DRILLING INACCURACY IN BLAST PATTERNS: EXPERT TIPS FOR SAFETY, ACCURACY, EFFICIENCY, AND PROBABILITY

JUNE 2019

ABSTRACT

// RESPEC's drill and blast team has spent a significant amount of time traveling the globe to work with surface and underground mining operations and construction projects with the goal to improve safety, accuracy, efficiency, and profitability. The first step in helping any drill and blast operation, regardless of application, is to understand its baseline practices, and there is no better way to do that than to visually observe the operation and collect data from drill and blast instrumentation tools and survey equipment.

This white paper provides an overview of the survey equipment that our team uses to identify the root causes of issues related to drill and blast operations. Without proper measurement, one can usually only guesstimate a root cause or possibly address a single surficial problem that could create additional complications. The instrumentation discussed here can help point to causes of problems, from the inherent geologic environment to drill and blast design, drill and blast practices, drill equipment, and explosives issues, among other potential sources.

The benefits of using borehole survey equipment, downhole cameras, and other drill and blast survey equipment for as-drilled surveys in surface and underground environments are discused in this white paper. Provided case study examples demonstrate how new technology has improved safety and prevented potentially significant mishaps. This document includes the following sections:

- Background on Drilling Inaccuracy
- Negative Effects of Drilling Inaccuracy
- Causes of Drilling Inaccuracy
- How to Quantify Drilling Accuracy
- Selecting Preloading Drill and Blast Survey Tools

Our professionals are pleased to collaborate with you to solve all of your mining and operational needs. For more detailed technical information about RESPEC's drill and blast expertise, contact Nathan Rouse (*nathan.rouse@respec.com*).

INTRODUCTION

Around the world, surface mining and quarrying operations are investing in drones and other improved state-of-the-art technology for measurement and data acquisition. This technology has, in turn, drastically improved RESPEC's capabilities in the field by allowing us to survey every blast and evaluate and account for blast variables that have not been traditionally managed.

In the past, blasters received inadequate data for their projects, which caused incorrect decisions to be made during the blasting process and undesired costs to accumulate. Today, RESPEC's clients receive better data, increased accuracy, and significant cost savings by using technological improvements that access previously unmeasurable or off-limit areas in both surface and underground operations. Drones, laser technology, photogrammetry, and other survey methods now help us better understand every detail of a blast before a shot is fired as well as account for those details in the blast design. As a result, our clients save incalculable amounts of time and money.

This white paper focuses on the technology that RESPEC uses to measure the design of blastholes to actual as-drilled blasthole geometry.

RESPEC'S SOLUTION FOR AN INDUSTRY PROBLEM

Best practices are not always followed in the drill and blast industry because of perceived cost and time issues. Specifically, many decision-makers believe that preloading surveys are too expensive or take too much time and will, therefore, interfere with production.

From a safety and quality perspective, RESPEC's solution includes practices that are helpful but also quick and relatively inexpensive; in fact, some practices have little to no cost. The efficiency and cost-savings benefits of these practices often cause clients to change their perspectives and operational methods almost immediately.

To understand the benefits of measurement in the drill and blast industry, one must first understand the background of geology, drilling, and drilling practices. Accordingly, this document provides contextual information on these points before discussing the instrumentation and technology associated with drilling accuracy measurement.

Background on Drilling Inaccuracy

// Drilling inaccuracy is defined as drilling that is not to design. Understanding drilling inaccuracies and their causes is an important step in analyzing the data we collect with drill and blast instrumentation. To achieve accuracy, your team needs to understand the four types of drilling inaccuracies that can occur. Figure 1 shows these inaccuracies in a surface-mine setting with a free faced bench, but these definitions can apply equally to underground applications.

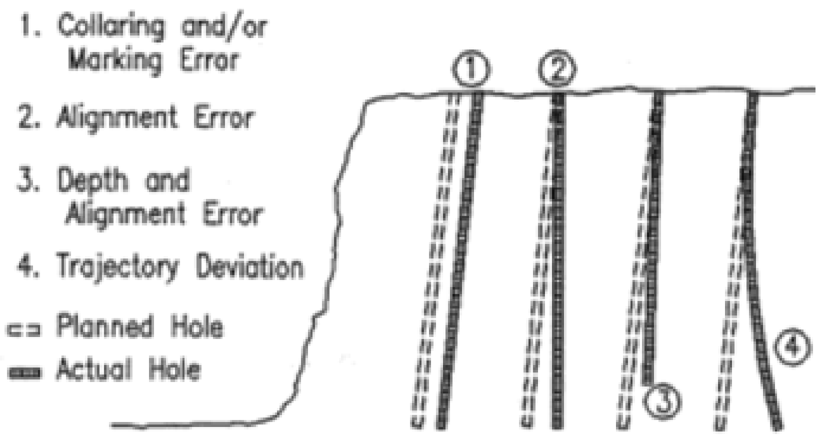

Figure 1. Four Types of Drilling Inaccuracy [Singh, 1996].

