6. New applications and training

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Innovative method to measure velocity of detonation by electromagnetic pulse (EMP): identifying suitable antennae and decay rate of EMP

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ABSTRACT: Velocity of detonation (VOD) is an important parameter when evaluating the performance of mine blasts. Typically, individual probes have to be loaded into each blast hole to measure VOD, which increases the loading time and is not representative of the whole blast. Experimental studies of electromagnetic pulse (EMP) from the detonation of explosives charges show that electric and magnetic field signals are observed when chemical explosions occur in the air, at the ground surface, and underground. EMP has the potential to evaluate VOD of the whole blast without impeding the loading process. Due to a variety of physical causes, which make the electromagnetic effects complex, measuring EMP from the detonation of an explosive charge is not well understood. This paper discusses a study of the decay rate of the EMP amplitude over distance to determine the best location to place antennae and relate the EMP signal to VOD. Two different antennae were tested with three different explosives commonly used in the mining industry. From these experiments, an EMP decay trend was obtained which provides a better understanding about EMP signals for the tested explosive charges. VOD was calculated to be close to the manufactures published VOD for emulsion-based explosives.

1 INTRODUCTION

Velocity of detonation (VOD) can be used to evaluate and compare relative performance of explosives in mine blasts. VOD of an explosive can be calculated by empirical mathematical equations or, more commonly, measured in-hole by VOD meters. However, conventional methods to measure a VOD are limited to a low number of holes, due to the high cost of consumables and systems only allowing a certain number of holes to be measured. Furthermore, loading probes to measure VOD down hole takes extra time to prepare the blast. In order to evaluate VOD for all holes in a blast, there is a possibility of using electromagnetic pulse (EMP) produced from the detonation of explosives. Measuring EMPs created from the detonation of explosive charges has not been studied in depth, and to the authors' knowledge, there is no known comparison to VOD. Many parameters affect the EMP generated from explosive charges. This paper summarised an investigation of the EMP produced by detonating explosives with various types of antennae at varying distances from the detonation source. Wire, copper, and aluminium tapes were found to be the most suitable antenna to measure EMP data in the field from previous testing reported by Seo (*et al.* 2019). Torrance (*et al. 2019)* recorded EMP signals from a production blast but the phenomenon must be better understood before post processing calculations of VOD can be done with large data sets. This paper studied how the signal decays over distance and time to confirm the signal is an EMP, and the distance from the antennae to the blast source is not an important factor. The EMP trace was captured by both an aluminium tape and a copper rod. The results from both antennae were compared to determine if movement of the antennae due to air movement was a factor. High-speed videography was used to compare the shock wave velocity to the EMP signal captured from the antennae.

2 BACKGROUND

This section is separated into three subsections to discuss the present VOD measuring methods, EMP uses in the mining industry, and impact of distance on the decay rate of the EMP.

2.1 Conventional methods of measuring VOD

As the demands and commodity prices decline, mining companies have increased need for more accurate theoretical predictions and physical measurements of the effects of explosives. The effects of explosives have a direct relationship with fragmentation, which influences the production rate of the mine. Since the 1940s, there are only three common techniques to determine the VOD of an explosive: D'Autriche method, point-to-point system, and continuous system.

