AXPRO GROUP

Advanced Explosive Processing Research Group

Explosive Research and Education Center of Excellence

CDOT O'Bellex Phase III Progress Report

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1. Introduction

The Advanced Explosives Research Group (AXPRO) recently expanded the Explosive Research Laboratory (ERL) in Idaho Springs, CO to include a new test slope laboratory for avalanche mitigation, shown in Figure 1. The capabilities at this test site are unique and will be used to validate the effectiveness of gas exploders by measuring properties such as shock and reflection waves, impulse, and vibration. This site is fully instrumented with 10 channels PCB probe, VOD probe, and oscilloscope capabilities to characterize explosive charges. It is also equipped with two high-speed imaging bunkers at side-on and top viewpoints to capture the entire slope. This 80 ft by 100 ft test site has a slope of 35° and is located at 8,000 feet (2,400 m) above sea level. The surface is rough and rocky, which is typical of avalanche zones in Colorado. This test site therefore provides a unique opportunity to study snow avalanche triggering at high altitude topography. Installed in the middle of test slope is a concrete foundation to support gas exploders or exploding towers for evaluation and characterization of their effectiveness. This facility will also be used for new 8-hours safety training for Colorado Department of Transportation (CDOT) safety training. This safety training will include the use, maintenance, handling, transportation, and storage of gas exploders.

Figure 1: Aerial drone images of new AXPRO avalanche mitigation test slope in Idaho Springs, CO before blasting (left) and during blasting (right).

Phase 2 of this project was placed on temporary hold due to delays in the delivery of the gas exploder O'Bellex from France. This testing is now expected take place in the summer to winter of 2019.

Phase 3 consists of two parts: characterizing solid explosive charges for comparison to gas explosions and using Shadowgraph to study shock wave propagation and reflection from an inclined slope. This data will be used for future numerical modeling capabilities at the Colorado School of Mines. For the first part of phase 3 AXPRO evaluated the solid explosives ANFO and Pentolite boosters for use in avalanche mitigation at high altitude. Overpressure, ground vibration, and high-speed imaging data was collected and analyzed with respect to charge type, size, and charge orientation. A total of four tests were conducted; one each of ANFO and Pentolite boosters at horizontal and vertical orientations. Each charge had ~10 lbs TNT equivalency [1]. Overpressure and time of arrival experimental data was then compared to theoretical results for equivalent weights of TNT using ConWep.

The explosives were chosen due to differences in price (ANFO costs less than pentolite boosters), velocity of detonation (3,000 m/s for ANFO vs 7,000 for pentolite), peak overpressure, duration, and impulse [2].

2. Solid Explosives Charge Design

The two types of explosive charges tested where ~10 lbs ANFO charges and ~8 lbs pentolite charge. The pentolite was assumed to be 50% PETN and 50% TNT by composition [3]. The approximate TNT equivalencies for ANFO and PETN are 0.80 and 1.20, respectively. All charges had a calculated TNT equivalency of ~10 lbs. The ANFO charge consisted of bulk ANFO filling a PVC pipe that was 2 feet long and 6 inches in diameter, capped at both ends with holes to run detonating cord and the VOD Probe through. A 1-lb booster will be also be placed within the pipe and will be used to detonate the non-cap-sensitive ANFO. The pentolite charge will consist of 6 1-lb boosters stacked in layers of three to form a roughly-cylindrical charge. Matching the geometries of the charges was an important design consideration in attempting to keep the shockwave properties as similar as possible. The layers were held together with duct tape. The VOD probe and detonating cord will be run down a gap between the three boosters in each layer. The charge designs are shown in Figure 2 below:

