Lateral (47W FWL) levels. These headings were chosen by SMC personnel based on several considerations. First, the development headings were deemed as "typical" of the conditions encountered and methods used at the mine. Secondly, the headings were of a lower priority, which allowed scheduling flexibility to accommodate research needs. Because of the lower priority, the 44W was only being worked on a single shift. This provided maximum access to the mining cycle without having to provide around-the-clock coverage. Third, both of the headings were easily accessible, making it possible to transport equipment and personnel via the 4800 decline. Finally, the headings were generally isolated from the rest of the activities at the mine, minimizing the disruption of the mine's productivity.

Laser scans were acquired before and after a series of development drift rounds for a two-week period. Average advance rates were approximately 3.7 to 4.0-m [12 to 13-ft] per round. The scanner was operated using a laptop computer connected via a network cable. The scanner was powered by one of two batteries that came with the system, while the laptop relied on internal battery power. Figure 2 shows the scanner and a typical field setup.

Figure 2. Typical field setup of the laser scanner and laptop computer.

Post-blast scans were made after the heading had been mucked out, but prior to scaling and installation of ground support. This allowed the freshly blasted face to be scanned from a distance while ensuring personnel remained under safely supported ground.

Leica Geosystems and NIOSH-designed targets were numbered and placed throughout the scan scene (figure 3). These targets allowed the scanner processing software to merge adjacent scans collected over the course of two weeks into a combined digital survey of the area. SMC staff also surveyed the target locations so the scan data could be referenced to the local mine coordinate systems. The use of targets was also useful for editing the point clouds to limit the dataset to information of specific interest, such as cross- or long-sections of the drift, drill hole collars, instrument locations, and ground supports.

Figure 3. Example of NIOSH-developed rib-mounted spherical target and identification placard used to merge overlapping scan areas.

The targets were mounted along the rib straps using magnetic bases or were screwed into holes that had been drilled and tapped in the rock bolt plates. This allowed for easy removal of the targets so they would not be damaged during blasting, but allowed for easy and accurate remount in known positions for subsequent scans.

Pre-blast scans required a higher level of detail than post-blast scans. The primary purpose of the post-blast scans was to gather sufficient information to represent the size and shape of the excavation, whereas pre-blast scans involved collection of collar locations and approximation of blasthole angles. The scanner is capable of collecting x, y, z information every 1.2-mm [0.05-in], but there is a trade-off between time to collect scan data and scan data density. The time it takes for the HDS 3000 to acquire scan data is largely dependent on the horizontal density of the scan. Many different horizontal densities were tried over the two-week period until a density was found that optimized the data density and the scan time. A full 360-degree scan at the highest density possible would require approximately four hours of actual scan time, which is impractical. NIOSH researchers determined for roughly a 6-m [20-ft] scan range a scan density of approximately 7.5-mm by 5-mm [0.3-in by 0.2-in] provided ample detail and could be completed in 45 minutes or less. At the Stillwater Mine, a 45-minute scan could easily be completed while the development crew was cycling equipment, retrieving explosives from the magazines, or conducting other tasks.

Once the face was drilled-out, but before the drill holes were loaded, a detailed face scan was performed to locate the hole collars and to estimate the drill hole orientations. To accomplish this, "scan aids" that consisted of two-foot long pieces of plastic PVC pipe were inserted in each drill hole, and the collar of each drill hole was spray-painted (Fig. 4). The paint enhanced the reflected signal of the laser at the collar location of each drill hole and made the point cloud display easier to interpret. The scan aid pipes provided an approximation of the hole

Figure 4. Laser scan of drill hole collars and scan aids. (Note: this is the actual point cloud and not a photograph).

