Underground Airblast Monitoring for Blast Performance Diagnosis and Detailed Attenuation Modelling

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Abstract

Two test blasts were conducted at the Sanford Underground Research Facility to establish optimum blast designs and to limit blast effects on existing research rooms and equipment in preparation for the largest deep underground excavation in North America. Located on the 4850 Level (4,850 ft below the surface) at the former Homestake Mine in Lead, SD, this excavation is part of the U.S. Department of Energy’s Long-Baseline Neutrino Facility that will house particle detectors for the international Deep Underground Neutrino Experiment hosted by Fermilab. A large array of seismographs was deployed throughout the 4850 Level to measure ground vibrations and airblast pressures in tunnel drifts and in lab spaces.

A detailed analysis of data from this array was carried out to diagnose the performance of the first test blast during which two misfires occurred. As a result, only 60% of the round advance was achieved and airblast pressures were higher than expected. Ceiling tiles in a clean room, located 830 ft (253 m) from the blast, were dislodged by blast pressures. Review of the airblast records revealed the locations of the two unfired electronic detonators, one in the burn cut, which resulted in excessive confinement around subsequent blast holes. Additionally, pressure waves from perimeter blast hole groups timed 5 ms apart were found to coalesce into one pressure front resulting in additive, amplified airblast pressure at the research rooms.

Based on these findings, Test Blast 2 was redesigned with nonelectric caps to prevent misfires, reconfigured blast-hole pattern and loading to achieve full round advance, and a minimum of 100 ms between all delays to prevent additive pressure waves. A bulkhead was also constructed between the blast and closest lab spaces. The second test blast was successful with the full rock volume pulled, good fragmentation, and no airblast impact to research rooms.

Detailed attenuation models of vibration and air pressure were developed with data from 14 monitoring locations during the two test blasts and three small trim blasts. Three airblast attenuation models were derived to account for the unique geometry of the mine layout including areas with a straight air path to the blast, areas around corners, and areas behind barriers. These models can be used for future production blast design as well as planning and designing protection measures for lab spaces.

Introduction

A series of test blasts were planned for late 2015/early 2016 in preparation for the largest deep underground excavation in North America, located on the 4850 Level (4,850 ft, 1,478 m below the surface) of the Sanford Underground Research Facility (SURF) at the former Homestake Mine in Lead, SD. In order to better understand the behavior of subatomic particles called neutrinos, Fermilab is hosting the international Deep Underground Neutrino Experiment which will emit neutrinos near Chicago and send them 800 miles through the Earth’s crust to be collected by detectors nearly a mile underground at SURF.
as shown in Figure 1. The large cavern excavation to be blasted in the future will hold the far-site detectors as part of the U.S. Department of Energy’s Long-Baseline Neutrino Facility (LBNF) and is shown in Figure 2 as part of the larger SURF facility. Approximately 800,000 tons of rock will be removed to house the detectors filled with 70,000 tons of liquid argon (Sanford Underground..., 2016).

Opened in 1876, the Homestake mine was the largest and deepest gold mine in North America until it closed in 2002 (HomeStake Visitor Center, 2015). It is famous as the site where solar neutrinos were first experimentally detected by Raymond Davis Jr. in the late 1960’s. The mine drifts on the 4850 Level provide a uniquely quite environment for particle detection because they are shielded from solar and surface natural radiation by nearly a mile of hard rock. The mine was reopened in 2009 and rehabilitated
to house a variety of facilities and experiments related to particle physics. Figure 3 shows current surface facilities at the top of the Yates shaft. Protecting existing lab spaces and ensuring no disruption to ongoing experiments and clean rooms was of prime concern when planning the extensive blasting and excavation involved with the new LBNF construction.

Figure 3  Yates surface facilities at SURF, Homestake Mine (Kapust, 2015)

The Blast Vibration Study (BVS) was formulated to test blasting methods and to measure ground vibrations and airblast pressures during a series of test blasts on the 4850 Level. The goal of the project was to establish optimum blasting design for future cavern blasting as well as determine vibration and air pressure effects in many locations throughout the mine level. Data gathered during the study will be used to plan future blasts and protection measures to limit impacts to existing lab spaces in the mine.

