ABSTRACT: A necessary requirement for optimization over the complete mine/mill/leach operation is continuous and accurate data at all steps of the process allowing fragmentation, crushability/ grindability/ leach-ability, slope stability, and safety to be evaluated simultaneously. In an ideal system, these data would be analyzed centrally and used in a feedback loop to modify mining operations and process-control variables as necessary to improve performance. The objective of the project described in this paper is to demonstrate technologies that can increase the amount of information obtained during drilling, and understand how this information can best be used to improve blasting results, route blasted rock, and increase the efficiency of downstream mineral processing. The technological goals of the project presented in this paper include development of various sensors, data-acquisition systems, and online analysis tools that will allow real-time characterization of the rock mass and bore-hole measurements of mineral content during drilling.

1 INTRODUCTION

Mining and mineral processing have traditionally been approached as if they were separate entities. However, the mining industry is beginning to look at mining and milling as two interrelated components that must be optimized as a whole. There is increasing realization that greater expenditures on blasting can lead to tremendous crushing and grinding energy savings or to an increase in leach recovery (e.g. Bulow et al., 1998). One of the requirements for being able to optimize the complete mine/mill/leach feedback loop is accurate, online, and continuous data on key information on the state of different parts of the "system." This information includes the characteristics of the rock about to be blasted, the characteristics of the blasted rock about to be sent to the primary crusher, the characteristics of the rock about to enter the flotation circuit, and so on. In recent years, online systems have been developed to provide some of this information on a continuous basis.

This paper focuses on optimization of blasting, an often overlooked part of the mine/mill/leach system. The information vital to optimizing blast design includes characterization of the rock mass prior to blasting; it is widely accepted that characterizing fractures and other discontinuities in the rock mass is one of the most important inputs to blast design to achieve optimal rock fragmentation. The work described here includes development of sensors, data acquisition systems, and online analysis tools that will allow real-time geophysical characterization of the rock mass and down-hole measurements of mineral content. In addition to optimizing the rock fragmentation that results from blasting, knowing the exact location of waste rock, rock to be milled, and rock to be leached, can minimize the amount of dilution that occurs in blasting and subsequent mucking and hauling.

Image-processing techniques are being used to perform pre-blast rock-mass characterization and post-blast fragmentation analysis. These analyses are then used to evaluate the effectiveness of geophysical and x-ray-fluorescence (XRF) data in improving blast design and routing of blasted rock. The ultimate goal of the project is to integrate geophysical and XRF data with drilling data to create an adaptive, online analysis tool to optimize subsequent drilling and blasting. This technology would also yield environmental benefits by minimizing the amount of mineable ore on waste piles and maximizing the amount of processable ore sent through the mill and put on leach piles (Hopkins et al. 2000).

2 DATA COLLECTION ACTIVITIES

Two state-of-the-art techniques form the basis for the pre- and post-blast data collection activities. The
first is ground penetrating radar (GPR) information that was collected and used to characterize, in three dimensions, the rock mass prior to blasting. This information was supplemented with other drill information such as penetration rate, power, torque, drilling time, hole depth, weight on bit, vibration, specific energy, and the blastability index, which were all collected by the Acquila system installed on the drill rig. In addition, laboratory data collected from drill cores, and geological and structural maps were available. The information is being used to characterize the rock mass in terms of the parameters that are known to have the greatest influence on blastability, namely intact rock strength, fracture density, fracture orientation, fracture aperture, and the location and orientation of major structural features. These data are being evaluated in conjunction with data obtained using the new technologies being developed as a part of this project (vibration of the drill stem and XRF analysis of the drill cuttings).

The second state-of-the-art technique involves the analysis of post-blast fragmentation using image-processing techniques. The Split image-processing system, developed at the University of Arizona, was used for this purpose. In this system, digital images are taken during the process of mucking or hauling the blasted rock. As an example, for a 30-by-30-foot hole pattern with 50-foot-deep holes, it takes about 30 bucket loads (assuming a 60-yard bucket) to remove the rock associated with each drill hole. A digital video camera is used to take video images on a bucket-by-bucket basis of an entire shot. Following the work of BoBo (1997), images were taken from the cab of the shovel. Images were scaled using a laser rangefinder device, and a laptop computer is used to process the images in the field using the Split software. Details of the Split software are given in Girdner et al. (1996), Kemeny (1994), and Kemeny et al. (1993). The Split software estimates the complete size distribution of the blasted rock with an error less than 10% (Girdner et al. 1996).