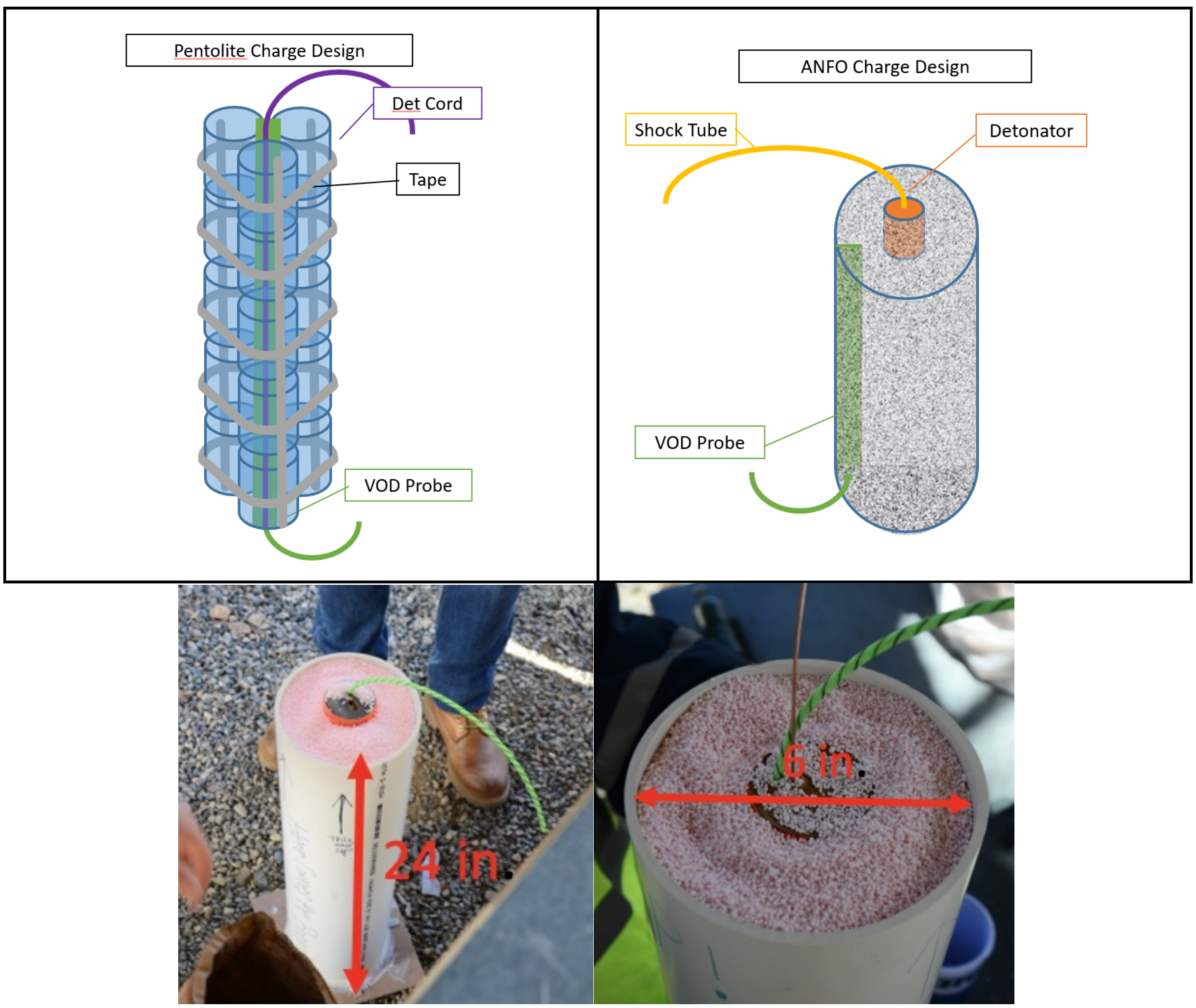

Figure 2: Top: ANFO and Pentolite Charge Designs. Bottom: ANFO charge in a PVC tube with a booster and detonating cord

The weights of explosives used and their calculated TNT equivalent weights are presented in Table 1 below.

Table 1: PETN and ANFO charge sizes with equivalent weights TNT.

