THE EFFECTS OF UNDERGROUND BLASTING ON NEARBY PRE-EXISTING STRUCTURES

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THE EFFECTS OF UNDERGROUND BLASTING ON NEARBY PRE-EXISTING STRUCTURES

By:
Logan Connolly

A thesis submitted in partial fulfillment of the requirements for the degree of

Masters of Science in Mining Engineering

Montana Tech
2018
Abstract

Butte, Montana holds a prestigious place in the history of mining, deemed “The Richest Hill on Earth,” containing a plethora of underground mines. The Orphan Boy/Orphan Girl underground mines, on the western side of Butte, operated from 1895-1956 producing zinc, lead, silver, and manganese. Today, the Orphan Boy mine is part of Montana Tech’s Underground Mine Education Center (UMEC) and the Orphan Girl mine houses the World Museum of Mining. Underground development in the Orphan Boy mine continues to progress as students from Montana Tech receive hands-on underground training; in addition, the UMEC is a multi-disciplinary research facility. Repeated underground blasting occurs in close proximity to old mine workings (wood supports installed circa 1950 or earlier). Research began to determine the impact of underground blasts on nearby pre-existing structures. Using the ISEE Field Practice Guidelines for Blasting Seismographs, one seismograph monitors the predominately-wooden structures to measure their response during each underground blast and one seismograph is positioned on the surface to monitor surface structure response to the blast. Thirteen underground blasts were monitored, and the resulting general conclusion was that the blasts were not causing structural damage to the nearby pre-existing structures. Recorded peak particle velocities from ground vibrations generated from the underground blasts interacting with the pre-existing structures ranged from 0.150 in/s to 2.20 in/s. All 13 blasts fell below the mining industries standard USBM RI 8507 damage threshold. This paper presents the findings of the research conducted to date for the project, includes analysis of the research data, additional conclusions determined from the research. Recommendations for the future work are included as well.

Keywords: Underground, Blasting, Pre-Existing Structures, Structure Response, Ground Vibrations
Acknowledgements

Special acknowledgements to White Industrial Seismology for providing training and expertise for the blasting seismographs used to obtain the research data.
# Table of Contents

ABSTRACT ................................................................................................................................................ II

DEDICATION ........................................................................................................................................... III

ACKNOWLEDGEMENTS ........................................................................................................................... III

LIST OF TABLES ....................................................................................................................................... VI

LIST OF FIGURES ..................................................................................................................................... VII

LIST OF EQUATIONS ................................................................................................................................. X

GLOSSARY OF TERMS (OPTIONAL) ........................................................................................................... X

1. **INTRODUCTION** ................................................................................................................................. 1

2. **BACKGROUND INFORMATION** ....................................................................................................... 3

   2.1. **Butte Mining District** .................................................................................................................. 3

   2.2. **Square-set Framing** .................................................................................................................... 4

   2.3. **The UMEC** ................................................................................................................................... 7

      2.3.1. North Area ................................................................................................................................... 9

      2.3.2. Orphan Girl Area ....................................................................................................................... 10

      2.3.3. Blast Design .............................................................................................................................. 11

   2.4. **Ground Vibrations** .................................................................................................................... 13

   2.5. **Structure Response** .................................................................................................................. 18

   2.6. **Predicting PPV** .......................................................................................................................... 20

   2.7. **Top-hole vs. Bottom-hole Priming** ........................................................................................... 23

3. **RESEARCH PROCEDURE** .................................................................................................................. 27

   3.1. **PPV Prediction Models** ............................................................................................................... 31

   3.2. **Top-hole vs. Bottom-hole Primed** ............................................................................................ 32

4. **DATA & RESULTS** ............................................................................................................................. 34

   4.1. **Underground Monitoring** .......................................................................................................... 34
4.1.1. North Area ............................................................................................................................ 34
  4.1.1.1. North A Heading .............................................................................................................. 34
  4.1.1.2. North B Heading .............................................................................................................. 37
  4.1.1.3. Shop Heading .................................................................................................................. 39
4.1.2. Orphan Girl Area .................................................................................................................... 42
  4.1.2.1. Orphan Girl Vein Heading ............................................................................................... 42

4.2. Surface Monitoring .................................................................................................................. 43

4.3. Prediction Models .................................................................................................................... 46

4.4. Top-hole vs. Bottom-hole Priming ....................................................................................... 49

5. CONCLUSION ............................................................................................................................ 51

6. RECOMMENDATIONS ................................................................................................................. 54

7. REFERENCES ............................................................................................................................. 56

8. APPENDIX ................................................................................................................................. 58
  8.1. Blast Reports .......................................................................................................................... 58
  8.2. Predictive Model Calculations .............................................................................................. 74
List of Tables

Table I: Material mined in the Butte Mining District from 1880-2005).................................3
Table II: North A heading underground blast data .................................................................35
Table III: North B heading underground blast data ...............................................................37
Table IV: Shop heading underground blast data.................................................................40
Table V: Orphan Girl Vein Data ..........................................................................................42
Table VI: North Area Surface Monitoring Data ......................................................................44
Table VII: Underground and surface seismograph monitoring PPV comparison ...............44
Table VIII: PPV Predictive Model Results ..............................................................................47
Table IX: Top vs Bottom Prime Data ..................................................................................49
Table X: Base Equation - Average .......................................................................................74
Table XI: Base Equation - 90% ............................................................................................74
Table XII: Base Equation - 99% ..........................................................................................74
Table XIII: Square-root Model ..............................................................................................75
Table XIV: Cube-root Model .................................................................................................76
Table XV: Experimental Model ...........................................................................................77
List of Figures

Figure 1: The UMEC, green and Orphan Girl, red (Google Earth) ..........................1
Figure 2: Square set timber schematic (Dunshee, 1913) ........................................5
Figure 3: Students standing under square sets in the UMEC North Area .............6
Figure 4: Square set timbers in the Orphan Girl 100-foot shaft station ...............6
Figure 5: Students operating jackleg drill in the UMEC ........................................7
Figure 6: UMEC and Orphan Boy 100-foot current (blue) and historical (orange) workings ..........................................................8
Figure 7: UMEC North Area headings including North A (red), North B (green), and Shop (yellow) ...............................................................10
Figure 8: Orphan Girl Area (white box) and Orphan Girl Vein heading (orange) ......11
Figure 9: UMEC development headings blast pattern designs ............................12
Figure 10: UMEC working face prior to loading explosives ..............................13
Figure 11: Blast vibration energy types (Engineers, Ground Vibration, 2001) ........15
Figure 12: Hypothetical single pulse source (Engineers, Ground Vibration, 2001) ....16
Figure 13: Wave particle motion for P-waves, S-waves and Rayleigh waves (Seismic, 2018) .................................................................17
Figure 14: P-waves (orange) and S-waves (blue) moving through varying mediums ...18
Figure 15: An example of a USBM RI 8507 chart ...............................................19
Figure 16: PPV vs. SD example plot (Favreau, 2014) ........................................22
Figure 17: Bottom-hole priming schematic depicting the direction of the explosive column .........................................................................................24
Figure 18: Top-hole priming schematic depicting the direction of the explosive column 25
Figure 19: Seismograph setup and placement including geophone (grey box) and microphone (orange box) ...........................................................................................................28

Figure 20: North Area underground and surface seismograph location (yellow star) ...... 29

Figure 21: Orphan Girl underground seismograph location (yellow star) ..................... 30

Figure 22: Top-hole priming test burn cut prior to loading explosives ......................... 32

Figure 23: Bottom-hole priming test burn cut prior to loading explosives ................... 33

Figure 24: North A heading second blast USBM RI 8507 plot ..................................... 35

Figure 25: North A heading combined blast USBM RI 8507 plot ................................ 36

Figure 26: North B heading first blast USBM RI 8507 plot ........................................ 37

Figure 27: North B heading blasts combined USBM RI 8507 plot ............................... 38

Figure 28: Shop heading first blast USBM RI 8507 plot ............................................. 40

Figure 29: Shop heading blasts combined USBM RI 8507 plot .................................... 41

