The application of a blast audit for production improvement

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**ABSTRACT:** An audit of the blasting operation at a large iron ore mine in North America was used to improve production and lower costs. The audit reviewed the blasting practices in order to identify opportunities for operational improvements. The approach taken in the audit was to evaluate general blasting practices, determine the effect of these practices on downstream processes and to compare current procedures to established best practices. The blasting audit was performed as part of a thorough review of blasting technologies to improve mining operations. The process began with the audit to examine the blasting procedures and their impact on other mining activities. Specific items covered in the audit included: blast design protocols, explosive characteristics, explosive energy distribution, geological influences, shovel/loader cycle times, muckpile digging conditions, crusher delays, and safety. Upon conclusion of the audit, a mine diggability team was formed that utilized the audit findings to develop productivity improvements, reduce oversize and lower mining costs. Some of the improvements achieved include reduced explosive costs, a 9% increase in loader productivity and a 44% reduction in crusher delays.

1 INTRODUCTION

The mine management of the Cliffs Natural Resources (CNR) Michigan Operations near Palmer, MI has long embraced technologic improvements, implementation of quality management systems, and has a continuous focus on improving the business. Recognizing the impact of blasting on the mining cycle, CNR desired a thorough review of blasting technologies to improve mining operations. The initial step for this process was to carry out a thorough audit of the blasting operation and its effect on the downstream mining processes. DynoConsult performed this audit at the request of the mine management at Tilden/Empire. The audit occurred during the period of 23 April to 10 May, 2007. The purpose of the audit was twofold: 1) to identify potential areas where the blasting operation could be improved to either reduce overall operating costs or increase production for the mine, and 2) identify any safety and/or procedural improvements that could be made relating to blast site activities.

In addition to the aforementioned purpose of the audit, the mine management requested DynoConsult to consider the following issues:

- The Empire mine was nearing the end of its life. Future production would transfer to the Tilden mine.
- Tilden would like to increase production. If the costs could also be lowered that would be an additional benefit.
- The productivity of the LeTourneau loaders was a concern as they frequently experienced difficult digging conditions. The intent of the LeTourneau loaders was to provide flexibility to the production while the shovels provide the base production. Due to the difficulty with the LeTourneau loaders, the mine lacked the desired production flexibility.
- A variety of explosive formulations were used at Tilden/Empire. Many of these formulations contained aluminum which significantly increased the cost of the explosive. The mine wanted to determine if the aluminum was really necessary.
- Production was primarily limited by the truck fleet. However, sometimes production was limited by the shovels.

2 DESCRIPTION OF PRIMARY MINING EQUIPMENT

The Tilden/Empire mines employed four P&H electric shovels: two 2800 shovels (26 & 27.5 m³ buckets) and two 2100 shovels (13 & 14.5 m³ buckets). The shovels were intended to provide the base production for the mines and as such it was desired to keep their nonproductive movement between...
muckpiles to a minimum. The shovels in the past had been trammed considerable distances between muckpiles which reduced pit productivity and increased costs.

In addition to the electric shovels, the Tilden/Empire mines used three LeTourneau 1850 front end loaders. The LeTourneau loaders were intended to add flexibility to the production thereby reducing the need to move the shovels around the various pits. Although the LeTourneau loaders were typically more expensive to operate than electric shovels, the intent was that the extra cost of the loaders would be more than offset by the improved efficiency of the electric shovels.

3 GEOLOGIC DESCRIPTION

The formation of concern at the Tilden/Empire mines was the Negaunee Iron Formation. This formation was described as having highly variable properties. Extensive fracturing and jointing appear regularly in the Negaunee Formation. Igneous intrusions consisting of a greenish altered metadiabase occur throughout the formation. Oxidation halos were present around the intrusions. The intrusive material had a lower density than the iron formation, but was more competent with a higher strength. Tables 1 and 2 provide a comparison of average mechanical property values between the two mines and the main rock types.