Instrumentation
A large array of sensors was deployed at 14 monitoring locations throughout the 4850 Level in mine drifts adjacent to the blast and at nearby lab spaces. Figure 4 (left) shows a typical instrumentation deployment in a mine drift which included a geophone and high-pressure (up to 10 psi) air sensor mounted to the rock wall of the tunnel. Lab spaces were monitored with geophones mounted to concrete floors in experiment rooms or closely adjacent as shown in Figure 4 (right). Also shown in figure 4 is a reflective toolbox which housed the data acquisition system and external battery which allowed for longer-term background vibration and pressure monitoring prior to the test blasts.

Locations were chosen to record vibration and airblast pressure data at key labs with sensitive equipment, in linear arrays close-in to the blasts to develop attenuation models and at intermediate locations to characterize airblast propagation throughout the mine’s unique geometry. Figure 5 shows the complete instrumentation map of the 4850 Level and the location of the test blasts. The Ross shaft, existing lab spaces, air doors, and the general area of future excavation for LBNF construction are also shown. The bulkhead/door shown with the arrow did not exist during Test Blast 1 (TB1) and was installed before Test Blast 2 (TB2).
Figure 4  Geophone and air pressure sensor on rock wall of drift (left) and geophone on concrete floor of lab space with toolbox containing data acquisition system and external battery (right)

Figure 5  Instrumentation map of 4850 Level
**Test Blast 1: Performance and Diagnosis**

TB1 was a full tunnel advance round consisting of 36 holes including a central burn cut and perimeter trim holes. Electronic detonators were utilized with a delay timing of 100 ms between individual burn cut holes and production holes. Perimeter trim holes were tied together in groups of 4 or 6 blast holes and separation timing between groups was 5 ms. After detonation, the blast was deemed unsuccessful as only 60% of the total advance was achieved and more than half of the drilled depth remained intact on the left side of the pattern. Post-blast inspection revealed that two blast holes failed to fire and the electronic detonators were recovered and found damaged by blast pressures. Additionally, ceiling tiles in a clean room located 830 ft (253 m) from the blast, were dislodged by blast pressures.

With the precise detonation timing of electronic detonators, the airblast record of the closest monitoring location could be reviewed to determine when pressure peaks were missing and hence the timing of the unfired holes. Figure 6 shows the radial ground velocity and air overpressure time histories. This analysis revealed that the 5th hole in the firing sequence with a planned 400 ms delay time did not fire. It was concluded that the misfire resulted in failure of the burn cut to completely clear the center of the round. This failure applied excessive confinement to subsequent holes in the delay sequence and the holes did not fracture the full drilled depth. Timing analysis and post-blast inspection revealed that a perimeter trim hole also misfired. The combined misfires resulted in poor blast performance.

A review of the airblast data indicated pressures were higher than expected throughout the mine. This was in part due to the excessive confinement releasing energy out the collar and into the tunnel. This was observed in TB1 as the first four holes generated expected pressure peaks. However, holes after 400 ms
with increased confinement produced waveform characteristics similar to an open-air detonation, with a sharp pressure rise, exponential decay, and lower frequency than the first four holes. This change in wave shape is shown in Figure 6 at 500 ms onward.

The peak pressure occurred at the delay times of 1100/1105/1110 ms representing groups of perimeter trim holes of 4, 5, and 4 holes, respectively. Figure 7 shows expanded radial ground velocity and air overpressure time histories. The delay interval of 5 ms between these groups effectively caused the pressure pulse to build as each pulse arrival constructively added to the amplitude of the previous air pressure pulse. This resulted in a peak that was nearly three time higher than the expected peak from a single delay.