Figure 30: Orphan Girl Vein heading first blast USBM RI 8507 Plot ........................... 42

Figure 31: North A heading first blast surface USBM RI 8507 Plot ............................. 45

Figure 32: Combined Surface Monitoring USBM RI 8507 Plot .................................. 46

Figure 33: Experimental Model PPV vs. Scaled Distance ............................................ 48

Figure 34: Top-hole vs bottom-hole priming USBM RI 8507 Plot .............................. 50

Figure 35: Blast 1: 4039 Seismograph Report .............................................................. 58

Figure 36: Blast 1: 6088 Seismograph Report .............................................................. 59

Figure 37: Blast 2: 4039 Seismograph Report .............................................................. 60

Figure 38: Blast 2: 6088 Seismograph Report .............................................................. 61

Figure 39: Blast 3: 4039 Seismograph Report .............................................................. 62

Figure 40: Blast 3: 6088 Seismograph Report .............................................................. 63
Figure 41: Blast 4: 4039 Seismograph Report ................................................................. 64
Figure 42: Blast 5: 4039 Seismograph Report ................................................................. 65
Figure 43: Blast 6: 4039 Seismograph Report ................................................................. 66
Figure 44: Blast 7: 4039 Seismograph Report ................................................................. 67
Figure 45: Blast 8: 4039 Seismograph Report ................................................................. 68
Figure 46: Blast 9: 4039 Seismograph Report ................................................................. 69
Figure 47: Blast 10: 4039 Seismograph Report ............................................................... 70
Figure 48: Blast 11: 4039 Seismograph Report ............................................................... 71
Figure 49: Blast 12: 4039 Seismograph Report ............................................................... 72
Figure 50: Blast 12: 6088 Seismograph Report ............................................................... 73
Figure 51: Square-root PPV vs. Scaled Distance Plot .................................................... 75
Figure 52: Cube-root PPV vs. Scaled Distance Plot ....................................................... 76
Figure 53: Experimental PPV vs. Distance Plot ............................................................ 77
List of Equations

Equation 1: Square Root Scaled Distance .................................................................20
Equation 2: Cube Root Scaled Distance .................................................................20
Equation 3: Peak Particle Velocity .................................................................21
Equation 4: Average Value Equation .................................................................22
Equation 5: 90% Bound Equation .................................................................22
Equation 6: 99% Bound Equation .................................................................23
1. Introduction

The Orphan Boy and Orphan Girl mines began production at the turn of the 20th century and continued to produce until their closure in the mid 1950’s. Today, these mines sit as living reminders of the dynamic and intricate mining history of Butte, MT. The Orphan Girl mine houses the World Museum of Mining facilities. The Orphan Boy mine hosts Montana Tech’s Underground Mine Education Center (UMEC). In 2005, the Orphan Girl decline was driven from the 65-foot level to the 100-foot level. In 2012, the UMEC decline was driven by Montana Tech students and faculty in order to reach the 100-foot level (Rosenthal, Personal Communication, 2017). The UMEC and Orphan Girl are connected on the 100-foot level. Figure 1 shows the location of the UMEC and Orphan Girl mines highlighted by the green and red boxes, respectively.

Figure 1: The UMEC, green and Orphan Girl, red (Google Earth)
The UMEC, located on Montana Tech’s campus, provides students the ability to gain hands-on experience with hardrock underground mining practices, guided by professors and industry professionals. The UMEC is the only on-campus student lab/mine in the United States, so the UMEC provides numerous, exclusive research opportunities. With the continual mine development of the UMEC, underground blasting occurs frequently throughout the year. Blasting often occurs in close-proximity to old mine workings. Research began in September 2016 to determine the effects of underground blasts on pre-existing mine structures. The research primarily focuses on the structural response of the historical mine workings. This paper will further elaborate on the procedure and results of the research, and provide conclusions and future work recommendations for the continuation of the research.
2. Background Information

2.1. Butte Mining District

Butte, Montana is home to the world-renowned Butte Mining District. Deemed the “Richest Hill on Earth,” the Butte Mining District began with humble placer mining operations in 1864. The focus on placer mining quickly changed to the valuable silver ores throughout the district. Butte’s silver-mining industry uncovered massive, rich copper ores. The first successful copper smelter in Butte was the Colorado Smelting Co. works, which treated custom ores and first operated in 1879. Following the advent of this smelter, the development of the copper mines was rapid (Daly et al, 1925). Butte quickly progressed into a staple of the mining industry. Table I shows the historical metal production from 1880-2005, excluding the metal production of Montana Resources’ Continental Pit (Czehura, 2006).

<table>
<thead>
<tr>
<th>Metal Production in Butte District (1880-2005)</th>
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<tbody>
<tr>
<td><strong>Copper</strong></td>
</tr>
<tr>
<td><strong>Zinc</strong></td>
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<tr>
<td><strong>Manganese</strong></td>
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<tr>
<td><strong>Lead</strong></td>
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<tr>
<td><strong>Silver</strong></td>
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<td><strong>Gold</strong></td>
</tr>
<tr>
<td><strong>Molybdenum</strong></td>
</tr>
</tbody>
</table>

The Orphan Boy and Orphan Girl mines operated from the late 1890’s to 1956 producing primarily zinc, lead, silver, and manganese (DEQ, 2017).
2.2. **Square-set Framing**

The ground support practice in the Butte District was square-set framing. Square-set framing excels in situations where large ore bodies were stopeed and the timbers would hold the ground from caving without any filling (Dunshee, 1913). The advantages of square-set framing include, but are not limited to (Mawdsley, 1924):

- General safety of the miners;
- Complete extraction of the ore;
- Ore is not diluted with waste material;
- Ore can be easily handled;
- Ore becomes available as soon as its broken;
- Subsequent filling with waste provides necessary support for excessively ‘heavy’ ground and avoids the use of very large expensive timbers; and,
- Backfilling prevents fire dangers.

The disadvantages of square-set framing is the demand for high quality timber. In the Butte District, mine managers adopted the square-set stope, back-filled with waste, as the most efficient method to apply to 80% of the mining operations (Mawdsley, 1924). Figure 2 illustrates square-set framing, showing both a profile view and a cross section view of a square set timber alignment.
The Orphan Girl and Orphan Boy mines are two mines that used square-set framing. Antiquated timbers still stand and support drifts/cross-cuts near active blasting faces. The ground vibration research presented in this paper focuses on evaluating the effects of the underground blasting on the square-set timbers exposed and accessible in the underground workings of the Orphan Boy mine. Figure 3 and 4, below are two examples of the square set timbering from the UMEC. Figure 3 displays students standing under a section of square set timbers in the North Area of the UMEC. Figure 4 presents the pre-existing workings in the Orphan Girl 100-foot shaft station.
Figure 3: Students standing under square sets in the UMEC North Area

Figure 4: Square set timbers in the Orphan Girl 100-foot shaft station
2.3. The UMEC

The UMEC offers students at Montana Tech the unique opportunity to receive hands-on experience with the traditional underground mining cycle: drill, blast, muck, haul, bolt, and repeat. Students are trained and use common underground mining equipment including jackleg drills, jumbos, and LHD muckers. Figure 5 shows students operating a jackleg drill, while practicing safe ground support methods by inserting rock bolts and mesh.

Figure 5: Students operating jackleg drill in the UMEC
At the UMEC, the water table sits at roughly the 115-foot level therefore restricting development to the 100-foot level. Since opening the UMEC in 2012, several areas of pre-existing square-set framing sections have been exposed. Figure 6 displays the current UMEC workings (blue) and the historical workings of the Orphan Boy mine (orange). The purple areas represent Orphan Boy workings filled with material (caved). The gridlines are 100-feet by 100-feet for scale. The North Area is highlighted by the green box and the Orphan Girl Area is in white.