The last task for the data collection activities is to create 3D maps throughout the shot area that show the pre-blast rock-mass parameters, the post-blast fragmentation, and the input explosive energy. GPS devices on the buckets allow the post-blast fragmentation information to be assigned to a location, which can be corrected for throw and other factors. The GPR and/or fragmentation information may be averaged to index all the information for a particular block size of interest.

3 DEVELOPMENT OF NEW SURFACE BLAST DESIGN MODELS

The data collection activities described above were the initial source for empirical data sets needed to develop the proposed new surface-blast design models. As described below, substantial data are available for each blast site. For the pre-blast stage: GPR 3D rock mass data, mine model geological information, blast-hole drill data from the drill monitoring system, and geotechnical properties of the intact rock together with ore content. Blast data: physical characteristics of each drill hole (diameter, location, depth, etc.), amount and type of explosive in each hole, timing patterns, and video tape of the blast itself. For the post-blast stage: rock-mass characteristics (size distribution, particle shapes, etc.) across the blast area, shape of blast pile, and other properties deemed useful. The first step was to use multi-variate statistical techniques to help identify important relationships between pre-blast, post-blast and actual blast design parameters. Then, using these initially identified relationships, and knowledge of existing blasting theory, empirical blast-design models are being developed. We propose to investigate several modeling approaches including neural networks (ability to develop mappings between input conditions and output parameters in complex environments) and fuzzy logic. Fuzzy-logic-based systems are well suited for making design decisions with imprecise, incomplete and uncertain information.

3.1 Development of an On-line Adaptive Surface Blast-Design System

Working closely with the mine operators and equipment developers, we propose to develop the functional components of an On-line Adaptive Surface Blast-Design System.

Adaptive blast design means that the blast design can be modified in real time, by changing hole patterns or the type and amount of explosive, based on newly acquired information about the rock mass. In order to implement an adaptive blast-design strategy for open-pit mines, two problems must first be solved.

First of all, technologies must be developed to accurately predict in-situ rock-mass properties. These properties must be available for a given shot before or during the drilling of holes for the shot. Secondly, accurate blast models must be available to provide guidance on how modifications to the blast design should be made in light of new information. For greatest accuracy, these models must be mine-specific, and constantly evolving based on new data. This requires feedback mechanisms in the operation that provide updated information on in-situ rock conditions, blasting parameters, and post-blast fragmentation.

The approach is simple, and is based on only three variables per hole: drilling specific energy, blast energy (kcal/ton), and post-blast F80. We recommend this as a first step in implementing an adaptive blast-design strategy. However, a limitation
ot this relatively simple approach is that it does not take into account several other important parameters, most notably fractures and the specific mineralogy of each unit volume of the lock mass. In addition, it uses only single variables to account for the blast parameters (kcal/ton) and to characterize post-blast fragmentation (F80). Although the model predicts fragmentation, it does not predict other quantities that are critical for downstream processing such as the crushability and grindability of the fragments (tor mill processing) or the leachability of the fragments (tor SX-EW processing). Technologies under development as part of the ancient project that are providing data during drilling can be used to address some of these shortcomings (Hopkins et al. 2002). These newly available data are being used to improve the adaptive blast-design model.

The path to commercialization is to integrate the blast design tool with existing commercial systems that collect and display data while drilling. The time frame for commercialization is on the order of 2-3 years. The blast-design tool can also be commercialized as a stand-alone system in which case all relevant data would be integrated and analyzed off-line to produce a blast design. In this case the time-frame for commercialization is 1-2 years.

