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Robert Quentin Eades

Kyle A. Perry
Missouri University of Science and Technology, kperry@mst.edu

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Understanding the connection between blasting and highwall stability

R. Quentin Eades *, Kyle Perry

Department of Mining and Nuclear Engineering, Missouri University of Science and Technology, Rolla, MO 65401, USA

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A B S T R A C T

Surface mines continue to implement highwalls for several reasons, such as increasing recovery, improving margins, and justifying higher stripping ratios. Highwall stability is a complex issue that is dependent upon a variety of mining and geologic factors, and a safe design is necessary for a successful surface operation. To improve highwall stability, it is important to understand the connection between local geology and blasting. Explosives are employed throughout the mining industry for primary rock breakage. There are a number of controlled blasting techniques that can be implemented to improve highwall stability. These include line drilling, smooth wall blasting, trim blasting, buffer blasting, air decking, and presplitting. Each of these techniques have associated advantages and disadvantages. Understanding local geology is necessary for selecting the appropriate controlled blasting technique. Furthermore, understanding the limitations and conditions for successful implementation of each technique is necessary. A discussion of the impact of geologic conditions on highwall stability is provided. Additionally, discussion is provided for the successful incorporation of the controlled blasting techniques listed above, and the associated mining and geologic factors that influence the selection and design of controlled blasting plans. Finally, a new methodology is proposed.

1. Introduction

Explosives are used throughout the mining industry as the standard for primary rock breakage, a critical part of the mining cycle. In 2015, the U.S. consumed 2.2 million tons of explosives [1]. The coal mining industry accounted for the majority of explosive consumption, accounting for approximately 63% of total explosives. The quarrying and nonmetal mining industries accounted for 12% of explosive consumption, and the metal mining industry accounted for 9% [1]. This constitutes 84% of the explosives used in the U.S. However, the energy released during the detonation process is often in excess of that required to adequately fragment the surrounding rock [2]. This excessive energy, along with over confinement and poor blast geometry, will cause damage to the undisturbed rock mass beyond the intended boundary of the blast. This event is known as overbreak or back-break [3].

There are a number of problems associated with excessive overbreak of a rock face. Chief among these are the safety concerns related to loose rock and bench stability due to cracking [3]. Other concerns include uneven burdens on the face for the next round of blasts. Overbreak can also cause voids within the rock mass that will reduce the overall effectiveness of the explosives. These concerns are compounded when blasting in a jointed rock mass. Those rock masses with joints dipping towards the face have the potential for sliding along the joints. Those that are dipping away from the face can lead to block toppling [3]. When slope stability becomes an issue, a controlled blasting technique must be used to improve stability.

There are a number of controlled blasting techniques that are used in the mining, construction, and tunneling industries. The most commonly used of these techniques is presplitting. However, there are issues related to presplitting that may reduce its applicability and performance. There are other techniques available to improve highwall stability that can be used when presplitting is not optimal. Each of these techniques has their own associated advantages and disadvantages. It is key that blasters and engineers have adequate knowledge of the tools available to ensure safety and economic goals are achieved simultaneously.

2. Background

There are six controlled blasting techniques that have been developed and designed to improve the stability of the final excavation. Each one of these has their unique features and design considerations for successful implementation into any blasting plan. The six controlled blasting techniques that will be discussed are

* Corresponding author.
E-mail address: ren2h@mst.edu (R.Q. Eades).

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(1) line drilling, (2) trim blasting, (3) buffer blasting, (4) smooth wall blasting, (5) air decking, and (6) presplitting.

There are a number of uncommonly used controlled blasting techniques. These techniques work efficiently in specific situations. The first among these more uncommon techniques is line drilling. This technique involves a single row of closely spaced, unloaded, small diameter holes drilled along the final excavation line. The primary difference between the line drilling technique and other forms of controlled blasting is the absence of explosives within the boreholes. These holes simply serve as a plane of weakness for which the blast can break toward but not past. Another uncommon technique is trim blasting, in which the annulus of the borehole is loaded with crushed stone along the entire length of the powder column. This acts as a coupling medium between the explosive and the surrounding rock mass. The crushed stone acts as a cushion to reduce stresses that are placed on the excavation line by the explosives. A third uncommon controlled blasting method is buffer blasting. This technique involves lightly loading the last row of production holes to reduce the amount of damage they will cause to the adjacent rock mass [4]. Buffer blasting is most often used in conjunction with another controlled blasting technique. Smooth wall blasting is the final uncommonly used controlled blasting technique. While this technique is uncommonly used on the surface, it is the most predominantly used technique for underground operations [3]. This technique is also referred to as post splitting, contour blasting, or perimeter blasting. Smooth wall blasting involves drilling a line of boreholes along the excavation limits, lightly loaded with explosives and decoupled from the sides of the borehole. These holes are fired on the last delay of the production blast.