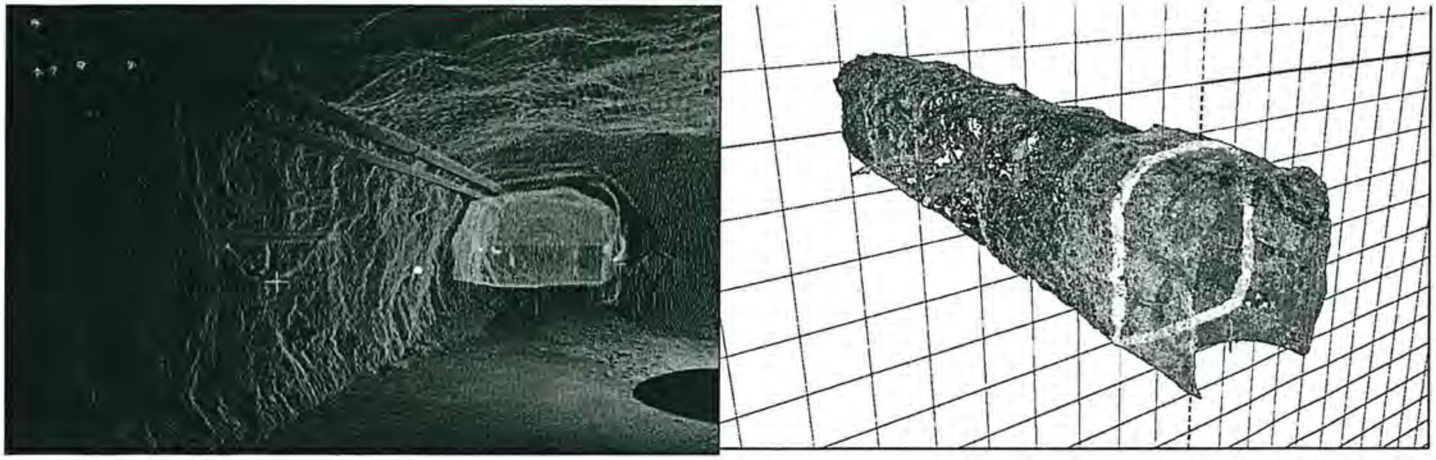

Figure 5. Examples of laser point cloud data shown from computer-generated viewpoints inside the drift (left) and outside the drift (right). Light-colored band on right side denotes a cross-sectional study area.

orientation that could later be displayed in three dimensions using the processing software.

Attempts were made to use the digital photography feature of the laser scanner. However, lighting provided by shining cap lamps in the photo region was insufficient. Subsequent attempts using auxiliary lighting from small underground man carriers were also unsuccessful. For these preliminary trials, it was decided that while the digital photographs would be useful, they were not a crucial piece of the data collection procedures.

3 RESULTS

The laser scanner output is in the form of a three-dimensional point cloud. Figures 4 and 5 illustrate samples of point cloud data. Figure 5 shows the point cloud data from two computer viewpoints: inside and outside the study drift. The information gathered in each of the scans was used to create profiles of the drift, locate the collars of the drill holes, and estimate the blast hole orientation. The data also provides a detailed image that can later be compared to field maps of geology and geotechnical data or used to view the types and amount of ground support installed.

3.1 *Computation of overbreak from point clouds*

To create cross-sections, the combined dataset was sliced into 1-foot cross-sections perpendicular to the axis of the drift. An example of one of these cross-sections is denoted by the light band on the right side of figure 5. The cross-sections were exported into AutoCAD, traced with a closed polyline, and mapped over a drawing of the planned drift geometry as shown in Figure 6. The areas and perimeters of the as-built and planned cross-section were then measured using AutoCAD and tabulated for analysis.