4 FIELD TESTS IN OPEN-PIT COPPER MINES

The test sites for the work described here are located in southeastern and southwestern Arizona (indicated by the arrows in Figure 1.) The Morenci mining district hosts the largest producing porphyry-copper deposits in North America. The mining complex consists of several open-pit mining areas, a concentrator with a capacity of 75,000 tons of ore per day, and the world's largest solvent extraction/electrowinning facility. Over 780,000 tons of rock per day are hauled to either in-pit crushing systems or leaching stockpiles. In 1999, the Morenci mining district produced over one-billion pounds of copper. Mineralization is associated with a co-magmatic calc-alkaline series of porphyritic intrusions ranging in composition from diorite and granodiorite to quartz monzonite and granite (Türler et al. 2002).

The Siernte Mountains are about 25 miles southwest of Tucson Arizona. The mine for the field work is located in the eastern foothills of the Siernte Mountians. The mine contains a low-grade copper deposit and became operational in 1969. Ransome (1922) noted that the Siernte range consisted primarily of an intrusive granitic core flanked by sedimentary and volcanic rocks that have been metamorphosed to various degrees. He also observed that the intruded rocks on the eastern side included volcanic and clastic sedimentary rocks of Mesozoic age as well as Paleozoic limestone and Precambrian granite. Where the test mine is located, the geology shows tertiauy intrusive rocks including andesite, diorite, granodiorite, quartz monzonite porphyry, and Jurassic quartz monzonite (Coopei 1971). The mine has an annual ore production of 40 million tons (of which 22 million tons goes to a solvent extraction/electrowinning facility). The average grade of copper is 0.3% and molybdenum is 0.03%. The mill cutoff value for copper is 0.33% Cu.
5 TECHNOLOGIES USED

5.1 X-ray-fluorescence (XRF) mineral-content sensor

X-ray-fluorescence (XRF) spectroscopy is routinely used to analyze atomic composition in a wide range of applications including mining, oil-well logging, environmental monitoring, and materials evaluation. The research challenges of adapting the technology for use as a downhole tool include ensuring reliable and accurate measurements in a harsh environment, ensuring worker safety, and minimizing interference with the drilling operation.

For the prototype system, dust and cuttings are collected through a nozzle placed near the borehole. A venturi-suction system using compressed air supplied from the drill rig provides a continuous sampling of material during drilling. Exhaust from the venturi system is routed to the cyclone where the solid material is separated from the air. Detailed information about the system is given by Türler et al. (2002).

Figure 2 While corresponds to high copper concentrations compared to darker colors, which indicate relatively low copper concentrations.

The borehole profiles shown in Figure 2 indicate that the distribution of copper ore varies considerably over the length of the borehole, and between boreholes on the same bench. These results must be confirmed by analyzing the effect of sampling bias introduced by the collection method.

There is also interest in determining if the XRF data can be used to help identify rock types or rock properties such as hardness that would be valuable information for blasting engineers. Classification methods were used to analyze 71 samples, for which 11 groups were identified (Figure 3). The rock classification task is complicated by several factors including sampling errors, mixing of dust particles in the borehole, and the difficulty of trying to discern rock properties based on elemental composition. The accuracy of classification techniques can be improved by including site-specific information in the analysis.

Figure 3 Rock groups in adjacent boreholes on the same bench

Work to date has demonstrated the feasibility of collecting samples during drilling and using x-ray-fluorescence (XRF) spectroscopy to analyze mineral content. There are several paths to commercialization. An integrated sample collection and real-time mineral-content analysis system could be built either as a stand-alone system, or integrated with existing software packages that collect and display other drill data. The technology for sampling dust/cuttings during drilling can be commercialized separately; in this scenario the samples would be analyzed off line, e.g., in the mine's assay lab.

Commercialization would be pursued with companies manufacturing drill rigs or equipment for rigs; companies have expressed an interest in the technology. The XRF analysis and display system can also be commercialized separately; in this scenario the portable system would be used by mining personnel to obtain real-time measurements of mineral content in the field using existing sample-collection techniques. Integrating analysis and display software developed for the project with commercially available portable XRF systems is the fastest path to commercialization for this technology, and could be achieved within 1-2 years.