Air decking is a widely used controlled blasting technique that requires an air space in the blast hole above the explosive charge [5]. The purpose of this air space, called a deck or air-deck, is to allow for the gases generated during the detonation process to fill the void instead of being forced into the adjacent rock mass [5]. A conceptual diagram of a borehole with an air deck is shown in Fig. 1. Air decking has a long history and has been used in a variety of applications, such as presplitting, ground vibration control, and blast economics improvement [2].

Presplit blasting is a technique that was initially developed during the Niagara power project [6]. The original intent was to reduce the amount of ground vibration that was created during blasting operations. However, it was also noted that rock breakage on one side of the fracture plane did not cause breakage on the other side—an obvious reduction in the amount of overbreak. Presplit blasting involves drilling a single row of holes along the back of the final excavation zone [3]. Unlike smooth wall blasting, the presplit holes are fired on the first delay of the production blast. The presplit technique is the most commonly used controlled blasting technique for surface operations.

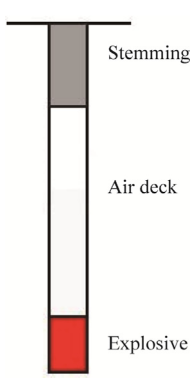


Fig. 1. Typical air deck schematic.

3. Methods

3.1. Line drilling

Line drilling has a number of requirements that must be satisfied to ensure success. The first requirement is that the drill holes must be 38 to 76 mm in diameter and not loaded with explosives. Drill holes that are greater than these diameters are seldom used due to performance issues and increased drilling costs. A second requirement is the reduction in the burden and spacing for the last row of production holes in the blast. The burden and spacing for the last row of holes is reduced 50% to 75% of the other production holes [3]. This is coupled with the fact that the last row of holes is loaded with less explosives. The last row of production holes is typically only loaded with 50% of the amount of explosives for other holes. The explosives in these holes should be well distributed along the entire length, through the use of decks, if necessary. A detonating cord is recommended downhole to ensure detonation. The final and most important requirement for line drilling is the spacing of the line drill boreholes. These boreholes are only spaced 2 to 4 times the diameter of the borehole. This will cause the boreholes to act as a perforated plane of weakness that will reduce the amount of overbreak that will occur during the production blast.

Due to the design of the line drill technique, there are a number of known limitations and considerations that affect the performance of any line drilling operation. The first and most important of these considerations is the high amount of drill accuracy required. While all controlled blasting techniques require varying degrees of drilling accuracy, it is imperative that borehole deviation is minimized when performing a line drill blast. Because the line drill holes are unloaded and simply act as a weakness plane, any deviation will directly affect the results of the excavation line.

In-plane deviation will cause an uneven face at the excavation line. There are two concerns related to this situation. The first is the potential safety concern related to the uneven material possibly being fractured by the production blast but not successfully fragmented from the excavation line. The fragmented material may eventually slough from the excavation line and can cause damage to personnel or equipment. The second concern is that there will be uneven burdens along the face for the next production blast, which may adversely affect the results of the blasting operation. Out-of-plane deviation will leave either excessive toe at the bottom of the blast or caprock at the top of the blast.

The final performance issue related to line drilling is the bench height limitation. By relying on the line drill holes as the only form of a weakness plane, complex geology will reduce the effectiveness of any line drill operation as stress will concentrate around these naturally occurring discontinuities over man-made discontinuities [7]. These geologic features will limit the effective height of the bench so that the amount of geologic conditions that are present in the blast are limited. The final consideration for line drilling is the expenses associated with drilling additional holes. Line drilling requires the most holes compared to other controlled blasting techniques and may be cost prohibitive.

3.2. Trim blasting

Trim blasting has relatively few requirements for successful implementation. Trim blasting is used in conjunction with large-diameter cartridge charges taped on detonating cord at predetermined intervals. These trim blast holes are often fired simultaneously or in groups to maximize the amount of charge per eight millisecond (8 ms) delay intervals. The final requirement for trim blasting is the drilling and initiation of the blast. Typically, trim blasts are drilled and initiated after the primary production blast has occurred. This makes trim blasting unique when compared to other controlled blasting techniques since it allows for full observation of the geology of the excavation line prior to drilling and loading of the holes. This reduces the number of assumptions that are required to design the trim blast when compared to other controlled blasting techniques.