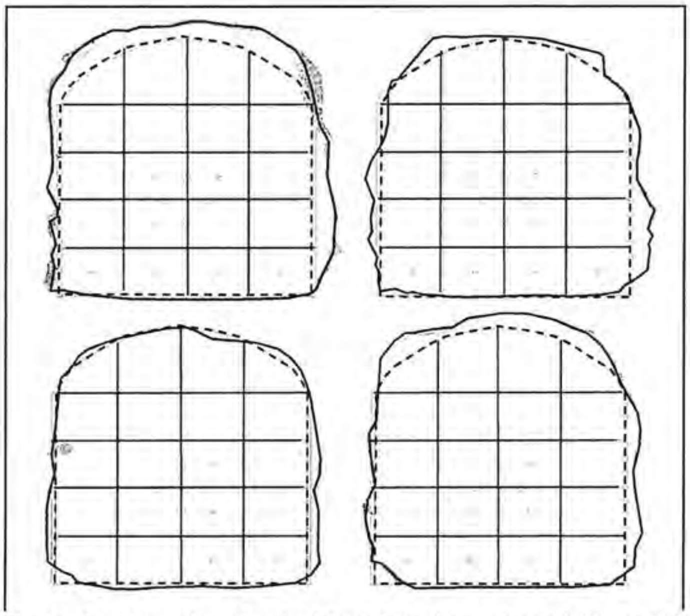

Figure 6. Examples of actual (solid line) vs. planned (dashed line) at the mid-point of select blast rounds.

Table 2 contains the measurements of percentage overbreak and cross-sectional area at the mid-point of the excavation for five blast rounds on the 44FW level. Each of the cross-sections indicated overbreak ranging from under 4 percent to over 16 percent.

Table 2. Percent overbreak and area for cross-sections along 44FW study drift.

Cross-section	% over-break	Cross-sectional area (m^2)	Overbreak area (m^2)
Planned	0%	11.3	0.0
Xsect00	16%	13.1	1.8
Xsect01	6%	11.9	0.7
Xsect02	4%	11.7	0.4
Xsect03	10%	12.4	1.1
Xsect04	4%	11.7	0.5

3.2 *Drill hole collar locations and estimation of drill hole orientation*

Along with the comparison of the as-built to the as-designed, drill hole collar locations and estimated orientations were also incorporated into the scans. Estimates of the drill hole orientations were computed by using the processing software to "fit" a cylinder to the point cloud data of a PVC pipe inserted in the drill holes as shown previously in figure 4. The processing software was used to extend the cylinders back through the entire length of the round and to estimate the end of the hole. This method of estimation does not take drill deviation into account, but does provide a quick and easy approximation of the drill hole orientation without requiring manual measurements.

In the scanner processing software, the ability to view the estimated drill hole data in three dimensions is extremely valuable. Figure 7 is a plan view of the estimated hole locations as projected from the scan aids. As can be seen in this figure, one hole near the center of the face appears to be substantially out-of-parallel with the majority of holes in the round, but overall, the hole alignment is fairly good. In contrast, figure 8 shows a side view of drill hole orientations for a sump cut-out made perpendicular to the drift. When angled in this manner, alignment of the drill boom is more difficult for the drill-jumbo operator and was most likely a contributing factor to the high degree of variability in drill hole orientations.

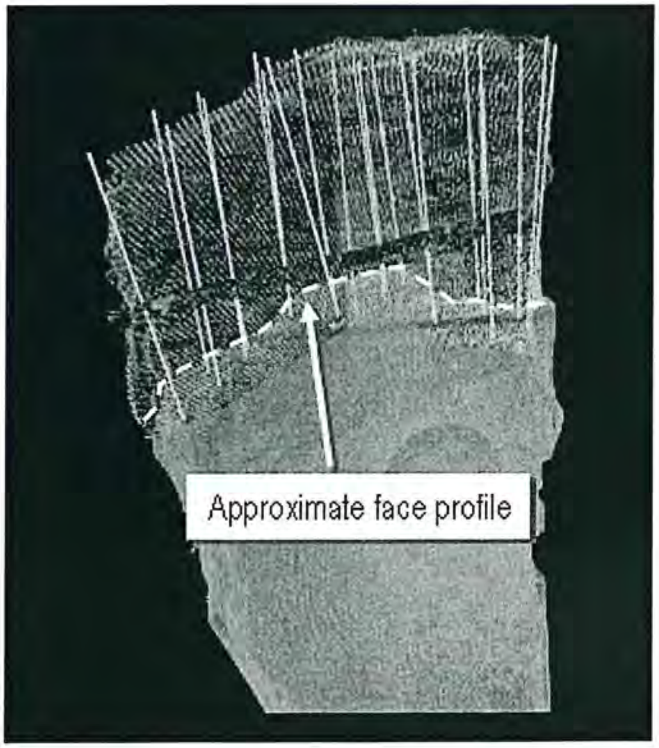

Figure 7. Plan view of drill hole locations and orientations as estimated from scan aids projected back through the length of the round.