The D'Autriche technique is one of the oldest

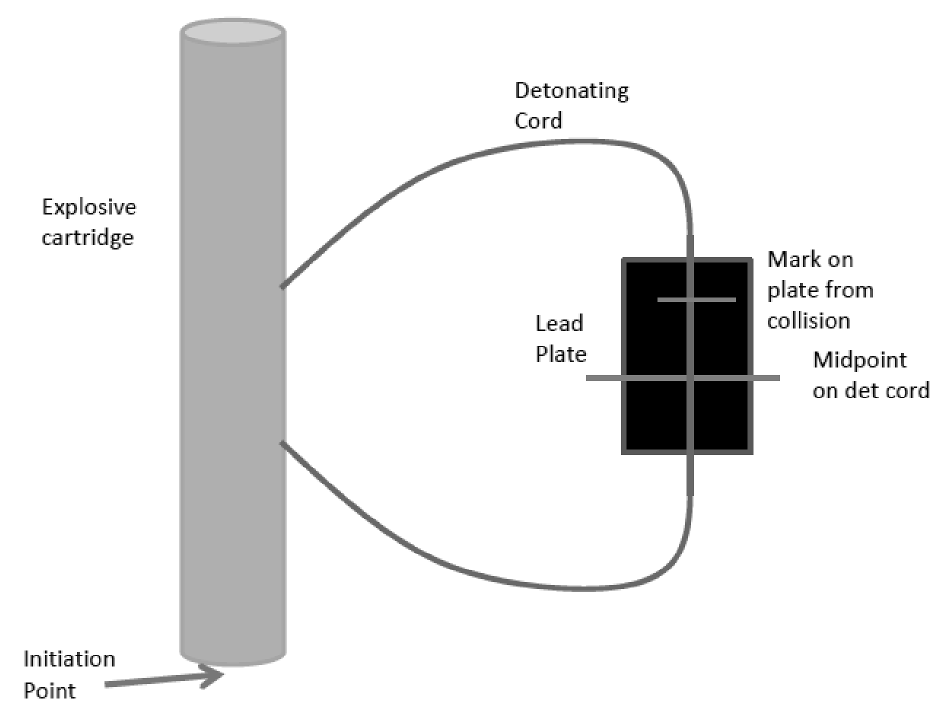

Figure 1. D'Autriche VOD method (Johnson 2014).

methods to measure VOD that is easy to implement and reasonably accurate for packaged explosives. Two ends of a length of detonating cord, with a known VOD, are inserted into an explosive a set distance apart forming a loop. The loop of detonating cord is placed on a lead plate with the centre of the loop marked. Upon detonation of the explosive column, each end of the detonating cord is initiated independently at the VOD of the packaged explosive; the collision point within the detonating cord loop is indicated on the lead plate due to the higher pressure. The packaged explosive VOD can be calculated by comparing the centre location of the detonating cord loop to the collision point with the known VOD of the detonating cord. A schematic of the D'Autriche method is shown in Figure 1.

The point-to-point system places pressure pin or time of arrival gauges at set distances along the length of the explosives. The explosive is detonated from one end and as the detonation progresses down the explosive, the pressure pins are activated, and the time is recorded. As the time and distance between the pins are known, VOD of the explosive can be calculated.

The continuous system is the only system practical in commercial mining operations in blast holes. A length of cable is lowered the entire length of the blast column with a constant current passing through a resistive wire pair. As the blast column detonates, the wires are shortened, changing the voltage output. The rate of voltage drop gives VOD. This is a common method used for monitoring individual holes during a production blast.

2.2 EMP from commercial explosives and uses in the mining industry

EMP is defined as an immediate and rapid acceleration of charged particles resulting in a short burst of electromagnetic energy (Seo *et al.* 2019, Torrance *et al.* 2019). Ivanov was the first to discover EMPs in 1940, which were produced from the detonation of explosive charges (Zenin & Mits 1963). Kolsky (1954), Koch and Takakura, Zenin *et al.* (1963), and Fine *et al.* (1998) made similar observations in their respective studies. The characteristics of the EMP were investigated and published in numerous studies to increase the understanding of this phenomenon (Zenin & Mits 1963, Sweeney 2011, O'Keefe & Thiel 1991, Kolsky 1954, Soloviev *et al.* 2002, Fine & Vinci 1998). The mass of the explosives, the duration of the explosion, the distance from the explosion, and frequency bands of the resultant EMP were studied by several researchers to determine how the relationship related to the recorded signal levels (Zenin & Mits 1963, Sweeney 2011, O'Keefe & Thiel 1991, Kolsky 1954, Soloviev *et al.* 2002, Fine & Vinci 1998). Soloviev *et al.* (2002) stated that an EMP is observed when an explosive detonates on the ground surface and arrives before both seismic and acoustic air waves. Soloviev *et al.* (2002) stated the three possible sources of the EMP were: gas ionisation (Kolsky 1954), explosion products electrification (Gorshunov *et al.* 1967), and polarisation of the ionised explosion area in the geoelectric field (Cook 1959). In 2005, Soloviev and Sweeny further refined the three sources of EMP to 1) detonation wave propagating through the explosive, 2) explosion products movement, and 3) shock wave propagating into the surrounding medium.