COLLARING AND/OR MARKING ERROR

The first inaccuracy shown in Figure 1 is a collaring (or marking) error, where the hole is not collared at the designed location. The Office of Surface Mining Reclamation and Enforcement (OSMRE) Drillers' Training Module [OSMRE, 2017] describes this error as "the lateral displacement of the hole from its planned starting point." Causes listed include site topography, poor setup, and equipment wear. Poor bench preparation can also hinder the driller's ability to accurately collar. In some instances, collar error will lead to drilling unnecessary holes if the correct burden and spacing are not used.

ALIGNMENT ERROR

If the hole is collared reasonably close to the planned position, additional inaccuracy could occur in the actual versus the planned borehole path. This inaccuracy can be distinguished in the alignment error, depth error, and trajectory deviation. In a drilling accuracy report by Harris [1999], the author stated that more than 50 percent of borehole path inaccuracy is caused by the drill operator.

Alignment deviation can be caused when the mast is not at the correct angle before drilling begins, as shown in Figure 1. The deviation occurs when the hole is started at a different inclination or azimuth than what is stated in the design. The inclination and azimuth can also be affected during the collaring process because of geology or equipment factors.

DEPTH AND ALIGNMENT ERROR

Figure 1 also shows a depth error, which can be caused by the operator, miscommunication, or the effects of other deviations. If the hole is drilled to the correct length but at the wrong inclination, the effective depth will either be higher or lower than planned. For example, if the hole is designed to be vertical but drilled at an angle, the effective depth will always be short and can thus affect floor breakage.

TRAJECTORY DEVIATION

Trajectory deviation is characterized by changes in the borehole path during the drilling process, but identifying the cause and quantifying the error for this type of drilling inaccuracy are difficult. Contributing factors can include hole design, drill parameters, equipment, and rock-mass properties [OSMRE, 2017]. In particular, the drillhole diameter, inclination, rock type, anisotropy, thrust, revolutions per minute, chuck type, drill string mechanics, and stabilizer characteristics have been determined to be major factors that govern this type of deviation [Hendricks et al., 1994].

Negative Effects of Drilling Inaccuracy

// Overburdened and underburdened blastholes can produce negative effects. The extent to which overburdening, underburdening, and varying confinement affect safety and blast performance depends on each operation, which is why preloading surveys are vital. The benefits of an optimized shot design can be negated by poorly confined blastholes.

FLYROCK

For surface operations, flyrock is the main safety concern in poorly confined blastholes, especially along the front row of a blast. If the actual burden drops below the critical burden, flyrock and premature blowout on the face can occur. Flyrock can be caused by a single hole deviating toward the face or lateral deviation toward another hole, which results in a higher concentration of explosives than originally designed for that point. Flyrock and blowouts can also occur because faces are undercut or have overhangs that remain from previous blasts.

A flyrock prevention program [Giles and Roller, 2012] was published in 2012 with the main objective of preventing hazardous scenarios. Two-dimensional (2D) face profilers were used to obtain the free-face geometry in front of each blasthole, and several types of deviation measurement devices were used to determine the actual hole path. Combined, this information showed the actual burden through the entire hole length compared to the design. The study concluded that the measurement of the face profile and borehole orientation were beneficial in reducing flyrock potential. Bench face information can also be obtained by using a three-dimensional (3D) face profiler or with a drone and photogrammetry. Choosing between a 2D or 3D device depends on the operation.

BENCH GEOMETRY

Poor confinement can cause negative effects in bench geometry. For example, uneven floors can occur when the hole is not drilled to the correct depth or is drilled at the wrong inclination. Changes in elevation can also result in inefficiencies and undercarriage wear. If not corrected, these conditions will be mirrored in the bench below [Fritz, 1998].

Drilling inaccuracies can also result in poor highwall conditions and create challenges for future blasts. For example, if the last row is not drilled straight, the face of the subsequent blast will be uneven and result in burden variances or extra time spent adjusting the pattern. Backbreak can also occur when a hole in the last row is drilled behind its designed position in the bench. The effects of any prefractures might not be realized until the next blast occurs.