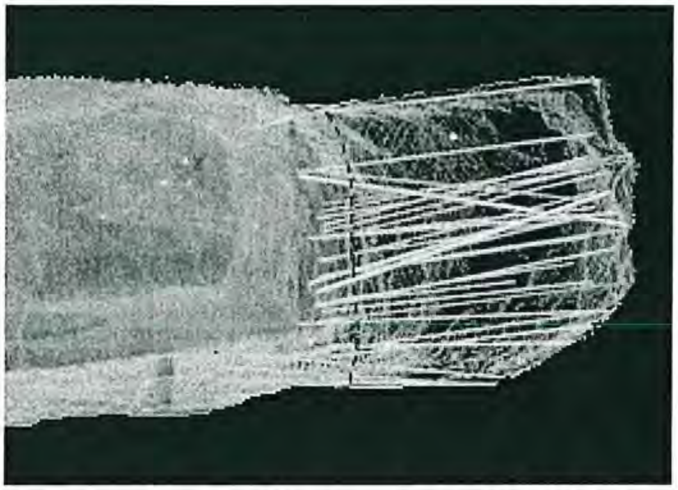

Figure 8. Cutaway side view of estimated drill hole locations and orientations for a sump being constructed perpendicular to the drift.

Poor drilling practices, poor hole alignment, collaring errors, and other deviations from the planned drill pattern can have a substantial impact on the results of a blast (Barkley, 2003; Forsyth et al., 1995, and others). Information from the laser scans could be used to help improve quality control in drilling and to show drillers the effect of imprecise drilling on the final excavation perimeter.

3.3 *Benefits of using a scanning laser in underground drill and blast excavations*

The use of the 3-D scanning laser decreases the amount of time needed to collect data on profiles, and collar locations, and provides a quick and easy estimation of borehole deviations. One previous study (Moser et al. 1996), reported that traditional surveying methods required a total of 3.5 hours for data collection (one hour to survey collar positions, one hour to survey borehole deviations, and 1.5 hours to survey blast profiles at three locations along the excavation) with additional time for data processing. With the use of a 3-D scanning laser, all of this data can be collected with a single 45-minute scan of the area and provides much more information than discrete profile measurements.

The NIOSH data collection methods satisfy the Maerz, et al. criteria – speed, accuracy, simplicity, cost, reliability, versatility, and clarity of results – for measuring drift profile. The mine personnel can view accurate and repeatable results in a readily understandable 3-D graphical format within a few minutes of completing and processing a scan. The simplicity and versatility of the system also make it possible to collect very detailed information without significantly affecting the mining cycle. The costs of the scanner are comparable to higher-end surveying equipment and therefore should be within the budgets of a typical mine.

One of the most substantial benefits of using a scanning laser is the level of detail provided by the data. High density, three-dimensional point cloud data could potentially be used to extract important geotechnical data automatically. Such efforts are currently underway by several researchers (Nasrallah et al. 2004, Kemeny & Handy 2004, Post et al. 2001, Poropat 2001, and others) to characterize the rock mass using remotely-sensed data including digital imagery and point cloud scan data. A sound understanding of the geotechnical environment is essential to develop drill and blast designs, but manual collection of information can be time-consuming and subjective and therefore is not always performed as a standard matter of practice in underground mines. However, when ground conditions are difficult to define prior to development, or when variable ground conditions exist, methods for designing and assessing the drilling and blasting practices is essential (Onederra et al., 2001) and will help ensure blast damage to the excavation is kept to a minimum. In the future blast designs may include the utilization of automated geotechnical data to refine pattern layouts and explosive selections.