4 TRADITIONAL DRILLING & BLASTING APPROACH

4.1 Blast design

Prior to this work the blast design parameters were based on the last results obtained at the specific location of the blast and the type of rock being shot. Several of the blast design parameters were fixed, such as bench height and hole diameter. The only parameters adjusted for the production blasts were the burden, spacing, explosive, and delay timing (Table 3). The traditional design methodology was to design the pattern to meet a specific explosive energy level throughout the blast. Therefore when the burden and spacing were changed, it was to achieve an energy level target based on past experience and personal judgment.

The average powder factor during 2006 was approximately 0.24 kg/tonne. At the end of March 2007, the average powder factor was increased to 0.254 kg/tonne. The increase in the powder factor was made in an attempt to improve the diggability of the muckpiles for the LeTourneau loaders. However the results were not satisfactory.

Blast areas in metal mines are rarely a nice rectangular shape. This was frequently the case at this operation where the front and back lines of the blast area were not parallel. As a result the mine had developed a practice on how to position the blastholes within the designated area. The traditional pattern layout method first established the drill line along which the back row of holes would be located (Figure 1). The front row was then positioned based on the back row from the previous blast(s) in front of the area considered. A 10.7 m offset from the previous blast was used to establish the front row along the new pattern. Once the back and front rows were established the remaining rows of holes were evenly spaced between them. When the back and front rows were not parallel, adjustments were required in the burdens to maintain the even distribution from the front to back. Spacings would also be adjusted when required by specific circumstances.

4.2 Explosive products

Two basic explosive types were loaded at the Tilden/Empire Mines. They were a 50/50 emulsion/
ANFO blend (an augured product) and a 67/33 emulsion/ANFO blend (a pumpable product). Traditionally, aluminum had been added to both products in quantities ranging from 2% to 7% to adjust the energy level to meet the perceived blasting requirement. The actual product selected for a hole was based on the amount of water in the hole and the hardness of the rock. The 50/50 formulations were commonly used in dry holes or holes that could be properly dewatered. The 67/33 formulations were loaded in wet holes. It was not uncommon for three or more explosive compositions to be loaded in the same pattern when it was felt the conditions warranted it.

5 DOWNSTREAM EFFECTS OF BLASTING

5.1 Muckpile characteristics

The muckpile characteristics were observed to have two major concerns. These concerns were somewhat interrelated, but not entirely so. The first was diggability of the muckpile, particularly for the LeTourneau loaders, and the second was the existence of oversize fragments in the muckpile which affected both the muckpile digging and the primary crushing.

5.1.1 Digging conditions

The digging conditions of the observed muckpiles varied considerably. In the weaker more structured horizons the digging was much easier than in the stronger, more massive horizons.

Most of the shovel operators consulted in the audit stated that the hardest digging usually occurred in the bottom of the muckpile. During observation of one shovel in the Tilden mine, the digging in the bottom of the muckpile was so difficult that the floor was raised one meter above grade. When the shovel would try to clean up the floor, it was obvious that the floor was broken, but the fragments were large and locked together due to a lack of movement during the blast.

The situation for the LeTourneau loaders was worse given their limited bucket reach and that loaders exhibit the greatest digging capability at the toe of the muckpile. Should the loaders encounter a hard toe that restricts penetration of the bucket, their principal digging advantage was lost. Furthermore, as the bucket of the loaders was raised during loading, their digging ability decreased. Hard spots encountered in the muckpile above the floor then became more difficult for the loaders to dig.

All of the observed muckpiles were found to stand vertically, or nearly vertical, during digging. In a few instances the muckpiles were so tight that overhangs were actually created on the active dig face. Material flow was minimal with occasional mass flow of material from the upper half of the muckpile when the dig face would become unstable. Vertical faces with minimal flow are preferable when shovels are used. However, front end loaders operate more efficiently when the dig face is angled back and the material flows towards the loader. In addition, the observed overhangs and mass flows that occurred present safety hazards to the loader operator.