DILUTION AND ORE LOSS

The negative effects of drilling inaccuracies can also include dilution and ore loss, especially in an underground setting. Dilution is overblasted rock, and ore loss is unblasted rock. Dilution results in unwanted material being mixed with the ore; this material needs to be mucked, hauled, and processed, which

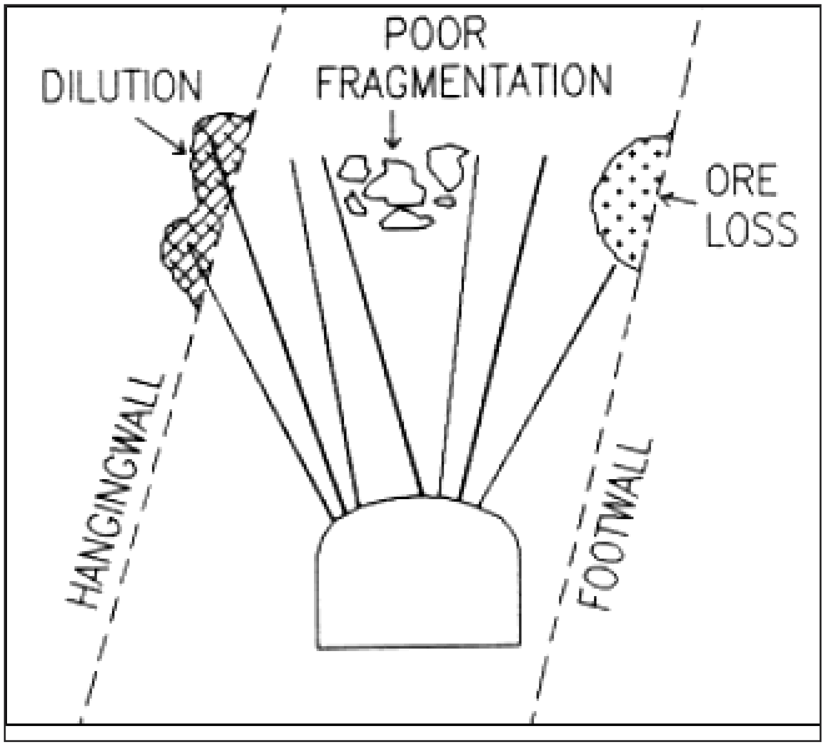

Figure 2. Types of Underground Drilling Inaccuracies [Singh, 1996].

affects drill and blast costs because of the volume of material (much of it waste). The opposite can be said for ore loss, where valuable material is left in a stope. Figure 2 illustrates how drill depth inaccuracy can cause dilution and ore loss in an underground setting. The figure also provides examples of collar, alignment, and depth inaccuracies in an underground setting.

POWDER DISTRIBUTION

Blast performance is affected by powder distribution within a pattern. Powder distribution can be poor and lead to fragmentation issues if drilling is poor; the effects of poor fragmentation, such as increased secondary breakage, are well known.

If the actual burden is greater than the designed burden, or if the drillholes deviate, the blast can be overconfined and cause the following problems:

- Oversize
- Poor fragmentation
- Stemming ejection
- High ground vibrations
- Excessive airblast.

If two holes converge toward one another, or if the holes are underburdened, the blast can be underconfined and cause the following problems:

- Premature blowout on the face
- Flyrock
- Excessive airblast
- Poor fragmentation
- Excessive fines
- Sympathetic detonation (i.e., high ground vibration)
- Deadpressing (i.e., no detonation).

Causes of Drilling Inaccuracy

// Knowing what to look for is the first step in understanding that an issue with poor drilling or poor face geometry has occurred. Many factors affect drill accuracy, but they can be divided into four overall categories: geology, driller experience, hole design, and equipment and practices.

GEOLOGY

The drilled geology has a significant effect on the hole's trajectory and the blast's loading conditions. According to a study by Hendricks et al. [1994], "the rock mass is the only factor which is entirely beyond control. Provided that judicious drilling practice is maintained, then trajectory drilling accuracy/deviation is predominantly a consequence of the bit-rock mass interaction." While this factor cannot be controlled by the operator, understanding how the geology affects the process is beneficial.

A detailed study [Singh, 1996] reviewed research from the oil-and-gas industry and conducted fieldwork to better understand the effects of geology in the blasthole drilling process. Figure 3 compares deviation tendencies when drilling through rocks of varying hardness. Deviation is caused by movement generated at the bit through the rock transition, and deviation caused by this transition was found to be worse with higher drill thrusts.