PETN (8 boosters used per PETN charge)		
	Horizontal Charge	Vertical Charge
Boosters (g)	3,463	3,476
Det Cord (g)	48	50
W_{equ} TNT (lbs)	10.08	10.20

ANFO		
	Horizontal Charge	Vertical Charge
ANFO (g)	4,800	4,800
Booster (g)	394	394
Det Cord (g)	30	32
W_{equ} TNT (lbs)	10.16	10.47

3. Instrumentation

The blast overpressure and impulse were recorded using six piezoelectric pressure gauges PCB models 137A23. These free-field ICP pressure probes are specifically designed for measuring field blast and shock tunnel pressure time profiles using a stable quartz piezoelectric element in an Invar housing. The sensors were dynamically calibrated by PCB using a hydraulic pulse technique with +/- 1% uncertainty. The gauge diaphragm was insulated using common vinyl electrical tape in order to minimize possible signals generated by flash temperatures due to the passing of the shock front. Vinyl electrical tape was used on the contact surfaces between the steel stands and the bodies of the gauges for the purpose of isolating the gauges from the ground.

The pressure sensors are connected by coaxial cable to a PCB sensor signal conditioner model 482C05. The outputs are also connected to the channels of two Tektronix DPO72004C Oscilloscopes where the signal provided by each gauge was recorded. Triggering was implemented from the firing system and a signal differentiator that provided a 2-volt output to the high-speed camera and the oscilloscopes. High speed imaging was used to record the shape of detonation and to characterize differences between ANFO and Pentolite explosions. The high-speed camera used was the Photron FastCam SA-X Type 324K-C4 with 12,500 frames per second and a 1,024x1,000 resolution. Five seismographs characterized the ground vibrations of the detonations.