Many of the limitations of trim blasting are shared with smooth wall blasting. Because trim blasting uses decoupled explosives, drill hole accuracy is critical to the success of the operation. Borehole deviations can cause excessive burdens throughout the excavation line, which reduces the overall effectiveness of the trim blast. Trim blasting is also dependent upon the "pseudo final excavation line" that was left after the primary blast. The excavation line will have variable burdens and will require a unique design each time to ensure a controlled excavation line after the trim blasting operation is complete [7]. In addition to these concerns, the primary limitation for trim blasting is related to the production and scheduling of blasts. Because trim blast is conducted after the primary production blast, additional time is required to move the drill rigs back on to the bench and drill holes for the controlled blast shot [4]. This creates a delay in preparations for the next production blast. This fact raises concerns with work and equipment safety. There will be a period of time where the personnel and equipment are working and operating near a highwall or an underground heading where no measures have been taken to reduce or control overbreak. Due to these issues, trim blasting is rarely chosen as the controlled blasting technique for many operations.

3.3. Buffer blasting

Buffer blasting is a compromise solution between production and safety. There are relatively few special requirements that must be met for a successful operation. However, buffer blasting is rarely used as the sole controlled blasting technique and is most often employed in conjunction with another controlled blasting technique, such as presplitting. This is shown conceptually in Fig. 2: production hole diameter, burden, and spacing are denoted as H, B, and S, respectively. Presplit hole diameter and spacing are denoted as h and s, respectively. The most important requirement for successfully conducting a buffer blast operation is that the last row of holes is loaded with no more than 50% of the explosives that are used in the other production holes. It is also important that these explosives are well distributed within the borehole to help improve fragmentation of the rock mass. This will cause a smaller amount of overbreak into the final excavation line, without significantly increasing the time required to perform the operation, or significantly increasing the economics of the blast operation.

3.4. Smooth wall blasting

Smooth wall blasting is the most commonly used underground technique and was developed in Sweden [3]. The smooth wall line technique is composed around the final excavation line underground where the holes are lightly loaded to reduce the amount

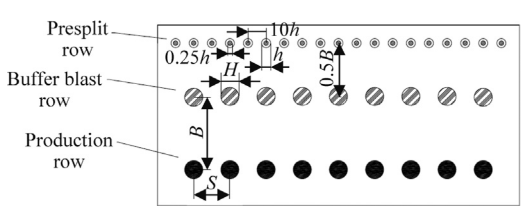


Fig. 2. Conceptual diagram of buffer blast holes used in conjunction with presplitting.

of overbreak. These explosives are also decoupled from the sides of the borehole [3]. The final feature of smooth wall blasting is that the smooth wall holes are initiated after the primary blast. Smooth wall blasting will allow blast damage to extend beyond the smooth wall line before they are initiated. The most damaged rock will be removed from the final excavation line and result in a smooth profile for the perimeter. If more smooth wall holes are required than can be initiated in a single 8 ms time period, the holes should be fired in groups that will maximize the charge per delay. The borehole spacing in smooth wall blasting can be larger than those used in presplit blasting operations. The typical starting point for burden-to-spacing ratio for smooth wall blasting is 1.5:1. To ensure maximum relief of the rock, a pilot heading is sometimes used. A pilot heading is a smaller tunnel that is excavated in the center or near the top of the designed tunnel. After the pilot heading has been completely excavated, the cross-section is drilled and shot. This allows for the use of smooth blasting around a greater portion of the excavation line [3].

The smooth wall technique also involves more perimeter drill holes when compared to conventional underground methods. Drilling costs have the greatest impact on the economics of any blasting operation [3]. Additionally, smooth wall blasting is known to have performance issues in weak rock formations [3]. If the rock mass is too weak to support itself, the smooth wall blast will not eliminate the need for additional support. Drilling accuracy is a paramount concern with smooth wall blasting. Due to the additional challenges of drilling and blasting in an underground heading, drill accuracy is critical to the success of a smooth wall blast. When the smooth wall holes cannot all be fired on a single delay, the relief is limited to the arch and partially down the rib because of the muckpile. Therefore, smooth blasting results will degrade further down the rib of the excavation line, which may cause safety concerns in larger entries.