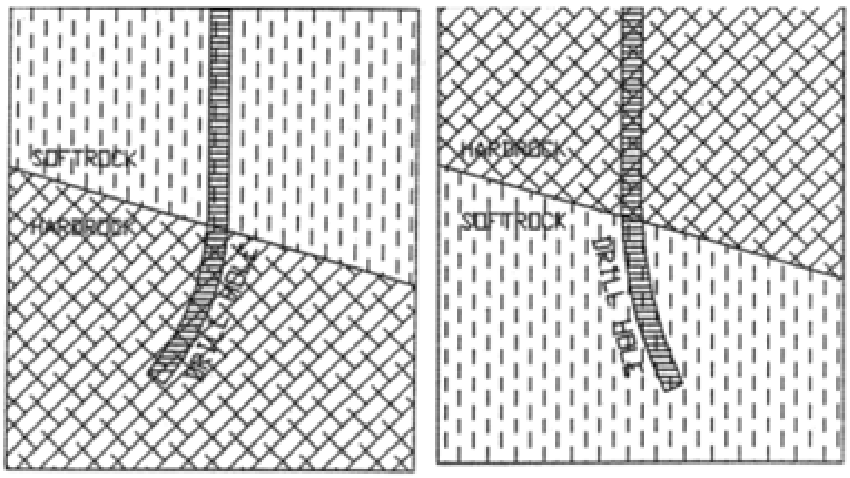

Figure 3. (Top Figure) Comparing Deviations Between Drilling From Soft Into Hard Rock (Left) to Drilling From Hard Into Soft Rock (Right) [Singh, 1996].

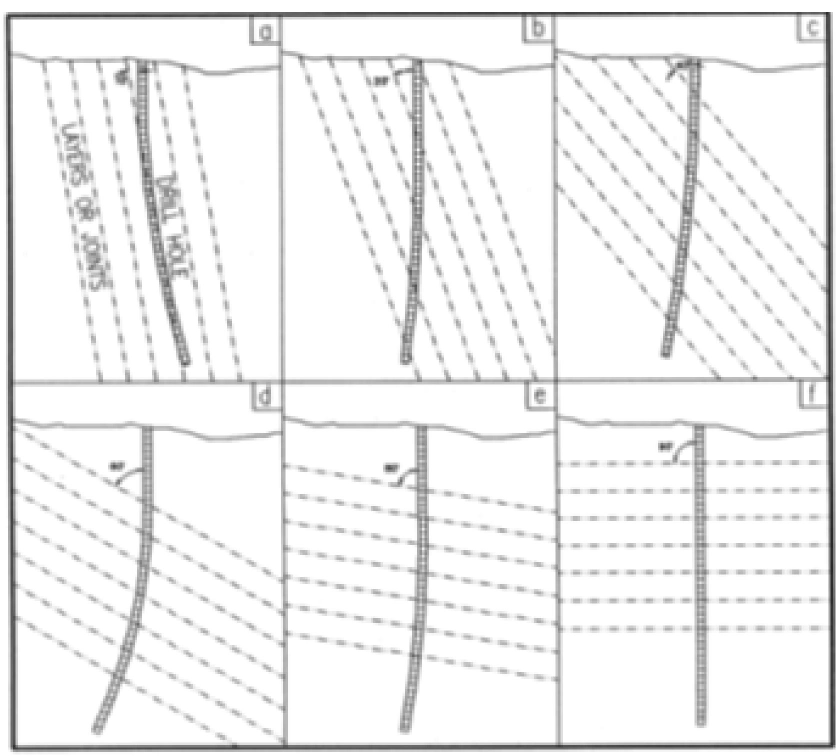

Figure 4. (Bottom Figure) Effects of Layer Inclination on Drillhole Deviation.

Figure 4 shows the effects of layer inclination on drillhole deviation and the trends of deviation based on the angle of foliation and bedding in the rock mass. If the bench is oriented so that the beds dip into the face, deviation will be toward the free face, which is concerning.

Singh [1996] found that, for soft and medium-hard rock, side cutting and other variables were more responsible for hole deviation, and the geological features "generally produced low key influence on hole trajectory." Side cutting is caused by the friction of the rod string against the hole wall when the rod is bent, which can enlarge the hole diameter at these points and increase the room available for the rod string to bend further. For hard rocks, Singh [1996] stated that "geological features play a more significant role in causing deviation," and also determined that weaker bonds and smaller layering intervals lead to higher deviation. Voids and clay infilling can also cause the drill bit to lose direction and deviate from its design path.