The relationship between frequency and EMP has also been studied. J. J. Sweeney (2011) reviewed EMPs at low frequencies. Fine and Vinci (1998) deduced results for the frequency bands that are based on the thermal effects of the detonation, which were considered the largest source of electromagnetic radiation. The extremely high temperatures within this region and the collisions between fast moving molecules cause ionisation of molecules and production of free electrons. O2+ ions, N2+ ions, and electrons were the most commonly found charged particles. Calculations were carried out for the radiation bandwidth, time-average electric field, and magnetic field amplitudes for each type of particle.

In 2000, O'Keefe *et al.* suggested that electromagnetic emissions show promise for mine safety monitoring and blast analysis (Sweeney 2011). A burst of EMP was found to occur after each hole detonated, as shown in Figure 2. The vertically and horizontally polarised electromagnetic pulses and a pulse from a microphone during a 3-hole test blast can be seen in Figure 2. The source of this pulse is believed to be emissions produced associated with the blast, and a possible contribution from the plasma produced by the explosives as well. O'Keefe *et al.* (1991) claimed that these blast-induced EMPs could be examined with a view to measure blast effectiveness.

2.3 EMP decay rates

The velocity of EMPs has been studied to understand the influencing factors (Rao 1999, Jensen *et al.* 2014, Johnson 2015). EMP velocities range from near the speed of light, or 2.998 x 105 km/s, down to of 10 km/s, which is faster than the

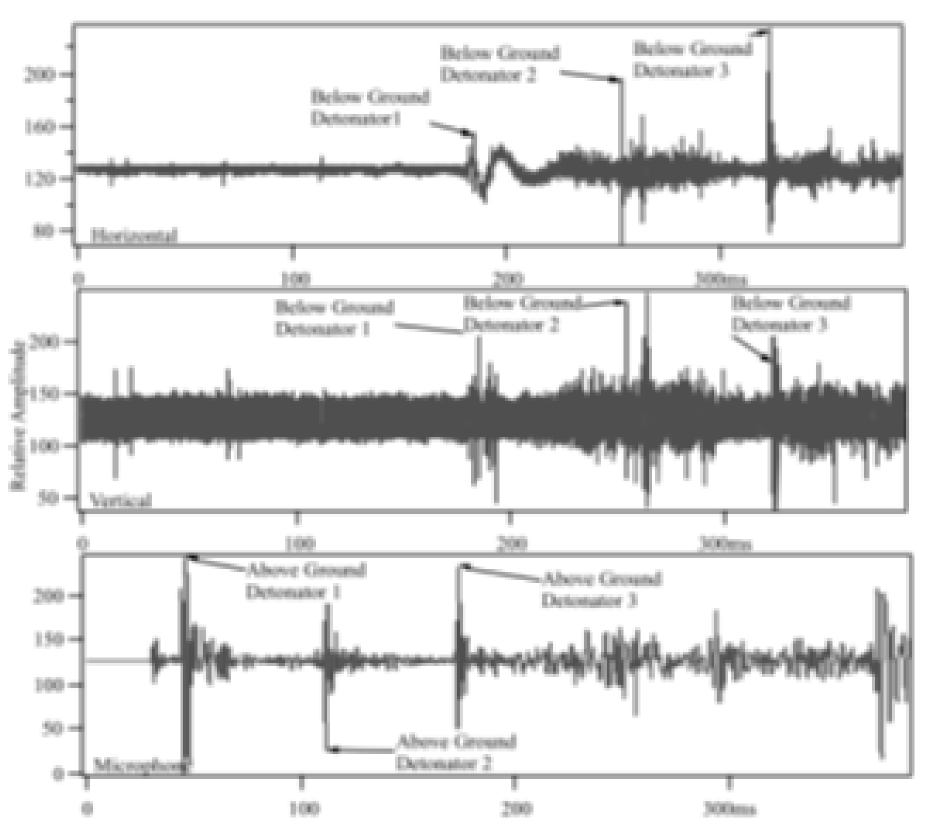

Figure 2. Vertically and horizontally polarised EMP and microphone pulse for a 3-hole blast (O'Keefe & Thiel 1991).

speed of sound in air (0.343 km/s). The velocity of the EMP is dependent upon several factors: the size of the charge, the height of the charge, and the surrounding media. The United States of America has studied the effects of nuclear EMPs and has found that these factors have a significant role in the strength of the EMP generated (Wilson 2008).