Figure 6: UMEC and Orphan Boy 100-foot current (blue) and historical (orange) workings
2.3.1. North Area

The North Area was selected due to open and accessible old square-set timbers, and because of the multiple active headings in the section. The two active headings are the North and the Shop. The North heading blasts fall into two additional classifications: Drift A and Drift B. North Drift A advanced north until the drift intersected a section of old Orphan Boy mine workings. The mine workings were backfilled preventing further advancement of the North Drift A. North Drift B diverts from North Drift A to the west after progression in North Drift A ceased. North Drift B is being driven with the intent to intersect Orphan Boy workings as well. The Shop heading was a series of blasts completed with the intent to establish an underground maintenance bay. Additionally, the Shop heading will serve as the intersection/starting point for a secondary decline connecting to the entrance to the UMEC’s powder magazine. Figure 7 shows the North Area with the directions of advance for the North Drift A (red), North Drift B (green), and the Shop (yellow). The gridlines are 50-feet by 50-feet for scale.
2.3.2. Orphan Girl Area

The Orphan Girl Area was a second testing area used during the research. The Orphan Girl Area is located within the Orphan Girl Mine. The Orphan Girl Area also had accessible square-set timbers in close proximity similar to the UMEC’s North Area. The Orphan Girl Area has one working heading called the Orphan Girl Vein. The Orphan Girl Vein heading follows the Orphan Girl Vein at the 100-foot level. The vein consists of zinc-lead-manganese-silver ore and provided ground vibration data similar to an underground blasts in a hard, competent rock body.
Figure 8 shows the boundary of the Orphan Girl Area (white box) and the Orphan Girl Vein heading (orange). The gridlines in Figure 8 are 50-feet by 50-feet for scale.

2.3.3. Blast Design

Persons working in the UMEC adhere to a standard development plan. Each heading, within the UMEC, is designed to be 10 feet wide by 10 high with 6 feet of advance each cycle. Typically, each blast in the UMEC consists of an average of 15 or 16 holes dependent on the center arrangement of the burn. It should be noted, the exact number of holes per shot vary with the differences in persons working on the heading in that particular time. A specific center
arrangement is not necessary as long as one or two of the blast holes within the center arrangement are left unloaded to utilize as burn holes. The burn holes allow material to move into a void space as the blasting sequence initiates. Figure 9, below, displays two common patterns used for the drilling face in the UMEC’s various headings. The left drawing displays a diamond center arrangement, and the right drawing shows a 6-pack center arrangement for the burn.

![Figure 9: UMEC development headings blast pattern designs](image)

In the UMEC, blasts occur every two or three weeks as teams of three students work in the heading three hours a week. Blast patterns are drilled using pneumatic jackleg drills operating at 95 psi using 6-foot drill steel with 1-5/8 inch carbide insert cross drill bits. Blasting is primarily done using ANFO with a sitting density of 0.85 g/cm³, and blown into the holes, the density becomes closer 1.00 g/cm³ (Rosenthal S. D., 2017). The average powder factor for the monitored blasts was 2.8 pounds of ANFO per ton of rock blasted. Initiating system uses non-
electric (Nonel) with 7000 millisecond in-hole delay and 300 millisecond delays between holes. Figure 10 is a working face in the UMEC ready to be loaded with explosives.

![Figure 10: UMEC working face prior to loading explosives](image)

### 2.4. Ground Vibrations

Ground vibrations can be created from naturally occurring events or from man-made activities. The amount of and type of vibrations that reach a site are dependent on (Engineers, 2001):

- The amount of energy released at the source;
- The energy travel pathways from the source to the site;
- The distance from the source to site; and,
- The characteristics of the site.
In regards to blasting, the amount of energy released at the source is directly related to the amount and type of explosives used. The energy travel pathways in blasting refer to changes in the geological conditions the ground vibrations travel through. Vibrations will travel differently in varying geological units. Hard, consistent rock formations have a tendency to support high frequency waves, while soft or unconsolidated formations tend to support lower frequency waves (Pruss, 1989). The distance from blasting source to the monitoring site is important because the greater the distance, the greater the attenuation of the vibration energy. Finally, the characteristics of the monitoring site will affect the ground vibrations. The material of the structure (i.e. wood, plaster, concrete) influence the interaction with the ground vibrations.

An explosive charge detonates to create two forms of energy: a shock wave and high gas pressures. The area approximately twice the blasthole radius is crushed from the initial burst energy. The interaction of the shockwave with the existing discontinuities in the rock begin to form radial cracks around the expanding cavity. The high pressure gas fills and expands the cracks eventually heaving the fractured rock mass outwards. Most of the energy is consumed when the rock breaks and moves, but small amounts of energy escape from the designated “work zone.” The escaped energy forms ground vibrations and/or air overpressure. Air overpressure is produced when portions of the escaped energy are liberated into the atmosphere. Due to the nature of underground blasting, excessive air over pressure is created. The remaining energy travels elastically through the rock body and is the resultant ground vibrations.

The ground vibrations generated from explosive blasts create a group of waves. The waves have different characteristics such as particle motion and traveling velocities that affect structural response. The waves are separated into two categories: body waves and surface waves. Body waves travel through the “body” of the material, and surface waves only travel along the
surface of the ground. Figure 11 presents the interactions between a surface blast and a structure, and the resulting energy forms generated.

![Diagram](image)

Figure 11: Blast vibration energy types (Engineers, Ground Vibration, 2001)

Body and surface waves travel at different velocities, resulting in varying arrival times with the body waves reaching the structure before the surface waves. The body waves from a blast consist of compressional waves (P-waves) and shear waves (S-waves). The most common surface waves created during a blast are Rayleigh waves. The P-waves arrive first to the structure, followed by the S-waves traveling at approximately 0.6 times the velocity of the P-waves. The Rayleigh waves arrive last and travel at about 0.6 times the velocity of the S-waves. The time between the arrivals of the different wave types changes depending on the distance from the blast origin, and the structure being monitored. A structure close to the blasting face will have all three waves arrive in a smaller window of time. A structure farther away from the blasting will have distinguishable signatures from the different wave types due to the difference in velocities as the waves travel through the ground. Figure 12, below, displays how a seismograph would interpret the change in waves between two distances. At short and intermediate distances, the different waves reach the structure almost in unison, but at larger distances the different waves are more distinguishable from one another.
Another characteristic to help distinguishing between the wave types is particle motion. P-wave particles move in a compression and expansion manner similar to an accordion. P-waves are the same wave type that transmit sound through air and water. S-wave particles move perpendicular to the motion of energy. S-waves typically have lower frequencies and larger displacements than P-waves, and can only move through solid rock masses (University, 2007). Rayleigh wave particles move in a circular motion. Figure 13 shows the different wave types and their respective particle motion.
Surface waves do not exist underground. Even P-waves may show only half the particle motion underground compared to the particle motion they show at the ground surface (Oriard, 2005). With that being stated, the ground vibrations generated from the underground blasts will produce only body waves. The underground headings and workings geometry will additionally affect the waves measured at the point of interest. S-waves cannot be transmitted or generated when moving from a solid rock mass to a liquid medium (air), so the wave energy is completely reflected back into the original medium (Oriard L. L., 1985). The result is an attenuation of the S-wave when the ground vibrations generated from the blast cross a heading or workings. S-waves still reach the monitoring point, but at a reduced form compared to their maximum potential due to the redirection caused by the opening. Figure 14 elaborate how the headings and
workings interact on the body waves. The blue arrows represent the S-waves, the orange arrows represent the P-waves, and the black box represents the monitoring point.

Figure 14: P-waves (orange) and S-waves (blue) moving through varying mediums

2.5. Structure Response

The United States Bureau of Mines (USBM) began issuing vibration criteria beginning in 1942 in attempts to mitigate the potential concerns with blasting causing structural damage to nearby housing developments (Reed, 2005). From 1942 to 1980, the USBM continued to conduct research and issue vibration criteria based upon their research. In 1980, the USBM issued Report of Investigations (RI) 8507, Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting. The vibration criteria presented in USBM RI 8507 is still
used in the mining industry today. Figure 15 shows an example of the USBM RI 8507 chart used for determining if the blasts caused structural damage. The solid blue line in Figure 15 is the threshold for damage.