DRILLER EXPERIENCE

Operator inexperience can contribute to all types of drilling inaccuracy, and the most common scenario is new operators rushing to compensate for their lack of experience. Because new operators are slower at running equipment than experienced drillers, they may take shortcuts to complete the job in the required time frame. Lack of attention can result in a less accurate collar location and reduced setup times, which can result in alignment errors. The hole will likely be drilled at a higher-than-optimal rate to minimize trajectory deviation, which can affect hole depth accuracy. Overcoming operator inexperience must be a combined effort between the driller and blaster.

HOLE DESIGN

In hole design, small-diameter holes have a greater potential to deviate than large-diameter holes [Singh, 1996], and angled holes have a higher tendency to deviate than vertical holes. Because the effects of drillhole design are widely known, these are not discussed in this white paper.

Quantifying drilling accuracy and face geometry is one of the most important safety steps for an operation. Fortunately, today's technology offers many measuring options.

EQUIPMENT AND PRACTICES

Drill parameters that affect deviation include thrust, percussion, rotation, and flushing velocities, while equipment parameters that affect deviation include the condition of the bits, rods, stabilizers, and couplings [OSMRE, 2017]. Drill-string mechanics and theories are discussed in further detail in a paper by Murphy and Cheatham [1966].

How to Quantify Drilling Accuracy

// Quantifying drilling accuracy and face geometry is one of the most important safety steps for an operation. Fortunately, today's technology offers many measuring options.

PREDRILLING INSTRUMENTS

Not all drills are equipped with devices that show the operator the rod angle before the drilling begins. For vertical holes, a bubble level can be used to prevent alignment errors and for angled holes, an inclinometer can help ensure that the drill rod is positioned correctly before collaring, as shown in Figure 5. To ensure that rows are straight and at the correct azimuth, the operator can use a guide wire. Physical surveying of drillhole collars is a good practice to ensure that the collaring locations are accurate. All of these devices are extremely affordable and can prevent collar and alignment errors.

Figure 5. In a Philippines Mine , RESPEC's Team Uses an Inclinometer Before Collaring.

POSTDRILLING INSTRUMENTS

After the hole has been drilled, a beneficial practice is to compare the results to the design. Figure 6 shows the deployment of a rodded Boretrak™ borehole survey tool. Downhole cameras, which have a wide range of cost options, are used to examine the borehole for cavities, damage, and actual length, as shown in Figure 7. Several methods are used to identify borehole deviation and are discussed in the following text.

LIGHT METHOD

The least-expensive method of identifying borehole deviation is to lower a flashlight or glowstick into the hole. If visibility of the light is obstructed, a trajectory deviation could exist in the hole. Note that, while the hole could appear straight, this method would not reveal whether or not the hole was drilled at the correct deviation unless it was extreme enough to be visible from the surface. The flashlight method is useful for projects with limited capital.

MIRROR METHOD

The mirror observation method is another way to examine drillholes [Australian Drilling Industry Training Committee, 2015]. A mirror (sometimes tripod mounted) is placed above the collar to reflect sunlight down the hole. A plumb bob is then lowered into the hole on a string, with the position of the string at the collar where the plumb bob touches the hole wall to indicate hole inclination. By measuring the distance between the string and the wall, along with the depth of the plumb bob, the inclination can be calculated by using simple trigonometry. The drawbacks to this method include insufficient sunlight and inclination. Moreover, depending on the hole's diameter, the hole might not have enough room at the collar for the plumb bob to hang freely, which is required for accurate measurements.

LIGHT WITH OPTICAL DEVICE

Optical devices that show deviation in degree measurements have been designed to improve on the flashlight method. One such device provides the inclination and direction for a given borehole [Stemlock, Inc., 2013]. An LED flashlight is first lowered into the hole, and then a handheld optical device is leveled

Figure 6. (Left) RESPEC's Team Deploys a Rodded Borehole Surveyor in a Ghana Mine.

Figure 7. (Right) RESPEC's Team Uses a Downhole Camera to Examine a Borehole in a Ghana Mine Project.

Optical flexure instruments determine direction changes by using optical measurements of light reflected off rings within the housing. As the instrument bends in the hole, the rings are offset accordingly, which indicates a change in direction.

and moved over the hole until the light lines up with the vertical crosshair, which has tick marks to indicate the inclination from the viewpoint to the light source. The direction is measured and compared to a baseline, which is usually a string that is parallel to the bench face. The optical device is then rotated 90 degrees, and the light is centered in the middle of the crosshair.