5.2 Fracture detection using GPR measurements and drill monitoring systems

Cross-hole radar surveys are conducted using a zero-offset profile method to obtain arrival time versus depth in adjacent boreholes. For the field tests in Arizona, the borehole radar system transmitting at either 50 MHz (for hole spacings between 20 and 30 feet) or 100 MHz (for holes spaced less than 20 feet apart) was used between adjacent boreholes (Hopkins el al. 2002). The bench where experiments were conducted at one of the mines included a fault.
providing the opportunity to test the sensitivity of radar to highly fractured zones. The radar data was used to help interpret data collected during drilling, and to determine the ability of the radar to delineate the fault zone. The first results show that GPR measurements distinguish the competent rock from the rock mass in the fault zone (Figures 4 a,b).

Figure 4a GPR signal from a heavily disturbed rock mass. Vertical axis is the depth of the borehole versus travel time of the waves.

Figure 4b GPR signal between the boreholes in competent rock.

The commercialization potential of field geophysical systems such as cross-hole radar depends on the value of the data. Costs are higher than for systems that can be deployed on the drill rig because of increased labor costs. Incorporating the geophysical data with other drilling data is less straightforward because it would not be collected at the same time. However, the data collected is likely to be more easily interpreted than data collected on the rig, and equipment to measure data is well developed and commercially available. Time to commercialization of a stand-alone system including software to analyze and visualize data is on the order of 1-2 years. The commercialization timeframe for a system integrated with other drill and rock-mass data is on the order of 2-3 years.

5.3 Fracture detection using accelerometers mounted on the drill rig

To determine the feasibility of using accelerometers to measure drill-rig vibration data during drilling and using the data to infer information about rock and fracture properties, field tests have been conducted using sensors attached to the drill rig. The accelerometers used have a bandwidth of 400 Hz and a range of +/- 40g. A specially designed collar to house the accelerometers was placed around the drill stem just below a vibration damper that is original equipment on the drill rig. This placement allowed the accelerometers to be as close to the drill bit as possible. Data was transmitted via FM radio at 418 and 433 MHz to a PC-based data-acquisition system (Figure 5). A sampling rate of 2000 samples/sec/channel was used to collect the data (Hopkins et al. 2002). The use of a wireless transmission system allowed installation of the collar on the drill stem and data collection during drilling with minimal impact on the rig and drilling operation.

Figure 5 Vibrations recorded on the drill stem by accelerometers. The horizontal axis is time (seconds) and the vertical axis is acceleration (g).

Data are being analyzed to determine if vibration of the drill stem can be used to identify fractures. Commercialization potential depends on value added by additional information gained from geophysical measurements under investigation. A system based on vibration measurements made on the drill rig has the shortest path to commercialization because it can be incorporated into existing commercial systems that collect and display other drill data. The project's drilling partner is interested in commercializing the technology if it proves viable, so that commercialization within a timeframe of 1-2 years is possible.
5.4 Split image processing software

A proven method to assess fragmentation is to acquire digital images of rock fragments and to process these images using digital image-processing techniques. For post-blast size characterization, this is the only practical method to estimate fragmentation because screening is impractical on a large scale. The image-processing techniques being used for the assessment of fragmentation were developed at the University of Arizona between 1990 and 1997. Since 1997, development work has continued at Split Engineering, LLC.

At one of the test mines in Arizona, the Split online system is installed at the in-pit primary crusher, where digital images of both feed and product are continually processed and recorded (Figure 6a and 6b). These systems are set to process three contiguous images of either feed or product approximately every 90 seconds. The feed cameras are located at the truck dump bays; the product cameras are located above the discharge belts. The resulting size data from the Split system is imported into a mine-wide database where truck-by-truck averages of the feed and product sizes are determined.

Several new technologies are being utilized to trace the crusher feed and product size information back to the original position of the rock on the bench. This is accomplished on a truck-by-truck basis utilizing technologies that include an accurate time/date stamp incorporated into the Split data associated with each truckload of ore. Modular Mining’s dispatch system to trace the trucks back to the bench, and GPS-equipped shovels to determine the location of the material dumped into each truck (Kemeny et al., 2001, 2002). The values of the post-blast 80-percent passing size (F80) around each hole are averaged, and this hole-by-hole data is used in the development of fragmentation models.