The peak particle velocity (PPV) is plotted against their frequency for the recorded wave signatures. The blue line in the USBM RI 8507 chart denotes the threshold for damage for plaster. Plaster is considered the baseline for structural response since it was found to be the weakest material during the USBM RI 8507 research. If the PPVs at that respective frequency exceeds the threshold for damage, the wave has potential to cause a negative structural response (Siskind, Stagg, Kopp, & Dowding, 1980). The frequency of a wave is a very important factor. A wave with a particular PPV and a high frequency is less likely to cause structural damage than a
wave with the same PPV but a lower frequency (Dowding, Construction Vibrations, 2000). The
ground vibrations generated from the blasts at the UMEC use the vibration criterion from USBM
RI 8507 to assess if structural damage occurs to the pre-existing square-sets in the North Area.

2.6. Predicting PPV

The peak particle velocity (PPV) of a wave generated from a blast can be predicted by
using the relationship between the amount of explosives and distance from the blast. The amount
of explosives is commonly defined throughout the mining industry by the weight of explosives
detonated in a 8 millisecond interval. Realistically the amount of explosives and distance will
vary from blast to blast. Normalizing the data in order to predict a PPV is done by calculating the
scaled distance. The scaled distance utilizes the relationship between the distance and the weight
of explosives detonated per 8 milliseconds. The two most popular forms of scaled distances are
square-root and cubed root. Equations 1 and 2 show square root and cube root scaled distance
equations.

\[
\text{Equation 1: Square Root Scaled Distance} \\
S = \frac{D}{\sqrt{W}},
\]

\[
\text{Equation 2: Cube Root Scaled Distance} \\
S = \frac{D}{W^{3/2}},
\]

Where:

\(S\) = scaled distance (ft/lb^{1/2}),

\(D\) = distance from blast to structure (ft),

\(W\) = maximum weight of explosives detonated per 8 millisecond delay (lb).
Square root scaled distance is the more commonly used method (Dowding, 1985), and both approaches can be used to predict the peak particle velocity. The relationship between distance and charges that produce 2 in/s peak particle velocities from cube root and square root scaling relationships are not significantly different between 20 and 100 feet. Square root is more conservative from 100 feet and beyond, and inversely, cube root is more conservative from 20 feet or closer (Dowding, 1985). The scaled distance can be further related to PPV, as seen in Equation 3.

Equation 3: Peak Particle Velocity

\[ V = kS^{-m} \]

Where:

- \( V \) = peak particle velocity (in/s),
- \( k \) = site constant equal to y-intercept of the PPV vs scaled distance regression line,
- \( S \) = scaled distance (ft/lb^{1/2}),
- \( m \) = site constant equal to the slope the PPV vs scaled distance regression line.

Figure 16 below is an example of the PPV vs scaled distance plot used to find the site specific constants \( k \) and \( m \) from Equation 3. The plot utilizes logarithmic axis for both the PPV and scaled distance. A regression line fit to the data points determines the \( k \) and \( m \) values, with the \( k \) being the y-intercept and \( m \) being the slope of the regression line. The data points represent individual blasts. The more blasts recorded and previously monitored helps increase the accuracy for predictive model. Furthermore, general predictive models do exist, but are not recommended since two variables are specific to the individual mine and blasting site.
In certain situations, mines potentially do not have the ability to determine the site specific constants for their location. General equations have been developed to help counter this issue. Equation 4, 5, and 6 are the three most commonly accepted to predict peak particle velocities based on varying confidence intervals for typical data. The equations themselves work on the principle on making preliminary predictions that in many cases do not represent a technically accurate model, but rather the ground vibrations will not exceed the calculated amounts (Oriard L., 2005). Equation 4 calculates an average PPV value:

**Equation 4: Average Value Equation**

\[ V = 160S^{-1.6} \]

Equation 5 predicts a PPV based upon a 90% bound. This simply means that 90% of the blasts will remain at or below the calculated PPV:

**Equation 5: 90% Bound Equation**

\[ V = 242S^{-1.6} \]
Equation 6 estimates PPV based upon a 99% bound. As with the 90% bound, the calculated PPV with 99% bound equation represents the point at which 99% of the blasts will remain at or below the particular PPV.

**Equation 6: 99% Bound Equation**

\[ V = 605S^{-1.6} \]

Additionally, the research data gathered from the underground blasts will be used to create an experimental predictive model. The experimental model will differ from the other models, because it will only incorporate the distance from the blast face to the seismograph and negate the weight of explosives. Traditionally, a scaled distance variation is used to equalize blasts of different sizes, but recently researchers have attempted to create more accurate prediction models using unconventional methods (Favreau, 2014).

### 2.7. Top-hole vs. Bottom-hole Priming

The traditional priming method for underground blasting is referred to as bottom-hole priming. Bottom-hole priming is utilized because it retains and uses the energy from the explosive column the most effectively (Rosenthal S., 2018). In bottom-hole priming, the blasting cap and booster are placed at the bottom of the explosive column. The explosive column then detonates towards the open face. Figure 17 displays the a bottom-hole primed hole schematic. The red box represents the booster, and the blue box represents the blasting cap. The explosive column is denoted with the hatch lines. The green arrow shows the direction at which the explosive column detonates towards.
Top-hole priming is another method for underground mining. Top-hole priming is rarely used in modern underground blasting, but once was used within the Butte Mining District. In top-hole priming, the blasting cap and booster are situated near the open face and detonates the explosive column towards the bottom of the hole. Top-hole priming theoretically creates increased void space as the explosion travels downhole. The increased void space will then result in increased energy retention, fragmentation, and material displacement. Figure 18 displays the a top-hole primed hole schematic. The red box represents the booster, and the blue box represents the blasting cap. The explosive column is denoted with the hatch lines. The green arrow shows the direction which the explosive column detonates towards.
The ground vibration research for this thesis in the UMEC will compare the two priming methods. The ground vibration research evaluated the top-hole and bottom-hole priming methods based upon the energy signatures generated from each method. Theoretically, the associated PPV produced from a blast represents the amount of energy not being consumed from the explosives. A higher PPV means more energy is being transferred from the explosives into the surrounding rock body. In the case of our comparison between the two priming methods, the more energy being released into the rock body suggests the method utilizes the explosives to a better degree.

The method with the greater PPV would indicate the priming method requires less explosive
energy to blast the same volume of material, thus deeming it more effective. To negate for any variable differences, the top-hole vs bottom-hole priming tests utilized constant factors for:

- hole diameter,
- hole length,
- type of explosives,
- quantity of explosives,
- geological unit,
- directionality,
- travel path,

The constant factor eliminate the variables that effect the ground vibrations produced by the blast. The comparison was designed to only look at the energy component of the top-hole vs bottom-hole priming methods. The factors such as increased fragmentation and material movement were not considered in the comparison due to their qualitative nature.
3. Research Procedure

The ground vibration research was conducted using blasting seismographs, specifically White Industrial Seismology seismographs; the Mini-Seis and Mini-Seis II. The seismograph was located underground near old workings in proximity to the blast. The ground vibration research follows the International Society of Explosives Engineers (ISEE) protocol presented in *ISEE Field Practice Guidelines for Blasting Seismographs* (Engineers, 2015) insuring the reliability of the results and the professional integrity of the research. An important aspect of blast monitoring is the equipment. For the research conducted, a blasting seismograph is used. A blasting seismograph consist of two instruments: a geophone and a microphone. The geophone records particle displacement caused by the ground vibrations in three directions. The three directions are radial, transverse, and vertical. The geophone records the displacement information every 0.001 seconds and compiles the raw data in a time history. The microphone records the air over pressure generated from the blast. The blasting seismographs must be setup correctly to generate accurate results. Figure 19 shows the seismograph setup and placement next to a square set timber.
The persons working in the headings prepare the blast by drilling and loading the holes. One seismograph was placed on the ground next to the base of one of the square-set timbers. The second seismograph was placed on the surface directly above the underground seismograph’s location, when weather conditions permitted. The seismograph geophone is orientated in the direction of the blast face. The blasting sequence initiates and the seismograph records the ground vibrations generated from the blast. In order to eliminate discrepancies between data sets, the seismograph was placed next to the same square-set timber section for each monitored blast. Figure 20 displays the location of the seismograph, represented with the yellow star, for the North Area headings.
Figure 20: North Area underground and surface seismograph location (yellow star)

Figure 21 presents the location of the seismograph, again represented with the yellow star for the blasts in the Orphan Girl Area.
After monitoring the blast, the recorded data is transferred to a computer where the data analysis software transforms the raw time history data from the seismograph into useable particle velocity data. Since, White seismographs serve as the means for measurement, White’s Seismograph Data Analysis Version 12 Software was used to analyze the ground vibration data. The data analysis software calculates the particle velocity data from the three directions (radial, transverse, and vertical) and generates waveforms for each component. A vector sum for the three components at each time interval is used to create the overall waveform. The Seismograph Data Analysis Version 12 Software uses Fast Fourier Transform (FFT) calculations to plot the
waveform and particle velocity data onto the USBM RI 8507 chart (Rholl & Stagg, 1995). The data analysis software reports the PPV measured during the blast as well.