In a flyrock prevention program study from 2012 [Giles and Roller, 2012], accurately measuring the angled borehole deviation in the front row was crucial. However, the study found that using the optical device approach had positive and negative consequences. Affordability and ease of use were noted, along with measurement time being shorter than with a Boretrak™ system. Another advantage was that a computer was not required to process the information because readings are taken manually.

However, Giles and Roller [2012] also noted "numerous pitfalls, many that are quite substantial." Boreholes were measured using the optical device and a borehole survey system, but when the readings were compared, the optical device showed high variance. This variance was not caused by inaccuracy but by device limitations: the device only measured deviation perpendicular to the face, so deviation parallel to the face was not recorded.

The system also requires a line of sight because the operator must visually see the light in the borehole, which can become a problem at hole depths of 15 meters (50 feet) or greater [Giles and Roller, 2012]. The nature of the deviation also posed a potential problem: if the hole does not deviate constantly, the device might provide an inaccurate reading because it operates in a straight line from the handheld device to the light.

The study noted additional limitations, including excessive dust that limited the view in the hole and excessive water that caused problems by distorting the light. Collar pipes were also found to limit the view of the light past the end of the pipe. The report by Giles and Roller [2012] summarized all of these limitations by stating that "it can be difficult to take a reading at the necessary depth within a borehole in order to obtain the most accurate data."

OPTICAL FLEXURE AND SIGNAL-EMITTING DEVICES

Additional survey instrumentation includes optical flexure devices and signal-emitting devices. Optical flexure instruments determine direction changes by using optical measurements of light reflected off rings within the housing [Cook, 2005]. As the instrument bends in the hole, the rings are offset accordingly, which indicates a change in direction. A built-in camera records these changes, and accelerometers determine the corresponding dip. The software then processes this information to determine the borehole deviation based on the surveyed collar and starting azimuth. Optical flexure devices are not affected by magnetism and can be used in certain rock types and within the actual drill rods themselves. A signal-emitting device is operated by lowering an emitter probe to the bottom of the hole [Coda Technologies, 2017]. A receiver is held near the toe of the bench at a safe distance from the highwall, and the device determines the approximate burden at that point.

BOREHOLE SURVEY INSTRUMENTS

360°

Gyroscopes can be used to conduct surveys with a full 360 degrees from vertical in any direction and without magnetic interference.

To overcome line-of-sight limitations and obtain higher accuracy, borehole survey instruments were designed to survey the entire length of the surface and underground boreholes. These devices (e.g., the Carlson Boretrak™ borehole survey tool) have been used for many years and represent the best method of surveying drillhole accuracy. Sensors that are used to collect dip information are typically inclinometers or accelerometers, depending on the manufacturer [Hendricks et al., 1994]. The main difference between devices is in how they establish device orientation.

Cabled instruments, which can be used in downhole applications, measure device orientation by using a digital compass [Renishaw, 2016]. Orientation measurements are necessary because the instrument can rotate during the course of a survey and provide inaccurate results if uncorrected.

The presence of magnetic material can affect the operation of the digital compass. Survey results showing a “corkscrew” effect could indicate magnetic interference, so such devices must be carefully evaluated at each site before using them.

Oriented-rod instruments eliminate the need for a compass because the device is held at a fixed azimuth during the course of the survey [Renishaw, 2016]. Rodded devices also allow for uphole deployment in underground applications. The rods are typically hinged to allow for easy storage and deployment. One of the leading, oriented-rod device manufacturers uses 1 meter (3.3 feet) carbon fiber rods, which are flexible enough to follow the trajectory deviation. The maximum hole diameter for this system is 100 millimeters (3.9 inches) because of the potential for instrument movement within the borehole.

Only the collar location and rod stack orientation are required to begin a survey. Collar location can be found by global positioning survey (GPS), traditional survey methods, or a laser-scanning system and, in surface applications, the rod stack can be parallel or perpendicular to a row of holes. Because the collars will have been surveyed, the direction can be found by using the software. The borehole survey itself consists of taking readings, typically at 2-meter (6.6-foot) intervals, until reaching the bottom of the hole. At each point, the device is held still for 2 to 3 seconds to stabilize. The operator then presses “record” on the display, and the instrument determines the pitch and roll for that point. Worsey et al. [2017] explored using the type of rodded instrument shown in Figure 7.