Detailed digital records of the underground excavations could also be used to track the type and amount of ground support in particular regions. Subsequent scans of the area could be taken and compared to earlier point clouds to compute scaled volumes or to quantify the amount and location of sloughed material. Areas that require rehabilitation of ground support or experience rock falls could also be studied to evaluate whether the rehabilitation was necessary because of blast damage, blast disturbance, or other mining-induced causes. Any tools that could be developed to track and assess the damage from blasting would be valuable to manage the risks associated with this damage and to help mine operators design safer excavations.

4 FIELD LESSONS LEARNED

Several concepts were developed over the course of this initial study including: 1) the use of laser scan aids to register overlapping scans and to identify the drill holes in the face; 2) the use of point cloud processing software to estimate drill hole orientation; and 3) the ability to look at data in a three-dimensional environment as it is being acquired.

The custom-designed spherical targets provided the most efficient results because they could quickly be removed and reinstalled between blasts. These targets are also omni-directional, meaning they did not need to be directed toward the laser scanner, which reduced the amount of time needed to readjust the targets between scans.

Estimation of the drill-hole orientations using the scan-aids assumed that the drill holes were perfectly straight (the drill steel did not bend during drilling) and that the cylindrical scan aids placed in the hole collars were perfectly aligned with the axis of the drill hole. Precise hole orientations and deviations would require time-consuming down-the-hole surveys using specialized instrument. While the scan-aid technique of estimating the drill-hole orientations may not be exact, the information does provide a quick and reasonable approximation that can be used to monitor quality control and operator consistency.

From an operational perspective, a number of lessons were learned during the initial trials of the scanning laser in an underground environment. First, when power is not available, the laptop battery is the weakest link in the system. Provisions for extra batteries and/or a plan for re-charging need to be incorporated into the field plan. The stand-alone batteries for the scanner were sufficient to power the instrument for several scans covering an entire shift.

Standing water poses a problem for the laser scanner. The water surface may reflect and refract the laser beam adding erroneous time of flight to scanned point. Generally, this erroneous data falls outside of the confines of the scan area and can be quickly re-moved in the software but may cause problems if the noise interferes with important data.

The use of placards and spray paint on features of interest make analyzing data easier. The reflectivity of the spray paint is highly distinguishable from the host rock and makes recognition of items of interest like collars and geologic features stand out. Placards identifying target numbers, locations, and dates also greatly simplify analysis of the data.

When possible, the laser should be set up under a known point, (like a total station for surveying) to allow the data to be collected in the same coordinate system used by the mine. The software allows the user to translate the dataset to the mine coordinate system, but this adds yet another task in the data processing that would be unnecessary if the instrument was set up under a control point.

The laser needs to acclimate to the surrounding temperature. Bringing the laser from a cool environment to a warm mine causes condensation on the lenses that required upwards of an hour to dissipate.

Lighting provided by shining cap lamps or small underground man carriers in the photo region was insufficient to use the digital photography feature of the laser scanner.

Future testing of various lighting options to utilize the digital photography feature of the instrument is planned. Tests pertaining to sensitivity analyses of various scan aids, extraction of geotechnical data from point clouds, computation of scaled volumes, and analysis techniques for computation of displaced volumes are also planned.

5 DISCUSSION AND CONCLUSIONS

The collection of drift profiles, collar locations, and drill hole orientations to assess blast designs and blast performance is certainly not a novel concept. However, the authors have shown that by using current 3-D laser scanning technology to record detailed digital records of the final excavation perimeter, a wealth of information can be collected that surpasses many of the older, more traditional techniques. The instrument quickly and successfully collected data without a major disruption to the production cycle, and allowed researchers to analyze the point clouds in terms of overbreak, underbreak, and drift geometry as well as give an indication of the accuracy of drilling. Future research may allow mine operators to extract important geotechnical data automatically from the point clouds, which will foster improvements in blast design and ground support considerations. The detailed digital records provide data that can aid mine operators in tracking and assessing blast performance and quantifying effects of changing blast designs in order to improve safety for underground miners.