### 3.1. PPV Prediction Models

The blast data processed by White’s *Seismograph Data Analysis Version 12 Software* was used in attempt to create several predictive models dependent on the individual headings. An overall predictive model would more than likely be inaccurate due to changing geologic conditions, directionality variances, and continuity differences in the material the vibrations pass through. The predictive models for the individual headings are based upon the various methods:

- Base equations,
- Square-root scaled distance,
- Cube-root scaled distance,
- Distance,

The four methods used the same ground vibration data obtained from the *Seismograph Data Analysis Version 12 Software* along with the distances measured from the underground design model in Maptek’s *Vulcan Envisage 10.1.1*. The hole diameter, hole length, explosive density, and explosive fill factor were used to calculate the weight of explosives per hole. The scaled distances were determined and utilized accordingly. The base equations used the square-root variation of scaled distance to calculate the predictive PPV. The three other methods graph PPV vs. scaled distance to determine the site specific constants. These graphs are plotted on a log-log scale. The site specific constants were then used in tandem with the respective scaled distances to generate the predictive PPVs. The final step in the predictive models was to use the general information obtained from the next blast to compare the results to the predictive models.
3.2. **Top-hole vs. Bottom-hole Primed**

The top-hole vs. bottom-hole priming experiment used a slightly different procedure. Instead of drilling and blasting an entire round, a burn cut for each technique was monitored. The burn cut consisted of a center-hole surrounded by four holes. The five holes were drilled into the wall of a muck bay in the North Area pointed directly at the underground seismograph. The four outside holes were left unloaded (empty), and only the center-hole was loaded with explosives. The four unloaded perimeter holes establishes a volume of material for the loaded center hole to fragment. The burn cuts were designed to be as realistic as possible for sake of scientific integrity. Figures 22 and 23, display the burn cuts for the top-hole and bottom-hole test holes respectively.

![Figure 22: Top-hole priming test burn cut prior to loading explosives](image)
The burn cuts were shot in the same blasting sequence. A 4.5 second delay was used to ensure both blasting signatures could be easily distinguished by the seismograph. The burn cuts were also spaced over ten feet apart to negate the first hole in the sequence to potentially disrupt the second hole. The vibration data collected from the top-hole vs bottom-hole priming method comparison was then analyzed using the *Seismograph Data Analysis Version 12 Software*. 
4. Data & Results

A total of 13 blasts have been monitored to date. All of the blasts were monitored with an underground seismograph, and three blasts were monitored using an additional surface seismograph. Eleven development blasts were located within the North Area and one blast within the Orphan Girl Area. The 11 development blasts in the North Area can further be separated by three different headings: North A, North B, and Shop. Four blasts were monitored in the North A heading, four blasts were monitored in the North B heading, and three blasts were monitored in the Shop heading. The top-hole and bottom-hole priming holes were also tested in the North Area in a muck bay. In the Orphan Girl Area, the one monitored blasts was located in the Orphan Girl Vein heading. The data and results for the individual headings can be viewed in their respective sub-sections below. The data and results for the top-hole and bottom-hole primed comparison will be included in its own sub-section. Additionally, each sub-section displays an example USBM RI 8507 plot for one of the blasts relating to that heading. These USBM RI 8507 plots can be seen with their respective blast reports in Appendix 1 (section 8.1).

4.1. Underground Monitoring

4.1.1. North Area

4.1.1.1. North A Heading

A total of four blasts were located in the North A heading. Table II below provides the general information for the blasts monitored in the North A heading. The information in Table II includes the blast identification, recorded PPV, distance from the blast to the monitoring point, and the blast verdict dependent on if the blast exceeded the threshold for damage.
Table II: North A heading underground blast data

<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>Blast Verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA1</td>
<td>0.760</td>
<td>98.9</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>3</td>
<td>NA2</td>
<td>0.770</td>
<td>104.1</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>5</td>
<td>NA3</td>
<td>0.480</td>
<td>109.6</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>6</td>
<td>NA4</td>
<td>0.400</td>
<td>115.0</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>

The PPV’s in the North A heading ranged from 0.400 to 0.770 in/s. The distances from the blasting face to the underground seismograph ranged from 98.9 to 115.0 ft. All the blasts from the North A heading did not exceed the damage threshold of the USBM RI 8507 plot. Figure 24 below is a USBM RI 8507 plot generated by the data analysis software for the second North A blast (NA2). The different symbols on the USBM RI 8507 correlate to the respective wave component.

The NA2 USBM RI 8507 graph is very representative for the North A heading blasts.

The radial and vertical data points are predominately located in the higher frequency range of the plot. The transverse data points, however are spread throughout the lower and higher frequencies. The other three blasts in the North A heading showed a similar pattern in the range.
As previously mentioned above, radial and vertical components of the energy waves generated by the blasts in the North A heading predominately lie in the higher frequency portion of the USBM RI 8507 plot. The transverse components are spread throughout the graph and display higher PPVs at lower frequencies. None of the PPVs from the North A blasts have surpassed the threshold for damage, but the greatest potential to exceed the threshold would be from a transverse component with a low frequency.
4.1.1.2. North B Heading

In the North B heading, a total of four blasts have been monitored. The vibration data for the four blasts in the North B heading can be seen in Table III below. The information in Table III includes the blast identification, recorded PPV, distance from the blast to the monitoring point, and the blast verdict dependent on if the blast exceeded the threshold for damage.

<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>Blast Verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>NB1</td>
<td>0.700</td>
<td>76.4</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>8</td>
<td>NB2</td>
<td>0.510</td>
<td>81.2</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>9</td>
<td>NB3</td>
<td>0.490</td>
<td>86.7</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>11</td>
<td>NB4</td>
<td>0.160</td>
<td>113.4</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>

The PPVs in the North B heading ranged from 0.160 in/s to 0.700 in/s. The distances from the blasts face to the recording point varied from 76.4 feet to 113.4 feet. All four blasts monitored within the North B heading did not exceed the threshold for damage. The USBM RI 8507 for the first blast in the North B heading (NB1) can be viewed in Figure 26. The USBM RI 8507 for the NB1 blast was chosen because it had the highest recorded PPV for the four blasts within the North B heading, and it represents the other blasts in the heading well.

![Figure 26: North B heading first blast USBM RI 8507 plot](image)
The blasts within the North B heading generated similar wave signatures to the blasts within the North A heading. Predominately, the radial and vertical components of the waves were recorded at higher frequencies. The transverse wave components, however, were spread fairly evenly between the low and high frequencies. Figure 27 is the combined USBM RI 8507 graph for 4 blasts conducted within the North B heading.

![Figure 27: North B heading blasts combined USBM RI 8507 plot](image)

The blasts monitored in the North B heading recorded similarly to the blasts in the North A heading with a few noticeable differences. Both headings recorded wave components spread throughout the frequency spectrum, but the North A heading blasts contained a higher
concentration of wave signatures with a low frequency and a high peak particle velocity. While none of monitored blasts have exceeded the damage threshold, waves with high velocities and lower frequencies have the greatest potential to cause damage to a structure.

