Performance Monitoring of a block cave mine using signal processing and waveform analysis of GPS data

Technical Literature

PERFORMANCE MONITORING OF A BLOCK CAVE MINE USING SIGNAL PROCESSING AND WAVEFORM ANALYSIS OF GPS DATA

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INTRODUCTION

Discrete (digital) signal processing techniques are proving to be very valuable tools for miners using the block cave method. Basic waveform analysis of different measured signals associated with active mining provides valuable information on production dynamics and safe operation of the mine. For example, correlation of the 3D surface displacement velocity waveform and the production output waveform reveals a remarkably predictable time-varying physical process. Studying the geometrical and temporal relationship between these two signals opens a broad window through which new management techniques become apparent. In this paper we discuss the techniques used to study these relationships, as well as the related implications for mining.

This research was carried out in association with the Chevron Mining underground molybdenum mine in Questa, New Mexico. The surface displacements were measured by a Global Positioning System (GPS) receiver, and consist of a series of discrete values. Here, the amount of ore extracted from the mine and the measured surface displacements are analyzed in the time domain. Some of these new techniques will be integrated into the decision management process at the mine, and will provide insight on ore production, draw control, and safe reclamation.

OVERVIEW

Block caving is a gravity-assisted ore extraction method that is used more and more in world mining. Mining engineers use the block cave technique to force large blocks of ore to collapse and fracture under their own weight into underground drawpoints. The ore is collected at the drawpoints and then moved to the surface for processing. Block caving is typically used to mine blocks of ore that have sufficient natural fractures to support the caving process as well as a consistent disseminated ore grade. A typical block cave operation involves the development of extensive underground infrastructure prior to mining activity. This includes items such as the ore passes, the ventilation system, roadways, and services. The basic structure of a block cave mine is shown in Figure 1. The undercut level is located at the base of the ore block, and exists to initiate the caving process. This is triggered by blasting radial networks of explosives. All underlying infrastructure must be in place and thoroughly tested before this can occur. The blasting

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process destroys the undercut level as the overlying block of ore caves into it and begins its gravity flow through the underlying passes. At Questa the fractured ore is concentrated at drawpoints, and then flows into the grizzly level (see Figure 2).

Figure 1. Structure of a block cave mine

A haulage level is located at the lowest level of the mine. This level contains associated rail and/or belt conveyor transport and is used to haul ore to a surface processing facility.

The task of the mining engineer is to maintain a steady flow at each draw point. When the draw control is uneven, the ore grade can drop due to dilution as rock outside the ore body is brought in. Block cave mining is used in several important diamond mines, at Freeport Mine in Indonesia, and at Palabora Mine in South Africa. It is used at one of the largest underground mines in the world (in Chile), and in numerous large mines in the USA, Canada, Australia and Indonesia (Laubscher, 2000).

CORRELATING THE 3D SURFACE DISPLACEMENT VELOCITY WAVEFORM WITH THE PRODUCTION OUTPUT WAVEFORM

The correlation between the 3D surface displacement velocity waveform (vectored XYZ) and the production output waveform is presented in this section. A continuously operating GPS station (arbitrarily named CHMA) is used to track the 3D surface displacements above the ore body (see Figure 3).

Figure 3: Location of GPS sensor CHMA with respect to surface expression of ore body
The production output is measured by tracking the number of ore cars that leave the haulage level. We explored the relationship between these two discrete waveforms by analyzing a series of months in 2005 and 2006. The monthly time periods analyzed are: June 2005, August 2005, October 2005, December 2005, January 2006, and March 2006. These time periods were chosen because they are representative of the overall data set. Please note that these data were collected after the effects of the underground production had reached the surface. Figure 4 displays the daily tonnage of molybdenum ore extracted (solid blue line) along with the daily GPS-derived 3D surface displacement velocities (dashed red line) for June 2005. All GPS data are from station CHMA.

![Figure 4: June 2005 ore production and 3D surface displacement velocities](image)

A correlation is evident between the daily 3D surface displacement velocities and the daily ore production, but the surface velocities are delayed in time with respect to the removal of ore. Signal processing tools are used to gain more information about the relationship between the two.

The following equation is used to calculate a linear coefficient that quantifies the geometrical agreement between the surface velocity waveform and the production waveform:

\[
 r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 (y_i - \bar{y})^2}}
\]

where \(x_i\) and \(y_i\) are the \(i\)th samples of the surface displacement velocity data and the production data and \(\bar{x}\) and \(\bar{y}\) are the corresponding sample means. This equation yields
a linear coefficient that approaches 1 if the two datasets are highly correlated, -1 if they have a high negative correlation and 0 if they are uncorrelated. The linear coefficient between the two waveforms displayed in Figure 4 is -0.05. This indicates the two are poorly correlated, but the poor correlation is clearly the result of the delayed response of the surface displacement with respect to the underground production.

To discover the characteristics of this delay, we use a second tool; shifting the 3D surface displacement velocity waveform back in time increments of 1 day (the maximum resolution since ore production is tallied in discrete daily samples). Shifting the surface displacement waveform by -1 day produces a linear coefficient of 0.64, a much better agreement. A -2 day shift reveals a linear coefficient of 0.78, which is significant (Figure 5).