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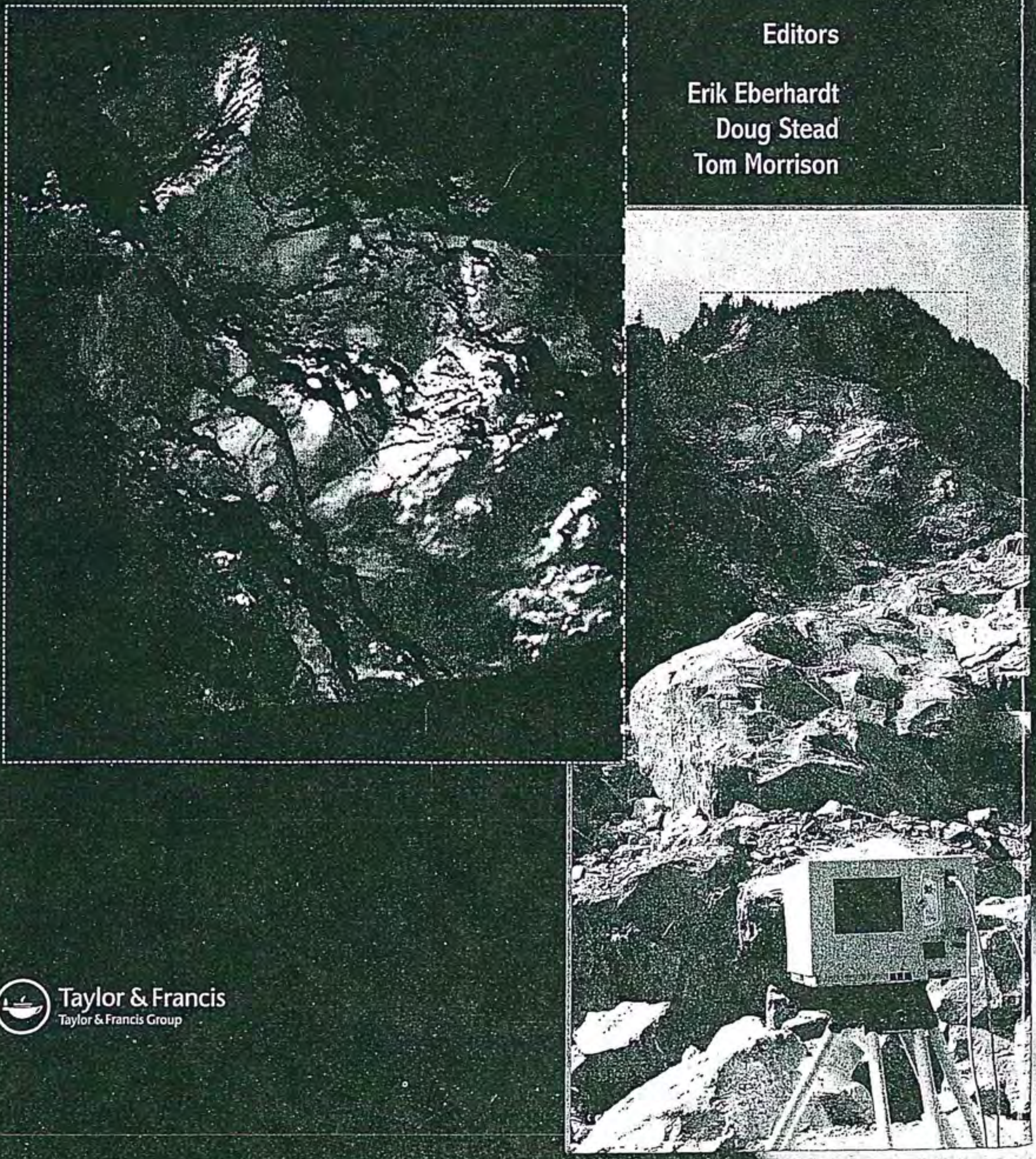

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