5.1.2 Oversized fragments

Based on direct observations and discussions with the shovel operators, a significant portion of the oversize fragments originated from the top of the bench blasted. This is a common occurrence when oversize particles have been defined prior to the blast either by pre-existing fractures and/or geologic structure (Figure 2).

The existing geology along with the blast damage created by previous blasts, pre-condition the rock with numerous fractures. The distribution of

![Figure 1. Sequence used to determine hole layout for a blast pattern.](image)

![Figure 2. Geologically defined fragmentation (left—insitu, right—liberated).](image)
these fractures ultimately determined the size of the fragments produced in the blast. Once created, there were only two mechanisms by which these predefined fragments could undergo reduction during a blast. These were exposure to sufficiently high dynamic strains produced by explosive detonation and in-flight collisions of the fragments. As mentioned previously, the blast geometry concentrated the explosive energy around the bottom half of the blastholes. This left vast volumes of the blast with insufficient energy to fracture the fragments between the holes and above the powder column. Due to the limited movement of the muckpile, there was no real possibility for rock movement to provide additional breakage.

5.2 Equipment digging conditions

The digging of several muckpiles was observed for any evidence of potential improvements in the blast results that could increase the production rates or reduce the maintenance of the loading equipment. Not only did the loading cycle increase for both shovel sizes in more difficult digging conditions, but the variability in the loading cycles increased as well.

In Table 4 the cycle times to fill the shovel bucket are provided. This table also provides information on how the digging conditions not only affect cycle times, but also the variability in the equipment operation. The table shows that as the digging conditions became more difficult, both the bucket cycle time average and standard deviation increased.

The occurrence of poor digging conditions increased the cycle times for the shovels and loaders and also increased the maintenance requirements as well. Cleaning of the walls was reported as the principal shovel activity resulting in required maintenance. Second was the digging of hard toes. Both activities require the loading equipment to expend considerable force through their buckets against a variable resistance. This transmits intense dynamic forces through the equipment as the bucket cycles through sudden releases followed by high impact when digging through the hard material. Loading equipment operates at its peak levels and lowest costs when the bucket passes smoothly and evenly through the material being removed. The observed muckpile resistance against the buckets and the manner in which the shovels shuddered during loading indicated they were operating below their optimal level and at higher costs.

5.3 Crushing

Prior to the project, the primary crushing experienced frequent blockages caused by oversize fragments. Crusher information from the mine dispatch system showed that for the year 2006, the three primary crushers at the Tilden/Empire mines had a collective total of 37 shifts (293 hours) of downtime due to blockages at the crusher.

During times when the crusher was down, the haul trucks were rerouted to dump at the surge pile. The material dumped at the surge pile represented a considerable amount of waste in the process stream as the material required rehandling. It is important to realize that oversize blockages at the crusher affected more than the crusher itself. It should be recalled that the production was limited by the truck fleet. Elimination of the truck delays at the crusher would reduce haulage cycle times and provide more truck capacity to the shovels and loaders thereby increasing the mine production.

6 BLASTING ANALYSIS & IMPROVEMENTS

6.1 Production blast pattern geometry

The rock hardness and geologic structure varied throughout the Tilden/Empire operations. It would be expected therefore that a variety of blast designs would have existed to address the various rock types and the intended results for each. However, in the audit it was found that the same basic design was used throughout for all the development and production blasting. Variations in the burden and spacing did occur for the various rock types, however, they minimally affected the overall blast geometry. As an example, a standard bench height of 13.7 m was used throughout both mines. As presented previously the burdens and spacings both varied from 10.7–13.7 m. This represented a change in the stiffness ratio of 1.28 to 1.00—not a significant difference.

Table 4. Observed bucket cycle times for shovels at Tilden/Empire.