3.5. Air decking

There are a few key features of air decking that must be followed to ensure successful implementation. The first is to ensure a uniform air deck length for each of the holes. Large deviations of air deck length between holes in the blast will create issues with stresses imparted on the adjacent rock mass and will reduce the effectiveness of the air deck. Two empirical correlations between air deck length and fragmentation are suggested by Mel'nikov et al. [8]. One of these used total charge length, including the air deck, and the other with charge diameter [8]. Further studies have shown conformity with these empirical correlations. Placement of the air deck within the powder column is an additional concern. Jhanwar conducted a study and found that placing the air deck in the middle or at the top of the column achieved similar results [9]. However, placing the air deck at the bottom of the powder column generated poor fragmentation and caused issues with excessive burden at the bottom of the face for the next blast. The standard practice for air decking is to place the air space in the middle of the explosive column. This will concentrate all of the explosive at the bottom of the borehole and reduce concerns with excessive burden at the toe. Additionally, any damage that does extend beyond the final excavation line is lower on the face when compared to a technique that distributes the explosive throughout the entire length of the powder column. This reduces danger to personnel and equipment if a rock fall does occur because it will happen lower on the face and have less travel time. The air deck should only be placed in the top of the explosive column when it is particularly important to ensure proper fragmentation of the top of the explosive column. There are a few design considerations that must be accounted for when using air decked blast holes.

The primary concern with the air decking technique is performance-related issues. Studies have shown that air decks perform optimally in soft- and medium-strength sedimentary rock masses [2]. The air decking technique is noted to work particularly well in highly jointed sedimentary rock masses because the amount of shock energy required to generate additional cracks is minimal [9]. This may result in incomplete fragmentation of the rock mass and leave loose fragments on the excavation line.

Another engineering concern with air decking is the placement of an instrument into the borehole to hold the stemming in place on top of the air deck. In most cases, a stemming plug is deployed down the hole to remedy this issue. However, it is difficult to accurately measure the depth at which the stemming plug is deployed in the borehole. This makes it difficult to keep the air deck length between holes similar, reducing the effectiveness of the air deck. A final consideration for air decking is the diameter of the borehole used in the blast. It is generally accepted that air decking will produce results that are comparable but not quite as good as presplitting. This is especially true in situations where a small borehole diameter is used. In these scenarios, it is more appropriate to employ the presplitting technique. When compared to the presplitting technique, the air decking technique does not require additional boreholes or specialty explosive products. Therefore, a large increase in blasting operations costs is not experienced.

3.6. Presplit blasting

The purpose of the presplit row of holes is to generate a vertical, continuous, and thorough fracture plane at the back of the excavation line. These holes are generally smaller in diameter than those holes drilled for primary production. Fig. 3 shows an example of a vertical presplit fracture plane created after a successful presplit blasting operation.

There are a few salient features of presplitting that are required for successful implementation. The first is that the holes in the presplit line are lightly loaded, which reduces damage to the rock that will remain after the blast. The second key feature of presplitting is that the explosives loaded in the holes must be decoupled from the sides of the blast hole along the entire length of the powder column. This will further reduce damage to the rock mass as the gas pressure will be able to “vent” to the air within the borehole instead of being forced into the fracture network of the rock mass. The final feature of presplit blasting is the timing of the presplit holes. The presplit holes should be detonated either before the production shot or on the first delay of the production shot, depending on the number of presplit holes utilized. If more presplit holes are required than can be initiated in a single 8 ms time period due to regulations, then the holes should be fired in groups that will maximize the charge per delay. Fig. 4 shows an example of the formation of the fracture plane with different timing patterns [10]. It is clearly evident that the presplit holes perform optimally when they are fired simultaneously. When they are grouped together with a minimum 8 ms delay between groups, there is deviation in the fracture plane. However, when the holes are fired individually, there is a greater chance for the gas pressure to escape into the fracture network and not drive the fracture plane. These delays reduce the effectiveness of the presplit blast. Specialized presplitting explosive products are often used to ensure success of the presplit line [11].

Fig. 3. Vertical fracture plane generated from presplit blasting, adapted from study by Konya and Walter [7].

Presplit blasting has both economic and performance concerns. The economic concerns are due to the requirement of drilling additional holes with different diameters and the use of specialized explosive product. In order to successfully implement a presplit, additional holes of smaller diameter must be drilled. These additional holes can significantly increase the amount of time spent drilling, which can affect blast economics significantly. When a situation requires a specialized explosive product to ensure success of the presplit, additional expense will be necessary when compared to bulk explosive product.