![Figure 7](image)

**Test Blast 2: Modifications to Blast Design and Results**

Modifications to the TB2 design were made based on the airblast analysis and blast diagnosis of TB1 along with recommendations by blast consultants and engineers. Electronic caps were replaced by non-electric blasting caps to prevent misfires in the extremely high pressure underground blasting environment. The blast pattern and loading were altered to ensure the burn cut succeeded in fully pulling the center of the round to provide ample relief for subsequent production and perimeter holes. Figure 8 shows the round markup on the tunnel face before drilling. A minimum of 100 ms delay timing between all holes or groups of perimeter holes was chosen to prevent the additive air pressures observed in TB1. A bulkhead with door was constructed in the access drift between the blast and lab spaces to the west to lower blast pressures in the clean room, location shown in Figure 5.
After a small trim blast to square the face, TB2 was detonated in March of 2016. The blast was considered a success, achieving the full tunnel advance and pulling the entire volume of rock to leave a clean, straight face. Fragmentation was also good and no airblast impacts to the labs were reported.

Figure 8  Mark-up of TB2 blast design before drilling (Kapust, 2016)

Attenuation Models
A large amount of data was collected at the 14 monitoring locations during the BVS. A total of five blasts were detonated, including a small trim blast before TB1, a reshoot following a cutoff in the trim blast, TB1, a small trim blast before TB2, and TB2.

The attenuation of peak particle velocity (PPV) and peak particle acceleration (PPA) with scaled distance (SD) are given in Figure 9. The equations for the linear regression best-fit line are shown. Data include only the highest recorded velocity or acceleration in any one component and are separated by blast. Both show good correlation, 0.88 for PPV and 0.87 for PPA.

During TB1, where firing times of electronic detonators were precisely known, vibration and pressure peaks were correlated with specific delays and individual blast holes. Up to 13 data points were analyzed at each monitoring location. These data along with peaks recorded during the other four blasts resulting in an expanded set of data used to evaluate attenuation properties. Figure 10 shows the expanded data in terms of delay-time-correlated velocity (V) versus scaled distance and delay-time-correlated air pressure (AP) versus cube-root scaled distance (CRSD). In addition to the 50-percentile regression lines, 95% upper prediction interval lines are also shown and equations for each are given in the figures.

The attenuation of ground motion in Figure 10 (left) has a strong correlation of 0.84 and shows consistent scatter across all scaled distances. However, the attenuation of air pressures in Figure 10 (right) has a weaker correlation at 0.72 and the distribution is not consistent across the range of scaled distances. Pressure amplitudes were all higher than the 50-percentile line at medium-range scaled distances, indicating other influences such as the mine geometry on airblast propagation throughout the 4850 Level.
Effects of Mine Geometry

Certain areas of the 4850 Level shown in Figure 11 were given designations based on spatial relations to the blast to better understand and characterize airblast propagation within the mine tunnel geometry. Locations with a straight (or nearly straight) air path to the blast are shown as a solid line, tunnels obliquely oriented with the main blast tunnel are considered “around corners” and shown with a dashed line, and tunnels or areas behind an air door or bulkhead are designated with light grey boxes. Airblast pressure data were separated based on these spatial designations and three separate attenuation models were created as shown in Figure 12. The creation of these different models is important to the design of future blasts and will allow blasters to better control and limit air overpressures in research rooms.
Figure 11  Map of 4850 Level with area designations by spatial relation to blast

Figure 12  Air pressure attenuation separated by location designation

\[
\text{Straight Air Path} \\
95\% \text{ upper prediction} \\
\text{AP} = 54.05 \text{ CRSD}^{-0.706}
\]

\[
\text{Around Corners} \\
50\% \text{ percentile} \\
\text{AP} = 357.23 \text{ CRSD}^{-1.303}
\]

\[
\text{Behind Doors} \\
95\% \text{ upper prediction} \\
\text{AP} = 63.50 \text{ CRSD}^{-1.068}
\]

\[
\text{Straight Air Path} \\
50\% \text{ percentile} \\
\text{AP} = 18.12 \text{ CRSD}^{-0.706}
\]

\[
\text{Behind Doors} \\
50\% \text{ percentile} \\
\text{AP} = 20.50 \text{ CRSD}^{-1.078}
\]
In Figure 12, each data set contains a 50-percentile regression line representing the median pressure across the range of scaled distance. Also given for the straight air path and behind doors sets is an upper 95% prediction interval (PI) that can be used for predicting any future pressure data based on what was measured during the BVS. As such, there is a 2.5% probability that a future data point will fall above the dashed lines. The around corners data set did not have enough points to calculate an upper PI.