<table>
<thead>
<tr>
<th></th>
<th>Easy</th>
<th>Normal</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>2800 Shovels Ave.</td>
<td>38.7 sec</td>
<td>55.9 sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2100 Shovels Ave.</td>
<td>35.8 sec</td>
<td>46.2 sec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.3 sec</td>
<td></td>
<td>11.5 sec</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 illustrates the distribution of the explosive energy for a cross section of a blast. In this figure it is shown that the explosive energy was concentrated in the lower portion of the bench and around the blastholes.
The effect of the high energy concentrations was evidenced by the overall rock movement during the blast. Video recordings taken of the observed blasts revealed that movement of the rock on the top of the bench was not uniform. The areas around the hole collars showed the greatest movement with the areas between being relatively subdued. In addition, some areas of the bench top were less energetic than others demonstrating inadequate energy not only occurred between holes, but within sections of a pattern as well.

With the explosive energy concentrated in the bottom of the hole and the limited rock movement observed during blasts, considerable amounts of subdrill damage could occur. When the subdrill damage occurred, it fractured the rock with a network of fractures radiating out from the blasthole. The spacing between these fractures increased with distance from the blasthole. These fractures contributed to predefining the fragmentation for the top of the next bench below and contributed to the oversize fragments from this region. Calculations of the energy distribution within the blast patterns indicated the subdrill damage could occur up to 3 m below the floor grade of a blast, depending on the proximity of a blasthole to a given area. Observations of the drilling support the depth to which the subdrill damage was occurring. Both comments from the drillers and measurements taken during the audit indicated subdrill damage occurred down to 3 m from the top of the bench. This was consistent with the general blast damage identified by drilling data shown in Figure 4.

6.2 Hole placement

Another item that affected rock movement and breakage was the designed layout and spacing of the holes. The traditional pattern layout method as discussed previously and shown in Figure 1 resulted in a pattern with variable pattern footage and hence variable energy distribution (Figure 5). From these energy distributions it can be seen the uniformity of the energy distribution varied not only from blast to blast but also within an individual blast as well. When the energy distribution varied within a pattern, it would be expected that rock displacement and breakage would also vary within the pattern. This was confirmed by video recordings of blasts.

As previously mentioned, the variation in the energy distribution created a situation where the breakage and movement of the rock during the blast was non-uniform. This was mostly evident in the face and bench top where cratering was observed. As shown in Figure 6 when sufficient...
relief is not provided, the blast geometry allowed for the blastholes to crater. This resulted in poor fragmentation and movement of the rock in the lower portions of the bench and increased the subdrill damage.

Since cratering was the result of highly confined holes with little or no horizontal movement, it should be expected that the diggability of the rock in the areas between the craters would be difficult. This phenomena was confirmed by a comment from one shovel operator who stated that the shots with less vertical movement dug easier than the shots with a lot of vertical movement.

As a result of the audit, the mine changed the hole layout to a staggered pattern instead of the traditional square pattern. The staggered pattern better distributed the explosive energy within the blast which improved fragmentation and movement (Figure 7).

6.3 Explosive energy

As previously mentioned, energy was one of the prime properties used in the selection of an explosive for a given blast at the mine. Although energy information is useful for many purposes, it should be viewed in the proper context when selecting an explosive for practical applications. The field performance of an explosive can not be determined solely by its theoretical ideal energy content. Explosive performance in the field also depends upon how the energy is released and transmitted into the rock to produce fragmentation and movement.

The addition of the aluminum altered the energy partitioning within the explosive. The principal purpose of the aluminum was to add heat to the gases resulting from the detonation, thereby increasing the gas pressure. A side affect of the aluminum was that it also decreased the velocity of detonation and shock energy provided by the explosive. The effect of the aluminum on the 50/50 blend are shown in Figures 8 and 9 and listed in Table 5.