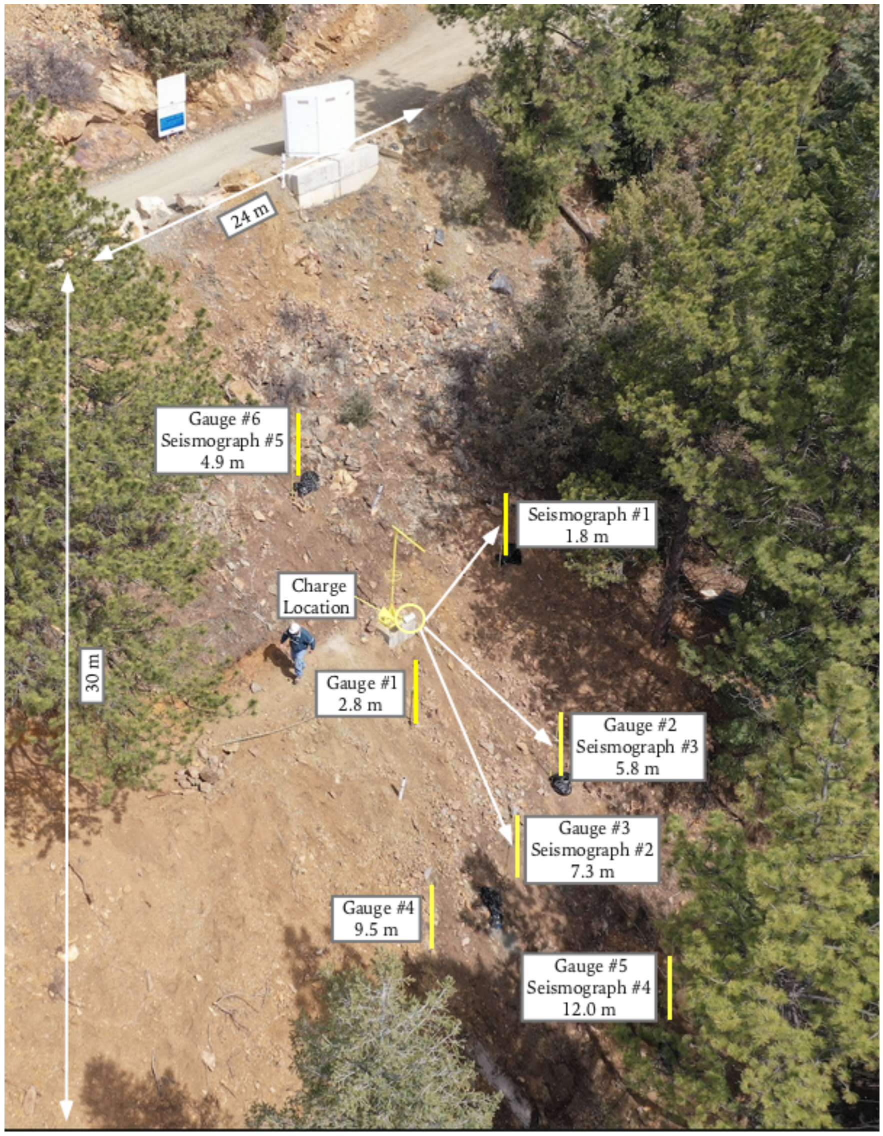

Figure 3: Gauge and seismograph locations on the avalanche mitigation test slope at the ERL.

4. Solid Explosives Testing

The test site is a hillside with a length of 90 ft and a slope of 35 degrees that resides within the Explosive Research Laboratory of the CSM owned Edgar Mine. The test site includes instrumentation such as test stands, pressure probes, high-speed imaging cameras, seismographs, and geophones.

Figure 4: Explosive stand with horizontal charge orientation test setup with 130 cm standoff distance from the slope.

The charges were suspended 130 cm from the ground. The testing was conducted as follows:
Test 1: 10 lbs ANFO with 1 lb Pentolite Booster Horizontal Configuration
Test 2: 8 lbs Pentolite Horizontal Configuration
Test 3: 10 lbs ANFO with 1 lb Pentolite Booster Vertical Configuration
Test 4: 8 lbs Pentolite Vertical Configuration

5. Solid Explosives Results

The experimentally measured velocity of detonation was 2,300 m/s for the ANFO charges and 6,800 m/s for the pentolite booster charges. The overpressure, time of arrival, and impulse results at each of the gauge locations for all four tests are given in Table 2.

Table 2: Peak overpressure and time of arrival results and comparison to ConWep prediction for equivalent weights of TNT.

Peak Overpressure (psi)					ConWep TNT	
Gauge	ANFO Horizontal	Pentolite Horizontal	ANFO Vertical	Pentolite Vertical	9.43 lbs (ANFO Comparison)	9.68 lbs (Pentolite Comparison)
1	56.000	86.000*	50.120	86.000**	36.100	36.800
2	15.720	17.940	12.180	12.300	7.400	7.600
3	8.600	9.080	6.040	9.080	4.800	4.900
4	4.420	4.780	4.580	5.980	3.100	3.100
5	2.814	3.262	3.087	3.729	2.100	2.100
6	9.844	8.438	N/A***	11.719	10.700	10.800

Time of Arrival (ms)					ConWep TNT	
Gauge	ANFO Horizontal	Pentolite Horizontal	ANFO Vertical	Pentolite Vertical	9.43 lbs (ANFO Comparison)	9.68 lbs (Pentolite Comparison)
1	1.717	1.135	1.590	1.184	1.900	1.900
2	6.154	6.130	6.748	5.546	6.900	6.900
3	9.498	8.507	10.231	8.291	10.000	10.000
4	15.631	14.198	15.874	13.738	14.800	14.800
5	21.032	20.310	22.033	19.884	20.500	20.400
6	7.068	5.400	N/A***	7.199	5.100	5.100

Impulse (psi-s)					ConWep TNT	
Gauge	ANFO Horizontal	Pentolite Horizontal	ANFO Vertical	Pentolite Vertical	9.43 lbs (ANFO Comparison)	9.68 lbs (Pentolite Comparison)
1	0.0493	0.0967	0.0346	0.0454	0.02274	0.02313
2	0.0301	0.0321	0.0631	0.0208	0.01186	0.01206
3	0.0181	0.0258	0.0132	0.0128	0.009677	0.009839
4	0.0116	0.0126	0.0113	0.0127	0.007638	0.007768
5	0.0069	0.0093	0.0081	0.0118	0.006155	0.006276

*Data clipped after 81.600 psi, peak estimated to be 86 psi

**Data clipped after 57.120 psi, peak estimated to be 86 psi

***Cable was cut at 6.817 ms due to fly rock

Plots of this data are given in Figures 5-8 to show the impact of charge type and orientation on the peak overpressure, time of arrival, and impulse.