Manufacturers, including Carlson, have recently experimented with gyroscopes in their borehole systems. Gyroscopes can be used to conduct surveys with a full 360 degrees from vertical in any direction and without magnetic interference. This technology will likely replace older compass- and accelerometer-based instruments.

Selecting Preloading Drill and Blast Survey Tools

// Using a best practices approach, RESPEC suggests measuring before and after drilling to see how well the blast design was implemented. These measurements should include surveying as-designed collar locations, drill alignment and inclination, and surveying drillhole deviation and depth. Such data can be used to track and audit key performance indicators of a site's drilling program and can ultimately lead to better blast performance, because a good blast can only be achieved with good drilling.

DRILL AND BLAST EQUIPMENT

Table 1 provides all of the equipment discussed in this document, along with relative cost categories and training requirements. This list is an equipment guide that can help you successfully evaluate the potential of any operation.

In this white paper, we have only discussed predrilling and postdrilling survey methods for drill and blast operations. Blasthole survey data should be compiled with a bench or face profile dataset to fully understand the potential

Table 1. Drill and Blast Equipment List

DEVICE	PURPOSE	RELATIVE COST	TRAINING REQUIRED
Inclinometer [(a)]	Aligns drill rod	Low	Minimal
Bubble Level	Aligns drill rod	Low	None
Guide Wire	Ensures straight rows at correct horizontal angle	Low	None
Flashlight	Identifies trajectory deviation	Low	None
Mirror	Determines hole inclination	Low	Minimal
Optical Device	Determines hole inclination and direction	Medium	Minimal
Cabled Borehole Surveyor [(a)]	Surveys full-length downhole (lmited by rock type)	High	1 Day
Rodded Borehole Surveyor [(a)]	Surveys full-length up- or downhole (any rock type)	High	1 Day
Optical Flexure	Surveys full-length up-or downhole (any rock type)	High	1 Day
Signal Emitting Device	Determines the true burden at the toe	High	Half-Day
Fishing Camera [(a)]	Examines borehole for cavities, crushing, and length	Low	Minimal
Borehole Camera	Examines borehole for cavities, crushing, and length	High	Half-Day

(a) Denotes items used by RESPEC's drill and blast consulting team for every blast that we help perform. To determine the best equipment available, we evaluate usefulness, capabilities, transportability, and cost.

effects of inaccuracies on a drill and blast site. Face profiling is key to an operation's understanding of face conditions. Visual inspections cannot provide a full understanding of or quantify face conditions, and can, in fact, miss or underestimate conditions such as the undercuts, overhangs, and toe.

When profiling a face, multiple tools are available that use either laser or photogrammetric measurement methods to create a point cloud and/or profile of the blast face. To obtain the actual bench face geometry, 2D profilers, 3D profilers, and drone photogrammetry can be used. To survey a mine face from the bench, 2D profilers (such as the Laser Technology Trupulse 200x™), 3D profilers (such as the Carlson Quarryman™), and drones or cameras can be used. These surveys are useful when paired with downhole survey data because the data can be used to export reports on actual burden for the length of each blasthole. The blaster can then use this information to adjust the explosives used in each blasthole.

As a leader in the drill and blast industry, RESPEC fully recommends these products. Specifically, the Carlson Boretrak™ and Quarryman™ product lines, that we use in our current mining and energy projects. If an operation is interested in evaluating the effectiveness of a preloading survey tool (such as Boretrak™), RESPEC can provide this service and has global experience in advising drill and blast clients during the testing and trial process. RESPEC's professional team looks forward to consulting with you for all of your drilling and blasting needs.

CONCLUSION

Incomplete data and partial views of the mine and bench can create serious operational issues and slow down the process. As drill and blast experts, RESPEC's professional mining team is ready to help your organization apply our extensive know-how across your mine's entire life cycle. From exploration through remediation, we are adept with technologies that enhance operational safety and increase productivity. Our focus is on empowering clients with better data for decision-making and improving accuracy for blasting outcomes. RESPEC's vast experience with diverse blasting will benefit your next project.