Due to the geologic structures and the high compressive strength of the rock, improved fragmentation would best be achieved with an explosive that produces higher shock energy and less gas energy. This was particularly important given the blast geometry which severely limited rock movement. As previously discussed, high levels of gas energy were primarily expended in producing cratering around each blasthole and offer little in improving fragmentation. Therefore, the removal of the aluminum from the explosives would not only reduce the explosive costs, but also improve muckpile diggability.

Figure 7. Comparison of energy distributions for square (top) and staggered (bottom) patterns.

Figure 8. Effect of aluminum on pressure from ideal detonation model of 50/50 blend.

Figure 9. Effect of aluminum on temperature from ideal detonation model of 50/50 blend.

Table 5. Effect of aluminum on velocity of detonation of 50/50 blend.

<table>
<thead>
<tr>
<th></th>
<th>VOD (m/s)</th>
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<tbody>
<tr>
<td>50/50 blend</td>
<td>4949</td>
</tr>
<tr>
<td>50/50 blend + 5% Al</td>
<td>4202</td>
</tr>
</tbody>
</table>
7 DOWNSTREAM IMPROVEMENTS

Based on the findings and suggestions of the blast audit, the mine formed a Diggability Team to study and improve the diggability of the muckpiles. This team followed the Six Sigma® process to ensure success (Koski & Giltner 2009). The Diggability Team made the following key changes to the blast design.

- Staggered pattern in place of the square pattern
- Increase the powder factor and uniformity of the energy distribution with improved hole layout methodology
- Removal of aluminum from the explosives

The improvements achieved by the Diggability Team are discussed in the following sections.

7.1 Dig rates

Figure 10 shows the improvement in the dig rates for the loaders. The data in the graph represents three different time periods. The first period shows the historic, or baseline, data recorded prior to any changes in the blasting program. The middle period beginning around Jul 07 represents the time during which the diggability project occurred. The third period represents the period after the diggability project had been completed and the gains were being sustained. The graph demonstrates that the dig rates of the loaders were improved from the baseline average of 1855 tonnes/hr to 2046 tonnes/hr.

7.2 Crusher delays

Figure 11 shows the improvement in the delays at the crushers due to oversize fragments. The data in the graph represents the same time periods shown in Figure 10. The graph reveals that the changes in the blasting program reduced the oversize related delays at the crushers from 25 hr/month to 14.1 hr/month. Obviously there is potential for further improvement, however a significant improvement was achieved.

7.3 Safety & environment

In the twelve months prior to team formation there were 9 ‘jostling’ incidents with loader operators and truck drivers. Jostling incidents occurred when a truck driver or loader operator was tossed around in the cab even though seat belts were worn. Difficult digging with poor bucket penetration in the mining face can cause a loader operator to be jostled. Similarly large chunks dumped into a production truck box can jostle the truck driver. Twelve months after completion of the project, there have been no jostling incidents.

Blasting vibration complaints from surrounding communities averaged 5–6 per year prior to the project. In the twelve months after the project there were none.

8 CONCLUSIONS

The pairing of the blast audit with the Diggability Team employing the Six Sigma® process allowed the mine to achieve significant productivity improvements. By employing the conclusions and recommendations of the audit the Diggability Team was able to achieve the following:

- Improved LT-1850 Loader productivity by 9%
- Decreased crusher chunk delays by 44%

Figure 10. LT 1850 loader dynamic dig rate before, during and after improvements.

Figure 11. Combined crusher chunk delays before, during and after improvements.
- Decreased blasting complaints from neighbors (5–6 per year to 0 in the 12 months after team formation)
- Improved safety for equipment operators through reduction of jostling incidents (9 incidents in the 12 months prior to the team formation compared to 0 incidents in the 12 months after team formation)

An independent technical and operating review of mining operations in January, 2008 stated, “The impact of the recent Diggability initiative is evident and muck piles were well and evenly fragmented. We noted that the muck piles had excellent fragmentation during the visit. The process has been the subject of a group focus which clearly enjoyed success. Continue to sustain the excellent performance seen during our visit.” (Decker 2008).

REFERENCES