The difference in the three data groups indicate that mine geometry has an effect on the airblast wave propagating throughout the 4850 Level. Sharp corners in tunnel drifts tends to decrease the pressure, especially at farther scaled distances from the blast, while barriers in drifts greatly diminish amplitudes. For the median (50-percentile) pressure at a CRSD of 300 ft/lb$^{1/3}$ (119 m/kg$^{1/3}$), corners and barriers reduce airblast amplitudes by 35% and 87% compared to straight air path pressures, respectively.

**Application of Attenuation Models**

The attenuation models based on mine geometry and barrier placement can provide useful tools during excavation the full LBNF detector caverns and supporting infrastructure. Figures 9 and 10 (left) may be used along with established limits for vibration in terms of velocity or acceleration to select safe charge weights when blasting approaches lab spaces or experiments.

Air pressure limits can be applied to attenuation models in Figures 10 (right) or 12 to determine safe charge weights which will not impact nearby clean rooms or lab spaces. Additionally, the separation of pressure attenuation by designation in Figure 12 can help with the design of protection measures and barriers which may be necessary during future blasting. For example, if a lab room is at a scaled distance of 200 ft/lb$^{1/3}$ (79.3 m/kg$^{1/3}$) from a future blast, the 95% upper pressure amplitude can be reduced from 1.28 to 0.22 psi (8.83 to 1.52 kPa) by installing a bulkhead or air door. Figure 12 can also be used to predict pressures very close in to future blasting where new critical infrastructure may be constructed in caverns adjacent to ongoing blasting. For example, a door built between caverns to protect a newly installed detector must be designed to withstand (with adequate factors of safety) as much as 4.9 psi (33.8 kPa) of blast pressure if it is 30 ft/lb$^{1/3}$ (11.9 m/kg$^{1/3}$) from a future blast.

**Summary and Conclusion**

After an unsuccessful TB1 in which only 60% of the round advance was achieved and ceiling tiles in a nearby lab were dislodged, post-blast inspection and careful review of the vibration and airblast records revealed critical blast parameters that were improved before TB2 to ensure blast success in the SURF facility nearly a mile underground. These measures were:

- Non-electric blasting caps were used to prevent misfires in electronic detonators that were crushed during TB1 by extreme pressures generated by adjacent blast holes.
- The blast pattern and loading was altered from TB1 design to ensure the central burn cut operates as designed to provide relief to surrounding holes.
- A minimum of 100 ms between delay groups was used to prevent the additive, amplified pressures observed in TB1 as a result of perimeter hole groups timed 5 ms apart.
- A bulkhead was installed in an access drift to protect sensitive lab areas from airblast pressures.

These measures proved successful as TB2 pulled the full volume of rock, leaving a straight face and no airblast impacts were reported at any lab spaces.

Data collected at 14 monitoring locations during the 5 blasts (2 test blasts and 3 trim blasts) of the BVS were analyzed and provided information on vibration and airblast attenuation on the 4850 Level.
Vibration propagation was consistent throughout the facility and an attenuation model of velocity versus scaled distance was developed based on 166 data points. Airblast propagation was found to be affected by mine geometry and reduced in amplitude by sharp corners or barriers when compared with straight air paths in tunnel drifts. Three separate pressure attenuation models versus cube-root scaled distance were developed to represent the 4850 Level as designated by spatial relation to the blast. The 50-percentile and 95% upper PI models for tunnels and barriers can be used to design blasts and mitigate airblast pressure to protect existing experiment facilities to advance the large excavation of the Deep Underground Neutrino Experiment.

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References