Kolsky conducted a study to compare EMPs produced by lead azide, silver acetylide, nitrogen tri-iodide, and PETN. An EMP was observed to occur approximately 50 microseconds after detonation for the four different explosives (Kolsky 1954). The observed EMP took over 200 microseconds to decay. A small negative electrically charged pulse preceded the main peak for PETN but none of the explosives that contained metal, as such, we expect to see a negative pulse for the commercial explosives used in this study. Lint also observed that the recorded EMP had a decay rate (Adushkin & Soloviev 2004). This, however, was attributed to the equipment used to amplify pulses at slower sweeps.

Sweeney (2011) also compared chemical and nuclear blasts in his review paper on low frequency EMPs. Sweeney compared above and underground testing of both nuclear and chemical explosions. Extensive testing has been conducted above ground with charges at least 10 kg in weight and measured at least 9 m away. The recorded EMP's amplitude was influenced by the explosive mass, explosive characteristics, height above the ground, and distance to the antennae. When chemical explosives were compared to nuclear blasts, the rise time, pulse duration, and delay between detonation and EMP captured were found to be longer. A lower frequency for the EMP was also found when comparing chemical explosives to nuclear blasts.

Sweeney also cited two published collaborations between Lawrence Livermore National Laboratory (LLNL) and All-Russian Institute for Nuclear Physics (VNIITF) (Soloviev *et al.* 2002, Soloviev & Sweeny 2005). LLNL and VNIITF conducted tests in the air, on the surface, and underground for frequency ranges between 10 Hz and 10 MHz over distances of tens of metres. Borehole testing was also conducted and the produced EMP was theorised to have a decay rate of 1/r4 with respect to distance when measured within the one wavelength range. From the results, LLNL and VNIITF concluded that chemical explosives have less conductivity resulting in magnetic fields two orders of magnitude smaller than observed in nuclear testing. LLNL and VNIITF also found the EMP results from the disturbance to the ambient field as the field is perturbed and then relaxes back into the steady state once the source of charge (due to cooling or end of intense fission) disappears (Soloviev *et al.* 2002, Soloviev & Sweeny 2005).

Table 1. List of charge sizes and types for underground tests with measured EMPs.

Yield	Maximum range in metres	
	Chemical explosion	Nuclear explosion
10 kg	9-12	41-54
100 kg	19-25	87-116
1 ton	41-54	188-250
10 tons	87-116	405-539
100 tons	188-250	874-1160

Through the review of published works on comparison of chemical explosive and nuclear weapons detonated underground summarised in Table 1, Sweeney noted that four amplitude decay rates were observed for recorded EMPs. The amplitude decay rate is of high importance to measuring VOD as it influences the time component of the velocity measurement. The decay rates are summarized in Equation 1, where r is distance from the explosion (Sweeney 2011) and R0 is the typical size of explosive cloud at time of maximum signal, which varies for each explosive and weight (Soloviev *et al.* 2002). The R0 value has not been fully defined for each explosive type or explosive weight. LLNL, VNIITF, and Sweeney (2011, Soloviev *et al.* 2002, Soloviev & Sweeny 2005) noted the seismic wave and the EMP arrive at the sensor in quick succession at close range, which can make monitoring problematic.

Decay rate for r < R0 and above ground explosions = 1/r4

Decay rate for r > R0 = 1/r3

Decay rate for r >> R0 = 1/r21

Decay rate for r >>> R0 = 1/r

Based on the reviewed materials presented here, little work has been conducted on EMPs produced from commercially available explosives used in the mining industry and there is no correlation to VOD. Whereas, EMPs produced by different explosives have had experimental studies, empirical dependences, and mathematical models published. This paper will investigate if EMPs produced from commercial mining explosives can be used to calculate VOD. Additionally, the four decay rates reviewed will be compared to results collected to determine whether the amplitude of the signal affects the calculation of VOD.

3. EXPERIMENTAL DESIGN

Two different experimental setups were used to ascertain if EMPs produced from a single Dyno AP emulsion chub 0.4 m (490 g), a single Austin Powder Red D Gel-B permissible dynamite stick 0.4 m (455 g), or a single 0.102 m (90 g) Austin cast booster could be used to calculate VOD. The antennae were placed at distances related to a radius R, R2, R3, R4, and R9 to determine if the previously published decay rates could be related to VOD. The radius used was 1.5 m, meaning the remaining distances were calculated to be 2.25 m, 3.375 m, 5.0625 m, and 38.443 m shown in Figure 3. An additional distance of 1 m was used to have additional data points close to the charge where the highest amplitude signal and closest time between the velocity of the shockwave and EMP is expected. The first experimental setup solely utilised aluminium tape 1 m in length as the antenna to capture the EMP. Later tests utilised aluminium tape and copper rods to descry if physical movement of the antennae influenced the measured amplitude and decay rate of the EMP. A high-speed camera was used to determine the shock wave velocity of each explosive. A non-electric cap was used to initiate the explosive charge to remove any additional source of electric current. For both experimental setup ups, the oscilloscope was triggered by a break wire as the explosive detonated.