![Figure 5: June 2005 ore production and surface displacement velocities (-2 day shift)](image)

The high correlation obtained when shifting the surface displacement waveform -2 days raises several questions. Are these data always well correlated when the delay is accounted for, and is the delay consistently -2 days, or does it fluctuate? We analyzed five other time periods to shine light on these questions. Before these data are presented, it is important to say more about the linear coefficient that we are using to quantify the agreement between the two waveforms.

Because the production output is sampled once per day, we can only slide the daily surface displacement velocities in daily increments. In other words, if the production output were sampled at a higher rate, the increments available to slide would be shorter than a day, increasing the chance of finding the true delay and the highest degree of correlation. Figure 6 illustrates this point by showing the linear coefficients as the surface displacement velocities are shifted by -9 days and +9 days. The highest linear
coefficient can be seen at – 2 days ($r = 0.79$), and the diminishing weekly frequencies can be seen to each side of the peak (the strong up and down form of the curves occurs because the mine did not produce on the weekend when these data were collected). It is unlikely that the -2 day shift represents the highest linear coefficient, and thus the best-fit delay. Nevertheless, these waveforms generated from daily data are useful for analysis.

![Figure 6: Linear coefficient correlation curve for June 2005 data.](image)

![Figure 7: August 2005 ore production and surface displacement velocities (-2 day shift)](image)

The production output waveform and the surface displacement velocity waveform from August 2005 are displayed in Figure 7. The best-fit delay is -2 days, the same as the June
2005 data. The linear coefficient for these two curves is 0.81, slightly higher than for the June 2005 data.

Figure 8 displays data from October 2005. The linear coefficient for this dataset is 0.79, but the best-fit delay is -3 days instead of -2 days. Figure 9 displays data from January 2006. The best-fit delay is -2 days, and the linear coefficient for these two curves is 0.89, the highest yet.

Figure 8: October 2005 ore production and surface displacement velocities (-3 day shift)

Figure 9: January 2006 ore production and surface displacement velocities (-2 day shift)
These data clearly show that: 1) the surface displacement velocities lag behind the underground production in a very predictable manner, and 2) there is a consistent and high-degree of correlation between the surface displacement waveform and the production output waveform when this delay is accounted for.

Table 1 displays the linear coefficients for the different surface displacement velocity shifts, and displays the associated means for the six data sets. The -2 day shift has the highest linear coefficient at 0.79. The next highest linear coefficient is 0.47, and is found at the -3 day shift.

<table>
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<th>Month</th>
<th>-4 shift</th>
<th>-3 shift</th>
<th>-2 shift</th>
<th>-1 shift</th>
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<td>0.01</td>
<td>0.78</td>
<td>0.64</td>
<td>-0.05</td>
</tr>
<tr>
<td>August 2005</td>
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<td>0.35</td>
<td>0.81</td>
<td>0.39</td>
<td>-0.15</td>
</tr>
<tr>
<td>October 2005</td>
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<td>0.79</td>
<td>0.65</td>
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<tr>
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<td>0.76</td>
<td>0.75</td>
<td>0.27</td>
<td>0.08</td>
</tr>
<tr>
<td>January 2005</td>
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<td>0.57</td>
<td>0.89</td>
<td>0.44</td>
<td>-0.28</td>
</tr>
<tr>
<td>March 2005</td>
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<td>0.36</td>
<td>0.87</td>
<td>0.63</td>
<td>0.05</td>
</tr>
<tr>
<td>Mean</td>
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<td>0.47</td>
<td>0.79</td>
<td>0.39</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

Table 1: Individual linear coefficients and associated means

![Figure 10: Plot of mean linear coefficient values from each set of shifted data.](image)

The mean values from each set of shifted data are plotted as a line in Figure 10. For the purposes of this research, we consider any R value greater than 0.6 to represent significant...
correlation. Pursuant to this, the area under the curve that is 0.6 or higher has been shaded. The shaded area extends from roughly -2.5 days to -1.5 days, with the strongest linear correlation located at a -2 day shift. This means that the delay between the ore production and the surface displacement velocity ranges from 1.5 days to 2.5 days, and that most of the time is around 2 days.

**IMPLICATIONS FOR BLOCK CAVE MINES**

Correlating the 3D surface displacement velocity waveform and the production output waveform reveals a high-level of agreement once this delayed response is accounted for. This natural pattern has numerous implications for block cave mining. Ore production can be calculated based upon the magnitude of the surface displacements, providing an additional method to the underground logs to measure production.

In addition to being a useful check, analyzing production via the surface displacement data is a useful tool to ensure uniform draw control. A strategically designed GPS array over the surface expression adds the necessary spatial displacement information to track the surface effects of the underground caving. These data enable engineers to compare predicted with observed displacements. Deviation between the two produces a signal that the underground draw may not be uniform. Because the delay between production and surface displacement is relatively short (roughly -2 days in this case), it is then possible to make nimble adjustments to the mining strategy.