Comparing the North A and North B headings further, a difference between the recorded PPVs and their respective distance from the seismograph can be seen. The North A heading blasts generated higher PPVs at farther distances on average. For example, blast NA3 and blast NB3 had nearly identical PPVs (0.480 in/s and 0.490 in/s respectively), but the difference in distance from the blasting face to the seismograph is 22.9 ft. Both headings used the same blasting design, had similar geology, and are advancing away from the monitoring point. The only difference is the North B heading blast vibrations pass through an underground working before reaching the seismograph, whereas the North A heading travels through a constant rock medium. As represented in Figure 14, all of the S-wave energy generated from the North A blasts is reaching the seismograph, but only some of the S-wave energy from the North B blasts is reaching the monitoring point. This theory can be further backed by data with the lower concentration of lower frequency wave signatures in the North B heading.

4.1.1.3. Shop Heading

The Shop heading, located in the North A, had a total of three blasts monitored during the research. Table IV shows the vibration data for the three blasts located in the Shop heading. The information in Table IV includes the blast identification, recorded PPV, distance from the blast to the monitoring point, and the blast verdict dependent on if the blast exceeded the threshold for damage.
<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>Blast Verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>NS1</td>
<td>0.380</td>
<td>106.1</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>4</td>
<td>NS2</td>
<td>0.260</td>
<td>100.3</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>10</td>
<td>NS3</td>
<td>0.150</td>
<td>135.6</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>

The PPVs for the three blasts in the Shop heading ranged from 0.150 in/s to 0.380 in/s. The distances from the blasting face to the monitoring point ranged from 100.3 feet to 135.6 feet. The three blasts in the Shop heading all did not exceed the damage threshold. The first blast in the shop heading (NS1) recorded the highest PPV out of the three blasts in the Shop heading. The USBM RI 8507 plot for the NS1 blast can be viewed in Figure 28.

Figure 28: Shop heading first blast USBM RI 8507 plot

In the Shop heading, the three monitored blasts produced similar wave signatures. The radial and vertical wave components were predominately found in the higher frequency range, with the exception of a few outliers. The transverse wave components, however, were spread throughout the lower and higher frequency ranges. Figure 29 is the combined USBM RI 8507 for the three blasts in the Shop heading.
The Shop heading displayed wave characteristics parallel to the North A and North B headings. The radial and vertical components of the waves primarily stayed in the higher frequency portion of the USBM RI 8507 graph, but the transverse components were spread across all frequencies. As with the other headings, the Shop heading monitored blasts wave signatures followed this common pattern. The repetitive nature of the wave characteristics across the three individual headings (North A, North B, and Shop) leads to the conclusion that similar features from the blasts are driving this common trend.
4.1.2. Orphan Girl Area

4.1.2.1. Orphan Girl Vein Heading

One blast from the Orphan Girl Vein heading was monitored and analyzed. The seismograph was placed on the 100-foot level at the same elevation of the blast in the shaft station. Table V displays the vibration data from the blast in the Orphan Girl Vein heading. The information in Table V includes the blast identification, recorded PPV, distance from the blast to the monitoring point, and the blast verdict dependent on if the blast exceeded the threshold for damage.

Table V: Orphan Girl Vein Data

<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>Blast Verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>OG1</td>
<td>1.280</td>
<td>70.4</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>

The recorded peak particle velocity for the blast in the Orphan Girl Vein heading was 1.280 in/s. The distance from blast to the monitoring point was 70.4 feet. The blast was below damage threshold. The peak particle velocity of 1.280 in/s was the highest recorded PPV to date. Figure 30 is the USBM RI 8507 for the first blast in the Orphan Girl Vein heading.

![Figure 30: Orphan Girl Vein heading first blast USBM RI 8507 Plot](image-url)
The OG1 blast produced the highest recorded peak particle velocity from the research data collected. Compared to the blasts recorded in the North Area, a majority of the wave signatures are in the higher frequencies portions of the USBM RI 8507 plot. While several transverse wave components are seen at lower frequencies, the Orphan Girl Vein heading transverse wave components occur in lower concentration and at lower peak particle velocities than the North Area headings. A reasonable explanation is the differences in geology between the two areas. The North Area consists predominately of moderately weathered Butte Granite (Rose, 2017), and the Orphan Girl Vein heading is in a competent zinc-lead-manganese-silver vein. The weathered Butte Granite in the North A will inherently carry lower frequency vibrations, and the Orphan Girl Vein naturally will favor higher ground vibration frequencies. This natural tendency can be viewed in the wave signatures in the USBM RI 8507 plots for the North and Orphan Girl Areas. The North Area contains a larger concentration of lower frequency wave components. The wave components in the Orphan Girl Vein are predominately recorded at higher frequencies with fewer wave signatures present at the lower frequencies.

4.2. Surface Monitoring

The surface monitoring portion of the research was conducted during three blasts. The three blasts were all from the North Area. More specifically, two blasts were from the North A heading and the last blast being from the Shop heading. Table VI displays the data for the three blasts that were monitored on the surface. The information in Table VI includes the blast identification, recorded PPV, distance from the blast to the monitoring point, and the blast verdict dependent on if the blast exceeded the threshold for damage.
Table VI: North Area Surface Monitoring Data

<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>Blast Verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA1</td>
<td>0.245</td>
<td>122.0</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>2</td>
<td>NS1</td>
<td>0.210</td>
<td>176.0</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>3</td>
<td>NA2</td>
<td>0.230</td>
<td>125.4</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>

The recorded PPVs for the three blasts ranged from 0.210 in/s to 0.245 in/s. The distances between the blasting face and the seismograph ranged from 122.0 feet to 176.0 feet. The three blasts all registered below the threshold for damage from the surface monitoring point. The PPVs reported from the surface seismograph were significantly less than the PPVs reported from the underground seismograph for the same three blasts. Table VII presents the differences between the underground and surface data for the three blasts.

Table VII: Underground and surface seismograph monitoring PPV comparison

<table>
<thead>
<tr>
<th></th>
<th>Underground</th>
<th></th>
<th>Surface</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blast ID</strong></td>
<td><strong>PPV (in/s)</strong></td>
<td><strong>Distance (ft)</strong></td>
<td><strong>PPV (in/s)</strong></td>
<td><strong>Distance (ft)</strong></td>
</tr>
<tr>
<td>NA1</td>
<td>0.760</td>
<td>98.9</td>
<td>0.245</td>
<td>122.0</td>
</tr>
<tr>
<td>NS1</td>
<td>0.380</td>
<td>106.1</td>
<td>0.210</td>
<td>176.0</td>
</tr>
<tr>
<td>NA2</td>
<td>0.770</td>
<td>104.1</td>
<td>0.230</td>
<td>125.4</td>
</tr>
</tbody>
</table>

The NA1 blast generated the highest PPV for the three surface monitored blasts. Figure 31 is the RI 8507 graph for the surface monitoring data for the first blast in the North A heading that was recorded by the surface seismograph.
The USBM RI 8507 for the NA1 blast is representative for the ground vibrations monitored on the surface from the three blasts. The radial, vertical, and transverse wave components all fall in the higher frequency portion of the USBM RI 8507 plot. Additionally, the wave signatures all possess relatively low PPVs. Figure 32, below, is the combined USBM RI 8507 for the three blasts monitored with a surface seismograph. Unfortunately, the software was not able to create an interpretable USBM RI 8507 plot combining the surface and underground monitoring points.
4.3. Prediction Models

The goal of the prediction models was to create a simple, easy to use method to quickly determine the PPV and the outcome of the blast. The prediction models created used only the data from the North B heading. The North B heading was the active heading when the prediction models were created. Four different methods were used to construct the prediction models: base equations, squared distance, cubed distance, and distance. Table VIII displays the different methods and the variables used to calculate the PPV. The k and m values are the two site specific variables determined from plotting PPV vs. scaled distance (S). The equations and formulas can
be viewed in section 2.6. The percent difference is also included in Table VIII to show the relative accuracy between the predicted PPVs and the actual recorded PPV.