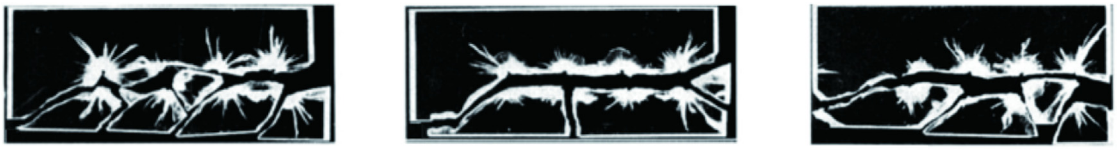
Presplitting has three noted concerns that can significantly affect the performance of the operation: (1) drilling accuracy, (2) post-blast assessment, and (3) assumption-based approach [3]. Due to the drilling requirements for a presplit blast, drill accuracy is a paramount concern for success. Borehole deviation caused by inaccurate drilling will have a significant impact on the generation of the vertical fracture plane. In cases where the deviation is out of plane, the presplit fracture plane may not be generated or be incomplete. In cases where the deviation is within the plane of the presplit row, there will be additional cratering around the side of the borehole that may allow the gas pressures generated during the detonation process to be released into the adjacent rock mass, reducing the effectiveness of the presplit operation.

It is difficult to assess the performance of presplit blasts until the material from the production blast has been mucked and the final excavation line is fully visible. This can create production issues if the presplit did not perform adequately. Design changes will have to be made at the same time that preparation for the next blast is beginning. The final concern with presplit blasting is that it is an assumption-based approach. Because presplitting is done before the primary blast is conducted, it is not possible to fully observe the local features of the rock mass, and assumptions must be made so that the blast can be designed and performed.

3.7. Fast delay presplit

A new technique is being investigated at Missouri S&T to address some of the issues related to using delays between presplit holes. Ideally, all presplit holes are fired simultaneously. However, due to pound per delay limits, some presplit holes are grouped together and fired on separate delays. With the advent of electronic detonators and the ability to program in one millisecond increments, new methodologies for presplit timing can be examined, such as delaying each hole by one millisecond or shooting pairs or groups at one millisecond delays depending on the allowable charge size per delay.

Electronic detonators are a relatively new technology that allows for the blaster to program a unique delay for each blasting cap. These delays are accurate to within 0.01% of the programmed delay [12]. Using this technology, the researchers will investigate incorporating small delay timing sequences for presplit blasting operations using electronic detonators while not exceeding the maximum charge weight per 8 ms delay period. The goal of this research is to promote smooth and continuous fracture



(a) Fired individually (b) Fired simultaneously (c) Fired with short delays

Fig. 4. Effects of using delays on presplit holes [10].

propagation along the designed excavation line. When the presplit holes cannot be fired simultaneously due to federal regulations regarding explosive charge per 8 ms delay, the resulting fracture plane will likely be jagged between groups of presplit holes, and loose rock may still be hanging from the excavation line. This results in a falling rock hazard for personnel and equipment operating around the highwall. The results of this research should yield timing sequences that can be incorporated into presplitting operations that will improve overall highwall stability and require less time and effort to stabilize the final excavation line. This will also result in less remediation efforts due to the increase in stability.

The research team will conduct three phases of experimentation in this study. The first phase will be conducted at laboratory scale using a solid, homogenous, and continuous material. This will allow for comparison to previous research in the area of presplit design. The second phase will test timing sequences in discontinuous geologic material at the Missouri S&T experimental mine facility. The final phase of experimentation will involve full-scale testing at an active mine site. This design will determine the effect of material and scale on the various selected timing sequences for presplit performance.

4. Conclusions

Explosives are heavily relied upon throughout the mining industry. When using explosives for rock breakage, there is always the potential to damage the final excavation line beyond the intended boundary of the blast site. Excessive amounts of overbreak on a rock face can cause several issues. The most important of these is the increased worker and equipment exposure to potential rock fall hazards. However, there are other issues related to bench stability, and future blast performance based on the amount of overbreak occurring during a blasting operation. To reduce the amount of overbreak occurring at the final excavation line, a number of controlled blasting techniques have been developed. It is important to understand the critical features of each technique and the associated limitations and considerations of each technique when selecting an appropriate technique or techniques for a blasting operation.

Presplitting is the most commonly used controlled blasting technique. However, there are issues related to presplitting that may reduce its applicability and performance. There are other techniques available to improve highwall stability that can be used when presplitting is not optimal. Each of these techniques is similar, but there are key features that must be accounted for to ensure successful implementation. If these features are not known or not designed, controlled blasting may not be successful or can hinder the mining operation as a whole. A new design is being studied by a research team at Missouri S&T that will incorporate timing sequences into presplitting operations using exact, programmable delays from electronic detonator technologies. The results of this research should provide mining operations and civil highway operations with a tool that will produce more stable excavation boundaries. This will result in lower costs and efforts to stabilize or remediate the excavation.

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