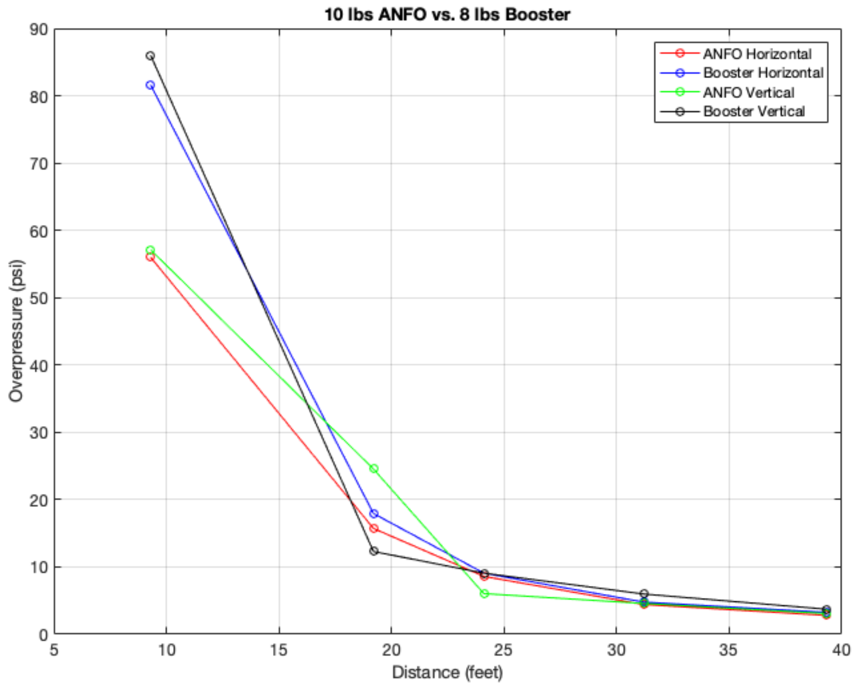

Figure 5: Results plot of overpressure verses distance from the charge.

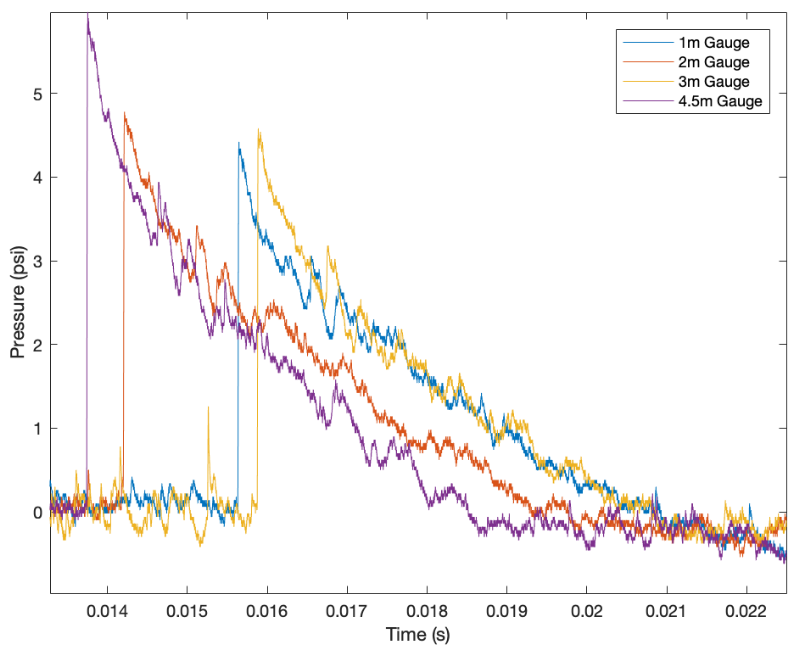

Figure 6: Results plot of pressure verses time to indicate the time of arrival.