For more detailed technical information or advice, RESPEC's professional team is pleased to consult with your staff about all of your mining, drilling, and blasting needs, including the following:

- Consulting for production, construction, and specialty drill and blast projects
- Surface and underground operations
- Explosives performance testing
- Blast vibration monitoring, control, and analysis
- Drill and blast data management/electronic reporting
- Drill-to-mill financial studies
- Drilling equipment selection
- Drilling rig selection
- Instrumentation training, sales, and consulting
- Contract drill and blast engineering services
- Safety and site-specific training for drillers, blasters, engineers, and management
- Bid management

ABOUT RESPEC

RESPEC is a global leader in geoscience, engineering, data, and integrated technology solutions. Our 100 percent employee-owned company has been advising clients for over 50 years, with most of our work performed for returning clients. Currently, RESPEC employs over 325 professionals in 13 states and 1 Canadian province. Since our founding in 1969, we have remain committed to serving our clients with the highest degree of integrity, honesty, and professionalism.

RESPEC features a diverse group of technical professionals who are focused on serving the market sectors that are critical to quality of life. No project is too large or too small. From water quality initiatives throughout Minnesota, to nation-wide information technology data management supporting Indian Health Service, to mine engineering design for global mining interests, we match the right team of specialists in mining, energy, water, environment, and technology to the uniqueness of each client and project to make a difference in the lives of others. Our team's expertise helps clients save time and money while upholding the highest standards of safety and quality.

We work with international clients to design and manage the full spectrum of large-scale drilling programs, including drilling management, exploration drilling, core logging, and other geological services. We provide comprehensive drilling management and full-procurement services, including well and casing design for exploration wells and complete disposal wells. RESPEC has an excellent reputation of providing services to the resource industry with fully compliant drilling programs and keeping our clients well-informed throughout the project's life.

Our combination of robust technical experience and engineering services is the driving force behind our explosives engineering group's ability to solve critical drill and blast issues safely and effectively. Our team combines advanced knowledge of drilling and blasting with experience in mine planning and operations to provide a unique approach that improves operations and overall mining unit costs.

RESPEC is actively involved in professional societies and associations to ensure that our personnel continue to be on the cutting edge of technologies and practices. RESPEC also actively works with educational institutions to provide top-notch academic and industry expertise. We have a proud history of delivering unique, safe solutions to common and uncommon drill and blast problems for our clients.

The technical content of this white paper was written by Dr. Nathan Rouse and Mr. Tristan Worsey and was heavily based on a white paper by K. Hall et al. [2018].

ABOUT THE AUTHORS

NATHAN ROUSE, PE, PHD

RESPEC, MANAGER, EXPLOSIVES ENGINEERING

Dr. Nathan Rouse has more than 10 years of combined experience in mining and explosives engineering. He has worked on projects for the surface and underground mining of limestone, coal, and metal deposits in North and South America, Europe, Africa, and Asia. Dr. Rouse specializes in blasting and explosives engineering, including blast operations optimization, specialized blasting, surface and underground blast design, blast vibration monitoring, blast vibration control, and energetics research. His knowledge of blast vibration control stems from his doctoral dissertation work, which focused on the relative effect of charge dimensions on blast vibrations and seismic energy concepts. He also set a precedent in the mining industry for instrumenting underground production blast air overpressures .

Dr. Rouse's mining engineering skills include geologic modeling and interpretation, mine design and planning, rock-mechanics evaluation, operational auditing, project and contractor management, reclamation planning, and permitting. He is involved in the International Society of Explosives Engineers (ISEE) and the Society for Mining, Metallurgy, & Exploration (SME). Dr. Rouse has published several papers through both of these societies.

TRISTAN WORSEY, PE

FORMER RESPEC DRILL AND BLAST SPECIALIST

Mr. Tristan Worsey has more than 10 years of experience in performing explosives and mining engineering work, with his technical specialty in drilling and blasting. He has worked at more than five mining operations in North America, and his expertise includes drill and blast optimization for surface and underground mines, blasting next to failures, fragmentation optimization, equipment rescue, collapse blasting, vibration and airblast monitoring, explosives safety audits, explosive storage design, proximity blasting, blaster training, and postblast investigations.

Mr. Worsey works with the University of Kentucky's Explosives Research team, which is housed in a world-class research facility. As the lead blaster on the team, he performs a wide range of explosives-related research, from explosives defense to mine blast optimization.

Mr. Worsey has experience in underground and surface mine operations, contracting and consulting companies, and academia. While in the contracting business, he worked at more than 20 mine sites, and he has experience in metal, coal, and aggregates mining operations. In the academic field, Mr. Worsey taught students who had never used a drill or a stick of explosives how to drill and blast.

Mr. Worsey is heavily involved in the SME and ISEE. He holds multiple positions within these societies and regularly publishes and presents at society meetings.

RESPEC

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