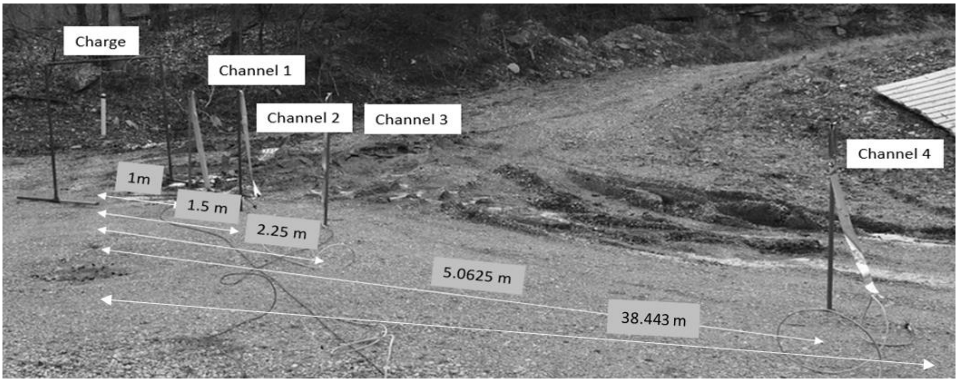

Figure 3. Layout of experimental testing.

4 RESULTS

The results are presented in four different subsections: determination of the initial peak, speed of the EMP, decay rate of EMP, and EMP correlation to VOD.

4.1 Initial peak

In all cases and consistent with published work (Kolsky 1954), a small negative pulse was observed before the maximum EMP peak, as shown in Figure 4. To further refine the initial peak among the numerous other fluctuations observed, the data points were filtered using MATLAB's low pass filter. Four points were defined to calculate the time duration of the peak, as shown in Figure 4, where A is the start of the negative decay, B is the amplitude of the negative pulse, C is the time returning to zero, and D is the end of the pulse where an additional spike is observed but at this time unsure of the cause. The time duration of the initial negative peak was calculated by subtracting the time of A from C. The time between A and B was the time to reach the local amplitude value. The time between A and D is the overall response of the antenna.

4.2 Speed of EMP

The speed the EMP travelled over the 38 m recorded distance was calculated using the data from the picoscope, which recorded at 10 million samples a second. The first response, A from Figure 4, from the 1 m and 38.443 m were used in the average speed calculation, where distance was divided by the arrival time difference. The average EMP speed could not be calculated for dynamite,

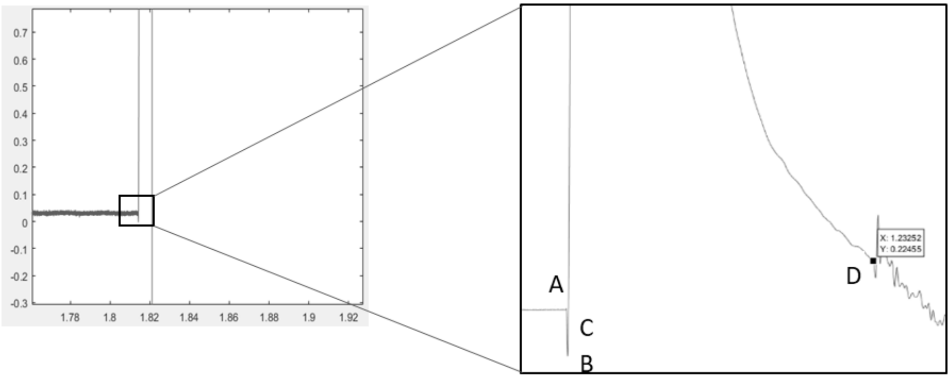

Figure 4. Field test 2 - Oscillograph of emulsion explosive (445 g and 0.4 m in length) from Channel 1.

because the data at 38.443 m was unable to be recorded. Literature states that charge mass has an impact on the EMP characteristics (Sweeney 2011), but it is unclear whether this is TNT equivalent mass or physical mass so both were used as a comparison. The VOD TNT equivalent masses were calculated to determine if detonation velocity influences the amplitude of the EMP and can be seen in Table 2.