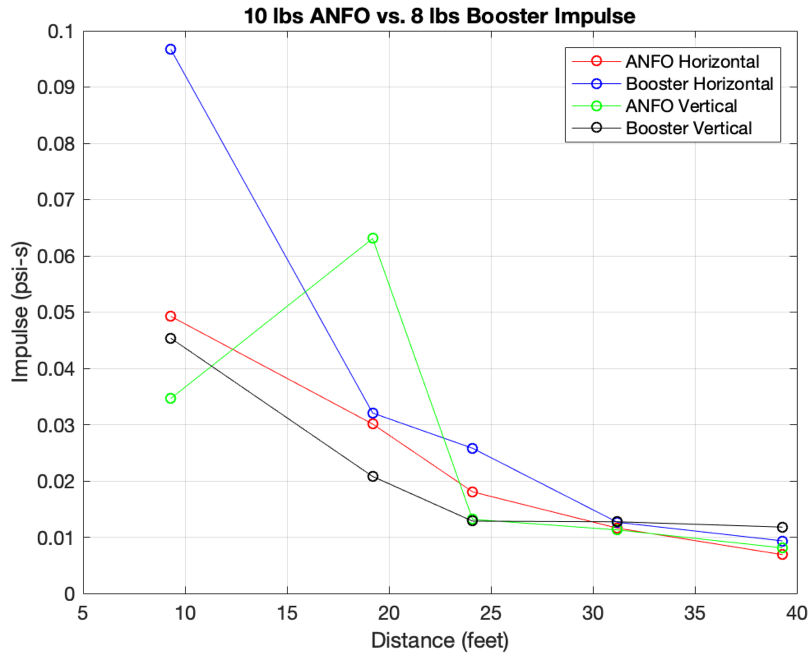

Figure 7: Results plot of impulse verses distance from the charge.

Instrumentation was hit with fly rock during the ANFO vertical test making this data point inconsistent. It is recommended to run a repeat test of ANFO at vertical orientation to obtain more precise data. At the first distance of 2.8 m the impulse was approximately double for pentolite than for ANFO. This difference decays with distance due to the decaying pressures. At a distance of 9.5 m, pentolite and ANFO have similar time durations but approximately 20% less peak pressure. This results in a lower impulse for ANFO at this distance (see Figure 8).

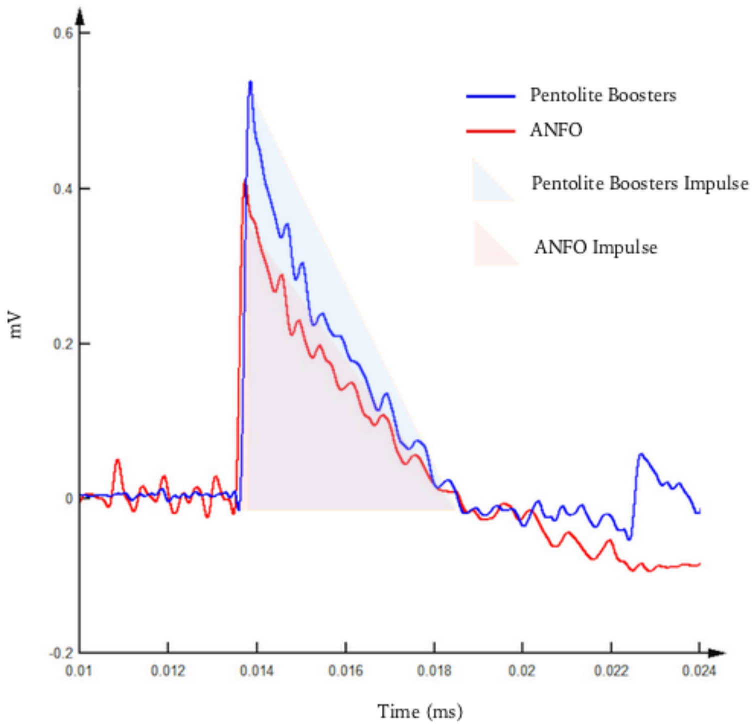

Figure 8: Oscilloscope data plot showing the differences in area of the pentolite and ANFO impulses at a distance of 9.5 m.