Surface displacements can also be used for reclamation planning and mine closure. The tight relationship between production and surface displacements implies that the majority of displacement (in this case predominantly subsidence) occurs in lock-step with active mining. Once mining ceases, surface displacement will be predominantly confined to consolidation and tunnel collapse.

**CALCULATING ORE PRODUCTION**

Production can be estimated by exploiting the relationship between the two discussed waveforms. Figures 11 and 12 each display the tonnage of molybdenum ore per 1 millimeter of 3D surface displacement as the integration time – in days – increases. Both converge at roughly 188 tons of ore per millimeter of surface displacement. The authors looked at other time periods and observed the same relationship. The relationship may vary as the ore body is diminished by active mining; however this should not matter as long as it is recalculated on a regular basis. The installation of a complete GPS array above the ore body will further strengthen and refine the art of transferring surface displacements into ore production.
We computed the number of tons of ore expected based upon the cumulative 2005 3D surface displacement, and then compared it to actual production. Over the course of 2006, the GPS station measured approximately 10.63 meters of 3D surface displacement. If we use our derived 188 tons per millimeters, then the 3D surface displacement translates into 1.998 million tons or ore. The official mine record for 2006 production is 2.015 million tons of ore. These two numbers are within 1% of one another, thereby
validating this as an effective technique for calculating ore production. Since we derived the 188 tons per millimeter relationship using empirical data from 2005 - and verified it using data from 2006 - an additional measure of credibility is obtained. This implies that the relationship between production and surface displacement must change slowly.

MINE RECLAMATION

The correlation between production and surface displacement (mostly subsidence) has significance for reclamation as well. In the case of the Questa Mine, we have now discovered that the surface displacement velocities faithfully lag behind ore production in a range of 1.5 to 2.5 days, and that when the surface displacement velocities are shifted back in time they exhibit a high degree of correlation in relation to ore production.

A priori this means that the surface deformation is occurring in step with production. Once mining stops, we can expect that the surface displacements associated with ongoing mining will stop within a week or so. This means that most of the surface displacement – predominantly subsidence - will have already occurred when the mine stops producing. Two other types of subsidence will continue over the long-term. When the different levels such as haulage, grizzly, and rail ultimately collapse, the surface displacement will follow the relationship between production and surface displacement already established. The magnitude of this can be approximated by calculating the volume of the various tunnels in terms of ore tonnage. Presumably this could take many years to occur, and would likely happen in different episodes, rather than all at once.

The consolidation and compaction of the fractured rock above the undercut level will also produce surface displacements. In both cases – tunnel collapse and consolidation – the associated surface displacements of these long-term processes will be a small fraction of what occurs during mining production, and they can be estimated.

FINAL COMMENTS

Discovering a reciprocal pattern between the subsurface extraction of molybdenum ore and the resulting cumulative 3D surface displacements improves our understanding of block cave mining. This study has established that: a) the surface displacements faithfully follow the removal of ore by roughly 2 days, b) a significant and consistent linear coefficient appears when this delay is accounted for, and c) this relationship is relatively constant and predictable. This knowledge can be successfully applied to numerous aspects of the mining process. By considering the correlation relationship as a type of equivalent exchange – ore for displacement and vice versa – we can calculate the amount of ore extracted when a millimeter of displacement velocity is observed at the surface. In this case it is roughly 188 tons of molybdenum ore per millimeter of surface displacement velocity. While it is likely that this relationship varies slightly as the overall geometry is changed, this general pattern almost certainly lays waiting to be discovered at each successful block cave mine.
Establishment of this inherent pattern means innovative draw control techniques are within easy reach; carrying the small cost of a GPS array and the domain knowledge presented here. Because the block cave surface displacements are in concert with ore production, the former can be easily analyzed to determine if the overall draw progression meets expectations. Disparities between the predicted and the observed provide timely notifications to the mine operator of potential issues. These can be detected through simple numerical analysis, through a GIS, and/or in tandem with existing geotechnical software.

Chevron Mining is a world leader in the reclamation process, and maintains a continuous dialogue with state and federal regulators. This research offers new insight on block cave reclamation, and the important transition from an active mine to a landscape closer to its original state. These data show that the 3D surface displacements – mostly subsidence – occur in lock-step with production. This means that ore production related displacements will stop within weeks rather than months or years. Subsidence will continue in the form of rock consolidation, but the magnitude of this can be modeled and calculated.

Additional research topics include 1) using the link between production and displacement to study arch formation and possible detection methods, and 2) studying how the block cave effects propagate upward after the undercutting process. The first entails contrasting synthetic waveforms that represent an arch formation episode with the continuously observed waveforms from active mining, and certainly encompasses mine safety. The second is production related and could unravel the mystery of how the underground caving effects break through to the surface.

Our research relies on signal processing and waveform analysis. It seems even more natural now to deploy these tools to block cave mining. The increase in performance transparency that these tools bring provides a valuable return in both mine economics and safety.

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References

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**When it has to be right.**