5.5 Measuremeiu-while-drilling (MWD) Data

In one of the field tests, data was recorded over a four-day period in March 2002. Drill data was collected through a SR-2 cable connected directly to the drill monitoring system. As the available memory in the system was small (less than 6 Mb), all blasthole data had to be downloaded immediately after drilling to prevent the data from being overwritten. Data from nineteen blastholes were recorded during the trial. In some cases, the MWD data was lost because the computer system crashed during drilling. In other cases data was lost when the satellite signal was lost. In one instance, it took a very long time to drill the hole, and the size of the MWD file generated by the acquisition system exceeded the available memory size and was lost. During drilling of each blast hole the drilling time, hole depth, rotation of the drill bit, weight on bit, torque, air pressure, vibration, blastability index and specific energy were recorded.

5.5.1 Data Acquisition

The normal sampling rate of the MWD acquisition system used was increased from approximately 5 Hz to 15 Hz during the trial. As there is more than one channel for data acquisition, the actual acquisition rate per channel is about 2 Hz per channel. Data was recorded directly into a laptop computer on the drilling rig because the higher sampling rate generated larger files than normal and the radio system at the mine site was already close to its maximum capacity.

5.5.2 Data Analysis and Interpretation

Based on the similarity of the mechanical processes in crushing and drilling, the concept of specific energy is potentially a link between MWD data and comminution properties (Segui 2001). Specific energy is defined as the work done per unit volume excavated. The concept is based on the assumption that
a certain amount of energy is necessary to excavate a
given volume of rock The amount of energy de­
pends entirely on the nature of the rock. In trying to
relate this theoretical value to what would be re­
quired to crush the rock in a mill, it would be neces­
sary to account for energy losses in the process,
for example, machine wear and mechanical losses.
Contour maps of specific energy were created for
all the shots monitored during the field tests. SE
contour maps for two shots separated by a backbreak
zone of about 15 m are shown in Figure 7. A highly
structured fault zone between the two shots created
the backbreak effect. There were no blastholes in
that area, and, thus, no information available in terms
of MWD data.
The geological maps of the mine show a north­
est-southwest fault that crosses exactly over the two
shots pictured in Figure 7. What can be inferred
from available specific-energy data is that the rock
strength is different on the two sides of the fault. The
rock mass on the eastern side of the fault is softer
than the rock on the western side

![Figure 7 Specific energy contours of the two shot locations. Lighter colors correspond to higher specific energy values compared to darker colors which indicate relatively low specific energy values. Low specific energy is associated with softer rock. The straight line indicates the trace of the fault line on the bench.](image)

6 CONCLUSIONS

Work to date has demonstrated the feasibility of in­
tegrating dulling, rock-mass, blasting and post-blast
fragmentation data to improve blast design. Data
from field tests have been successfully used to im­
pove blast-fragmentation models. Thus, an adaptive
blast-design tool that would allow blasting engineers
to better optimize blast parameters including the lo­
cation of boreholes, the charge per hole, and the
timing of detonation, has strong commercialization
potential. With this system, blasting could be opti­
mized for specific downstream processes on a hole­
by-hole basis, and would be applicable to most any
process including crushing and grinding, leaching,
and disposal on a waste pile.

Modeling work to date is based on three parame­
ters that are available for each blast hole: drilling
specific energy, explosive energy per volume of
rock and post-blast 80% passing size determined
using the Split imaging system.

New technologies under development as part of
the cement project are providing data during dulling
on rock properties, structures, and mineral content.
These data will be used to improve the blast-design
models. A dull collar housing accelerometers and a
wireless transmission system has been demonstrated
in the field. Field tests conducted with a prototype
dust-collection system demonstrate that it is possible
to continuously sample dust and cuttings during
drilling. Ground-penetrating radar measurements
seem promising to determine the major discontinui­
ties on the bench. Ongoing work is focused on un­
derstanding how to use the data and vibration data
to detect fractures, and on developing a fully poit­
able on-line dust collection system for mineral con­
tent measurements.
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