From Table 1 it can be seen that impulse at 9.5 m is underpredicted by TNT equivalent weight by about 40%. The overall results indicate no significant difference between horizontal and vertical orientations in regards to overpressure, time of arrival, and impulse. Pentolite booster charges exhibited a higher peak overpressure with a sharper pressure decay than the ANFO charges. From rough estimations, it can be predicted that the pentolite charge should be effective up to 85 m and the ANFO charge should be effective up to 75 m.

The high-speed imaging results of the pentolite booster and ANFO charges are shown in Figure 9 below.

Figure 9: High-speed imaging sequence results of 8 lbs pentolite booster horizontal orientation (top) and 10 lbs ANFO vertical orientation (bottom).

From the high-speed imaging results, it can be seen that regardless of charge orientation, the shock wave expands spherically. It is also seen that there is a reflected shock wave that comes up from the slope. Due to these shock waves and gravity, much of the loose rock on the test slope was pushed to the bottom.

6. Solid Explosives Observations

Four experimental tests were conducted using 8 lbs pentolite booster charges and 10 lbs ANFO charges (~10 lbs equivalency TNT each) at both horizontal and vertical orientations.

- These tests should be repeated (3-9 tests each) to give more precise results. This is especially important because fly rock hit instrumentation and damaged cables which limited the results in these preliminary tests.
- Results should be validated by repeating tests on a flat surface to determine the effects of having a sloped angle.
- Future research should be conducted on the same slope and using the same charges but with 1, 2, and 3 feet of snow. This would determine how much the blast energy would be absorbed and reflected by the presence of snow. These results would allow for optimization of charge designs and charge locations.
- It was determined that horizontal verses vertical orientation had no significant effect on overpressure, time of arrival, or impulse.
- Pentolite booster charges exhibited a ~35% higher peak overpressure with a sharper pressure decay than the ANFO charges.
- Pentolite booster has a higher but shorter impulse than ANFO.
- Pentolite booster has higher VOD (6,800 m/s) than ANFO (2,300 m/s).
- Theoretical results of equivalent weight TNT do not provide accurate predictions for the overpressure and time of arrival behavior of the pentolite and ANFO charges.
- 8 lbs pentolite charge should be effective up to 85 m
- 10 lbs ANFO charge should be effective up to 75 m.

7. Shadowgraph Testing and Results

The second part of phase three involved using Shadowgraph to study shock wave propagation and reflection from an inclined avalanche slope. A model O'Bellex was 3D printed for replicate the shape that the shock wave would be exiting from. Shock tube was used as the charge inside the model O'Bellex to create the shock wave and was placed at the top of a 40° inclined slope to model an avalanche slope. Shadowgraph high-speed imaging was used to study the shape and propagation of the incident and reflected shock waves traveling down the slope. The propagation of these shock waves is shown in Figure 10 below.