A high-speed camera was used to record the shock wave travelling through the air to determine if the EMP had a higher speed than the shock wave. The camera was focused on the explosive charge, 1 m, and 1.5 m antennae. The high-speed footage was then analysed using the camera's software to calculate the velocity of the shock wave. The 0.5 m distance between the first two antennae was used to calibrate distance within the software. The time difference between the shock waves arrival at 1 m and 1.5 m antenna was found and the velocity of the shock wave was then outputted by the camera software. This method was used to calculate the shock wave velocities for emulsion and dynamite; however, the booster detonation could not be captured. Figure 5 displays three stills from an emulsion test, where Figure 5a is before the arrival of the shock wave, Figure 5b is the arrival of the ionised particles, and Figure 5c is the arrival of the shock wave at the 1 m antenna. The VOD, mass, equivalent TNT mass, and EMP speed values for the emulsion, booster, and dynamite are given in Table 2, as well as the relation to speed of light, speed of sound, and calculated shock wave velocity calculated from the high-speed camera.

From the values presented in Table 2, a number of conclusions can be made. First, the emulsion had a faster EMP than the booster, which is consistent with literature as the mass of the charge is higher for the emulsion charge. Second, the

Figure 5a. Emulsion blasting at frame 12.

Figure 5b. Emulsion blasting at frame 14.

physical mass difference has a closer relationship to the EMP than the TNT equivalent mass. Third, EMPs were travelling slower than the speed of light, and travelling faster than the shock wave and the speed of sound in air confirming that the signal we are measuring is an EMP. This finding is consistent with Sweeney's (2011) observation that the EMP can be slower than light and faster than sound. Fourth, the booster EMP was traveling at approximately 9.3% the emulsion EMP. Overall, an EMP was measured and confirmed in this testing.

4.3 Decay rate of EMP

How the EMP amplitude decays with distance is an important factor to consider when attempting to monitor a multiple hole blast, where blast holes will be at different distances from the antennae. To compare the recorded EMP amplitudes for an emulsion charge to the published decay rates of 1/r to 1/r4, Figure 6 was produced. The graph shows a log-log plot of distance vs EMP amplitude with the four decay rates from the background overlaid where R is 1.5 m. The recorded data was normalised by dividing the measured value by value recorded at 1 m. From the graph, the emulsion EMP had a decay rate close to 1/r, which is the far field. This result is consistent with Soloviev *et al.'s* (2002) work, as the R0 distance is very small for the 490 g explosive charge. Large scale testing is required to observe faster decay rates up to 1/r4, but based on these tests, R0 appears to be dependent on explosive mass.

Figure 5c. Emulsion blasting at frame 16.

4.4 Correlation to VOD

VOD calculations are the ultimate goal of monitoring EMP from a production blast in order to monitor the blast performance. The VOD was calculated by dividing explosive length by detonation duration (duration of the initial EMP spike) and then compared to the VOD provided by the manufacturer. The duration of the EMP was calculated using two different methods: 1) duration of the initial EMP peak and 2) duration of entire EMP. The duration of the initial EMP peak was found to give a better approximation of VOD than the main peak, which Kolsky (1954) also

Table 2. Speed of EMP and relation to equivalent mass and explosive mass for emulsion, booster, and dynamite.

Explosive	VOD m/s	mass g	Equivalent TNT mass g	EMP m/s	Speed of light %	Speed of sound %	Shock wave velocity m/s
Emulsion	4900	490	243.6	748,860	0.2498%	218327%	633.2
Booster	7800	90.0	113.4	69,339	0.0231%	20215%	n/a
Dynamite	5300	455	264.6	n/a	n/a	n/a	698.7

observed. The duration of the EMP was found to underestimate the manufacturers VOD. The calculated VOD for the emulsion at 1 m was 3,636.35 m/s, the theoretical VOD of the emulsion is 4,700 m/sec. The calculated VOD was within 24% of the predicted VOD when it is measured 1 m away from the charge but when the small-time difference and amplitude are considered with the recorded sample rate, the uncertainly in the measurement puts the value within an acceptable range. The calculated VOD decreased with distance from the charge, as the amplitude of the signal decreases over distance. The same procedure was applied to the dynamite and booster tests but the percent error was much higher than observed in the emulsion. The calculated VODs were less than 50% of the values provided by the manufacturer. A possible reason for this large disparity is the small size of the explosive charges only generated a small EMP signal. The booster had a short length and less mass, thus a weaker EMP was generated, but the VOD should have been much higher than the emulsion or dynamite.