<table>
<thead>
<tr>
<th>Method</th>
<th>k</th>
<th>m</th>
<th>S</th>
<th>PPV</th>
<th>%Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base EQ - Average</td>
<td>160</td>
<td>-1.6</td>
<td>29.44</td>
<td>0.714</td>
<td>346.3%</td>
</tr>
<tr>
<td>Base EQ - 90%</td>
<td>242</td>
<td>-1.6</td>
<td>29.44</td>
<td>1.080</td>
<td>575.0%</td>
</tr>
<tr>
<td>Base EQ - 99%</td>
<td>605</td>
<td>-1.6</td>
<td>29.44</td>
<td>2.700</td>
<td>1587.6%</td>
</tr>
<tr>
<td>Square-Root</td>
<td>2797</td>
<td>-2.79</td>
<td>29.44</td>
<td>0.221</td>
<td>37.9%</td>
</tr>
<tr>
<td>Cube-Root</td>
<td>10063</td>
<td>-2.79</td>
<td>46.57</td>
<td>0.221</td>
<td>37.9%</td>
</tr>
<tr>
<td>Experimental</td>
<td>120812</td>
<td>-2.79</td>
<td>113.41</td>
<td>0.221</td>
<td>37.8%</td>
</tr>
<tr>
<td>Actual</td>
<td></td>
<td></td>
<td></td>
<td>0.160</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

The predictive models generated PPVs that ranged from 0.221 in/s to 2.700 in/s. The scaled distances for the different models ranged from 29.44 to 113.41. The m values that were found from the varying methods PPV vs. scaled distance plots were all -2.79. The k constant values determined from the plots ranged from 2,797 to 120,812. Figure 33 is the PPV vs. scaled distance graph for the experimental model. The three blue points are the PPVs at their respective distance for the first three blasts in the North B heading. Additional calculations for the predictive models can be seen in Appendix 2 (section 8.2).
The comparison between the predicted and the recorded PPV varied drastically. The percent differences (seen in Table 7) ranged from 37.8% to 1,587.6%. The base equation method was the least accurate in predicting the PPV for the actual blast. The square-root scaled distance, cube-root scaled distance, and experimental scaled distance methods produced nearly identical results. These three methods were much more accurate comparatively, but overestimate PPVs by nearly 40%. The results from the predictive models could be utilized as a preliminary prediction of the PPV, but it is not recommended. A major issue with the predictive models is the lack of data points within an individual heading. The models could become more accurate with the monitoring of blast results within a single heading.
4.4. Top-hole vs. Bottom-hole Priming

The top-hole vs bottom-hole priming was a comparison to see which priming method was more effective at utilizing the explosive energy. The major theoretical differences between the two techniques such as fragmentation and displacement are qualitative in nature and were not considered during the comparison. The comparison analyzed the difference in energy between the two priming methods; more specifically, the differences in PPV between the two samples. Table IX presents the vibrational data recorded between the two methods.

Table IX: Top vs Bottom Prime Data

<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>Blast Verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Top</td>
<td>1.84</td>
<td>30.9</td>
<td>Below Threshold</td>
</tr>
<tr>
<td>13</td>
<td>Bot</td>
<td>2.20</td>
<td>29.3</td>
<td>Below Threshold</td>
</tr>
</tbody>
</table>

The PPV for the top primed test hole was recorded at 1.84 in/s. The distance from the top primed test hole and the monitoring seismograph was 30.9 feet. Although the top primed test had a high PPV of 1.84 in/s, the blast did not exceed the threshold for damage. The bottom primed test hole recorded a PPV of 2.20 in/s. The distance from the bottom primed test hole and the seismograph was 29.3 feet. The bottom primed test hole did not exceed the damage threshold. Based upon the recorded PPVs for the two priming methods, the bottom primed hole more effectively used the powder column within the hole than the top primed hole. The difference between the two methods PPVs was 16.4%. Figure 34, below, is the combined USBM RI 8507 graph for the top-hole and bottom-hole blasts.
While the top-hole vs. bottom-hole test holes were designed to determine if a difference between the two methods existed, additional information can be drawn from the results. The previous blasts during the research were shot in heading developing away from the seismographs. The top-hole vs. bottom-hole test holes, however, were shot directly at the seismograph. The top-hole vs. bottom-hole test holes were also in very close proximity to the seismograph. The recorded PPVs from the test holes were significantly higher than any other recorded PPVs during the research, including the OG1 blast in the Orphan Girl Vein heading. The data and information obtained from the top-hole vs. bottom-hole primed test holes lead to an important conclusion; a blast shot with the explosive energy directed towards and in very close proximity to the pre-existing structures did not cause structural damage.
5. Conclusions

The research data gathered from the underground blasts in the UMEC have led to several conclusions. The UMEC underground blasts are not causing structural damage to the square set timbers. The 13 monitored underground blasts failed to surpass the threshold for damage dictated by USBM RI 8507. The underground and surface seismographs reported PPV’s ranging from 0.150 in/s to 2.20 in/s. The PPV’s fell below the threshold for damage curve on the USBM RI 8507 chart. The blast closest to breaching the threshold for damage was NA2 in the North Area. The NA2 blast reported a PPV of 0.770 in/s, which was not the highest PPV, but had several wave signatures at lower frequencies lying close to the damage line. Overall, the underground blasts in the UMEC did not cause structural damage based on mining industry standards to the pre-existing structures in nearby proximity to the blasts.

The vibration data generated also showed that a blast pointing in the direction of the pre-existing structures at very close distances still fall below the USBM RI 8507 damage threshold. The bottom-hole primed test hole recorded a PPV of 2.20 in/s at a distance of 29.3 feet. Travel path was determined to also effect structures response to the ground vibrations. Blasts with the ground vibrations passing through heading and mine workings showed reductions in the PPVs reaching the seismograph compared to blasts passing through solid rock. This was evident between the blasts in the North A heading and North B heading.

The prediction models created from the vibration data collected during the research were not as effective in predicting the PPV as initially desired. The predictive models all calculated PPVs that were much higher than the actual recorded PPV. While, overestimating is not necessarily a bad thing, the overall accuracy of the prediction models were not successful. An improved prediction model could be developed with an increased amount of data points in an
individual heading. The varying degrees of weathering of the Butte Granite within the UMEC makes it extremely difficult to create a predictive model capable of being used throughout the mine. The more data that is collected from an individual heading will continue to make the predictive model for that particular heading more accurate.

The top-hole vs bottom-hole priming method comparison resulted in the bottom-hole priming being more effective at utilizing the explosive energy. The bottom-hole primed test hole produced a PPV of 2.20 in/s compared to the top-hole primed hole’s PPV of 1.84 in/s. The difference between the two methods PPVs was 16.4%. The higher PPV in the bottom-hole primed test hole represents excess energy being released into the surround rock body. The greater PPV indicates bottom-hole priming requires less explosive energy to blast the same volume of material, thus deeming it more effective. The top-hole vs bottom-hole priming test blasts also exhibited blasts can be in very close proximity to the pre-existing structures and still not surpass the threshold for damage determined by the USBM RI 8507. The test blasts also demonstrated blasts with the explosive energy directly focused in the direction of the pre-existing structures did not surpass the threshold for damage.

The data collected and findings from the research is potentially groundbreaking and important to the mining industry. Between metal prices increasing and mining becoming more difficult due to deposit availability, social, and political factors, going back and accessing ore bodies adjacent to old working may become more common. Based on our conditions, the research has shown heading development and potential ore extraction can be accomplished without jeopardizing the structural integrity of the pre-existing in close proximity. Winston Gold Corp, a Canadian junior mining company, has two projects focusing on underground narrow vein mining in orebodies adjacent to old workings (Corp., 2018). The research data collected from the
underground blasts at the UMEC presents the plausibility for this potential new trend in underground mining. The ground vibration data from the UMEC demonstrated mining activities can be done in very close proximity to pre-existing structures without causing structural damage to those structures.
6. Recommendations

The research conducted with the underground blasts in the UMEC have determined no structural damage is occurring to the pre-existing structures in the nearby vicinity of the blasts. The data gathered proved the general conclusion, but recommendations can be made to further expand on the research completed. These recommendations:

- Continue to monitor and accumulate the vibration data generated from the underground blasts in the UMEC. The additional vibration data will help to continually verify the overall conclusion of this research.