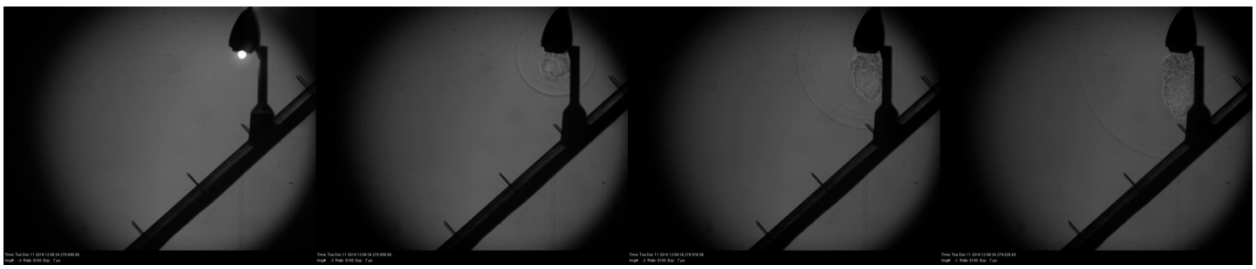

Figure 10: High-speed shadowgraph imaging sequence of shock tube in 3D printed O'Bellex model on a 40° inclined test slope showing both incident and reflected shock waves.

It is also of note that the incident shock wave coming from the O'Bellex is shown in Figure 10 to be spherical in shape.

The dust explosion from the shock tube is known to have a velocity of 2,000 m/s. When the shock wave leaves the model O'Bellex and expands, the speed of the propagating shock wave is reduced to about 400 m/s (see Figure 11). This means that the speed of the shock is approximately 5x slower in the air than in the tube.

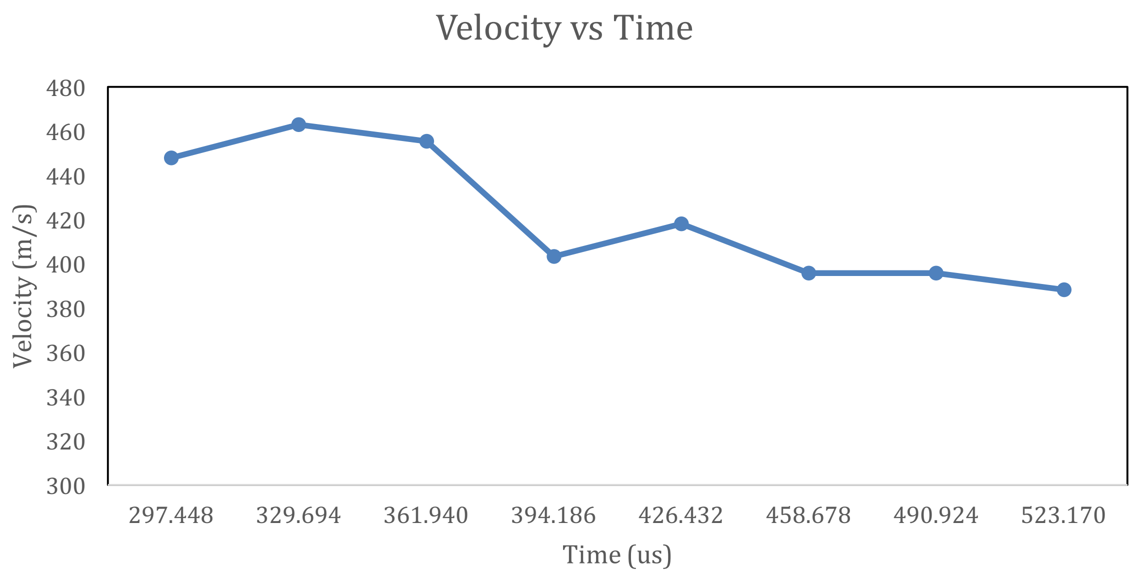

Figure 11. Velocity verses time plot of the shock speed in the air resulting from shock tube experimentation.

The average velocity of the shock tube in the air is 1.25 Mach verses in the shock tube is 5.8 Mach. This difference is due to confinement and the large increase in volume after exiting the O'Bellex. Further research with snow can be conducted to determine how much will be absorbed from the shock wave as well as the radius of reflection. This will help to continue to validate and characterize the shock wave properties of the O'Bellex.

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[2] Tonello, N.A., Berthet-Rambaud, P., "Numerical Modelling for Practical Safety Evaluation of Fast Oxy-Hydrogen Combustion Energy Release System", Proceedings of the Sixth International Seminar on Fire and Explosion Hazards, 2010, doi:10.3850/978-981-08-7724-8_07-07

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