The VOD calculated from the copper rod antennae had a greater disparity than the aluminium tape antennae. One possible reason is that the rods have less surface area facing the charge versus the aluminium tape, thus more EMP energy was captured by the aluminium tape. The increased surface area of the aluminium tape likely compensated for aluminium's lower conductivity as compared to copper.

5 SUMMARY AND CONCLUSIONS

This paper presents a study of EMP generation during the detonation of explosive charges with two types of antennae. Aluminium tapes were found to be the more suitable than the copper rod antenna for capturing EMP data in the field. The velocity of the EMP was calculated for emulsion and booster explosives. A high-speed camera was used to measure the velocity of the shock waves produced by the explosives. The signal detected by the antennae was an EMP, as the speeds were between the speed of light and the velocity of the shock wave. To calculate VOD of the explosives, the first response time from the oscillographs provides the most accurate value compared to predicted value. The VOD for emulsion was calculated to be 3636 m/s. The decay rate of the EMP amplitude was found to be 1/r for the emulsion, which is the far field for EMP based on

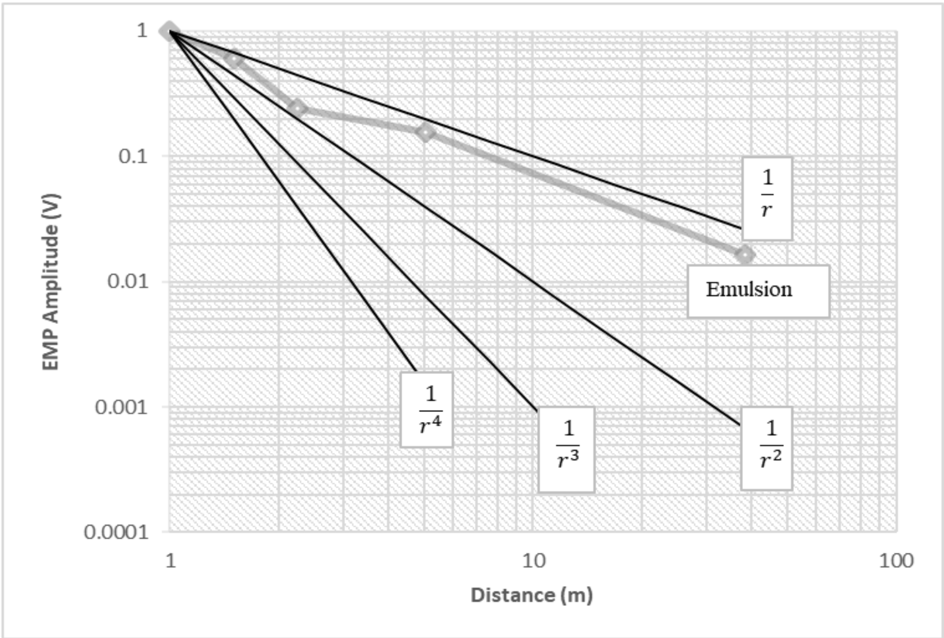

Figure 6. Log-Log plot of EMP amplitude of an emulsion charge over distance and comparison to previously published decay rates.

literature. The authors believe that a larger explosive mass may change the decay rate as a larger amplitude EMP would be recorded closer to the charge, however, large scale testing is needed to validate this finding. Overall, this technique shows promise for an improved method for measuring VOD in the field.

5.1 Future work

Additional testing will be conducted in the summer of 2019 to further the understanding of the relationship between EMP and commercial blasting performance parameters. Testing with the same experimental setup will be conducted. The high-speed camera will be set at a higher frame rate to capture the time difference between ionised particle movement and produced shock wave. The oscilloscope will be placed behind the furthest antenna to ensure that no current is induced in the cables before the arrival of the ionised particles. The ratio developed of 0.4/1.0 (length of explosive to distance from explosive), will be confirmed with a full-scale signature hole test.

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