- Ensure students working on drilling, loading, and tying in the blasts strictly adhere to the UMEC blast design. Following the blast design will help maintain a high level of scientific integrity.

- Conduct and monitor more underground blasts in the Orphan Girl Area. The research showed a drastic difference between the different geological conditions between the North Area and the Orphan Girl Area. Twelve of the thirteen blasts came from the North Area in the weathered, poor quality Butte Granite, and only one blast was monitored in the competent Pb-Zn-Mn-Ag vein Orphan Girl Vein heading. More blasts within the Orphan Girl area would add more data and understanding to the ground vibration behavior distances between the two geologic units.

- Experiment with different PPV prediction methods. The techniques used to create the predictive models in the paper were standard methods commonly used within the mining industry. The experimental model, slightly deviating from the traditional ways, displayed supportive results that there might be a potentially
better methodology to more accurately predict the PPV of a blast. For example, the PPV vs. scaled distance plots used to determine the site specific variables uses a linear regression line to fit to the data, but another form of regression line might better match the data set. The research data and future blast data could be used to develop a better prediction model that does not follow the traditional methods.

- Develop a heading that can be continually progressed with numerous underground blasts. The vibration data from the heading could then be used to create a prediction model more applicable to the underground blasts conducted in the UMEC.

- Further test the differences between top-hole priming and bottom-hole priming. The current research looked solely at the differences in energy, but the theoretical benefits associated with top-hole priming cannot be completely assessed through energy alone. Research analyzing the fragmentation, material movement, and heading development should be conducted to address all the potential advantages of top-hole priming.

- Look into a better ground vibration monitoring system. Ground vibration monitoring in the mining industry is heavily focused on surface monitoring, including seismographs. The research data and literature review demonstrated there were differences in wave behavior between surface and underground blasts. Seismographs are designed primarily for surface blast monitoring. Ground vibration monitoring technology continues to advance in the mining industry and the progression should be observed to find a ground vibration monitoring system that more efficiently and accurately depicts wave behavior underground.
7. References


Explosives Engineering, Construction Vibrations and Geotechnology (pp. 181-185).
Cleveland: International Society of Explosives Engineers.


Engineers, 1-7.


Damage Produced by Ground Vibration from Surface Mine Blasting. Twin Cities :

educational site for budding sesimologists: http://www.geo.mtu.edu/UPSeis/waves.html
8. Appendix

8.1. Blast Reports

Figure 35: Blast 1: 4039 Seismograph Report
Figure 36: Blast 1: 6088 Seismograph Report
Figure 37: Blast 2: 4039 Seismograph Report
Figure 38: Blast 2: 6088 Seismograph Report
Figure 39: Blast 3: 4039 Seismograph Report
Figure 40: Blast 3: 6088 Seismograph Report
Figure 41: Blast 4: 4039 Seismograph Report
Figure 42: Blast 5: 4039 Seismograph Report
Figure 43: Blast 6: 4039 Seismograph Report
Figure 44: Blast 7: 4039 Seismograph Report
Figure 45: Blast 8: 4039 Seismograph Report
Figure 46: Blast 9: 4039 Seismograph Report
Figure 47: Blast 10: 4039 Seismograph Report
Figure 48: Blast 11: 4039 Seismograph Report
Figure 49: Blast 12: 4039 Seismograph Report
Figure 50: Blast 12: 6088 Seismograph Report
### 8.2. Predictive Model Calculations

#### Table X: Base Equation - Average

<table>
<thead>
<tr>
<th>Blast No.</th>
<th>Blast ID</th>
<th>PPV (in/s)</th>
<th>Distance (ft)</th>
<th>IDmax (in)</th>
<th>LBP (ft)</th>
<th>VBH (ft³)</th>
<th>ρANFO (g/cm³)</th>
<th>FBH (W)</th>
<th>SDs (lbs/ft⁰.⁵)</th>
<th>PPV (in/s)</th>
<th>% Diff</th>
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<td>6.0</td>
<td>0.086</td>
<td>1.00</td>
<td>0.92</td>
<td>4.945</td>
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<td>0.92</td>
<td>4.945</td>
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<th>LBP (ft)</th>
<th>VBH (ft³)</th>
<th>ρANFO (g/cm³)</th>
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### Table XIII: Square-root Model

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<th>LBH (ft)</th>
<th>VBH (ft³)</th>
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<th>ANFO W (lbs)</th>
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<th>% Diff</th>
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**Figure 51: Square-root PPV vs. Scaled Distance Plot**

\[
y = 2796.9x^{-2.793} \\
R^2 = 0.8204
\]
### Table XIV: Cube-root Model

<table>
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<th>Blast No.</th>
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<th>Distance (ft)</th>
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<th>( l_{OB} ) (ft)</th>
<th>( V_{OB} ) (ft^2)</th>
<th>( p_{W,OB} ) (lb/cm^2)</th>
<th>( f_{OB} )</th>
<th>( W ) (lbs)</th>
<th>( S_{Dc} ) (lbs/ft^{0.33})</th>
<th>( H )</th>
<th>( \beta )</th>
<th>( PPV ) (in/s)</th>
<th>( % ) Diff</th>
</tr>
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<tbody>
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<td>6.0</td>
<td>0.086</td>
<td>1.00</td>
<td>0.92</td>
<td>4.945</td>
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</table>

**Inputs**

- Modified - Cubed

\[ y = 10063x^{-2.793} \]

\[ R^2 = 0.8204 \]

**Figure 52: Cube-root PPV vs. Scaled Distance Plot**
### Table XV: Experimental Model

| Blast No. | Blast ID | PPV (in/s) | Distance (ft) | SD (ft/lb) | \( r_{m} \) (in) | \( V_{m} \) (ft³) | \( \rho_{ANFO} \) (g/cm³) | \( F_{net} \) | \( W \) (lbs) | H | \( \beta \) | PPV (in/s) | % Diff |
|-----------|----------|------------|---------------|-------------|-----------------|-------------------|------------------------|----------|----------|----------------|---------|--------------|------------|--------|
| 7         | NB1      | 0.700      | 76.4          | 5.15        | 1.625           | 6.0               | 0.086                  | 1.00     | 0.92     | 4.945          | 120812  | -2.793       | 0.6650    | -5.0   |
| 8         | NB2      | 0.510      | 81.2          | 5.48        | 1.625           | 6.0               | 0.086                  | 1.00     | 0.92     | 4.945          | 120812  | -2.793       | 0.5600    | 9.8    |
| 9         | NB3      | 0.490      | 86.7          | 5.84        | 1.625           | 6.0               | 0.086                  | 1.00     | 0.92     | 4.945          | 120812  | -2.793       | 0.4668    | -4.7   |
| 11        | NB4      | 0.160      | 113.4         | 7.64        | 1.625           | 6.0               | 0.086                  | 1.00     | 0.92     | 4.945          | 120812  | -2.793       | 0.2206    | 37.85  |

**Figure 53: Experimental PPV vs. Distance Plot**
SIGNATURE PAGE

This is to certify that the thesis prepared by Logan Connolly entitled "The Effects of Underground Blasting on Pre-Existing Structures" has been examined and approved for acceptance by the Department of Mining Engineering, Montana Tech of The University of Montana, on this 27th day of April, 2018.

Scott D. Rosenthal, Associate Professor and Department Head
Department of Mining Engineering
Chair, Examination Committee

Paul W. Conrad, PhD, Professor
Department of Mining Engineering
Member, Examination Committee

Marvin A. Speece, PhD, Professor and Department Head
Department of Geophysical Engineering
Member, Examination Committee