ASSESSMENT OF VELOCITY OF DETONATION AT KUMTOR OPEN PIT GOLD MINE

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ABSTRACT

ASSESSMENT OF VELOCITY OF DETONATION AT KUMTOR OPEN PIT GOLD MINE

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One of the most important properties of an explosive is its velocity of detonation (VOD). It is essential that the explosive should detonate at its optimum rate and release sufficient detonation pressure to get good fragmentation under the existing field conditions.

The main objectives of this research study are to investigate the effects of explosive type, blast hole diameter, and degree of confinement on the VOD of bulk ANFO and bulk emulsion in Kumtor Open Pit Gold Mine. In this study, the continuous resistance wire method is employed to measure in-situ VOD of both bulk ANFO and bulk emulsion. The VOD values are measured for different hole diameters and under different confinements for both explosives. The ideality of bulk ANFO and bulk emulsion is calculated by comparing the in-situ measured VOD's and their ideal detonation values. It is found that the VOD of both explosives increases as the blast hole diameter and the degree of confinement increases. In addition to this, VOD of bulk ANFO decreases when it gets wet in the blast hole. Another finding is that, proportion of bulk emulsion ingredients has influence on its VOD. This research study provides a good understanding to use suitable explosive in existing rock conditions in Kumtor Open Pit Gold Mine.

Keywords: Velocity of detonation, degree of confinement, blast hole diameter, explosive, bulk ANFO, bulk emulsion, Kumtor Open Pit Gold Mine.

ÖZ

KUMTOR AÇIK OCAK ALTIN MADENİNDE İNFİLAK HIZININ ÖLÇÜMÜ VE DEĞERLENDİRMESİ

Düzgün, Özkan
Y. Lisans, Maden Mühendisliği Bölümü
Tez Danışmanı: Doç. Dr. H. Aydın Bilgin

Eylül 2011, 130 sayfa

Patlayıcıların en önemli özelliklerinden birisi İnfilak Hızı'dır. Mevcut saha koşullarında patlayıcının en uygun hızda infilak etmesi ve yeterli infilak basıncı oluşturması iyi bir parça boyut dağılımı elde edilmesi için gereklidir.

Bu çalışmanın temel amaçları, patlayıcı türü, delik çapı ve ortam sıkılığının Kumtor Açık Ocak Altın Madeni'ndeki dökme ANFO ve dökme emülsiyonun infilak hızları üzerine etkilerinin araştırılmasıdır. Bu çalışma kapsamında, dökme ANFO ve dökme emülsiyonun yerinde infilak hızlarının ölçümünde infilak hızı sürekli ölçüm yöntemi kullanılmıştır. İnfilak hızı değerleri her iki patlayıcı türü için farklı delik çapları ve ortam sıkılıklarında ölçülmüştür. Dökme ANFO ve dökme emülsiyon için ideallik derecesi, yerinde ölçülen infilak hızları ile ideal infilak hızlarının karşılaştırılmasıyla hesaplanmıştır. Her iki patlayıcı türünün infilak hızlarının artan delik çapı ve ortam sıkılığı ile arttığı saptanmıştır. Buna ek olarak, dökme ANFO'nun delik içinde ıslanması durumunda infilak hızı azalmaktadır. Diğer bir sonuç ise, dökme emülsiyon içeriğindeki malzeme oranının infilak hızını etkilemesidir. Bu çalışma, Kumtor Açık Ocak Altın Madeni'nde mevcut kaya

koşullarında uygun patlayıcı madde kullanımı hakkında önemli bulgular sağlamıştır.

Anahtar Kelimeler: İnfilak hızı, ortam sıkılığı, delik çapı, patlayıcı, dökme ANFO, dökme emülsiyon, Kumtor Açık Ocak Altın Madeni.

To My Mother

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VOD	**:**	Velocity of Detonation
$\mathbf{P_d}$	**:**	Detonation pressure
$\boldsymbol{\rho}$	**:**	Density of explosive
$\mathbf{C_p}$	**:**	P-wave velocity
$\mathbf{C_s}$	**:**	S-wave velocity
$\mathbf{D_i}$	**:**	Ideal detonation velocity
$\mathbf{d_i}$	**:**	Ideal blast hole diameter
$\mathbf{D_{cr}}$	**:**	Critical detonation velocity
$\mathbf{d_{cr}}$	**:**	Critical diameter
$\mathbf{V_{det}}$	**:**	Detonation velocity of detonating cord
AN	**:**	Ammonium Nitrate
ANFO	:	Ammonium Nitrate Fuel Oil
MMU	**:**	Mobile Manufacturing Unit
IMDG	**:**	International Maritime Dangerous Goods
E	**:**	Voltage
R	**:**	Resistance
I	**:**	Current

CHAPTER 1

INTRODUCTION

1.1 Background Information

Blasting is one of the critical stages in mining operations. The purpose of blasting is to convert rock from a solid piece to several smaller pieces capable of being excavated by available equipment (Hemphill, 1981). It is usually the first step in mining. A blasted rock muck pile and the fragment sizes within it are very important for the mining industry since they affect the downstream processes from hauling to grinding. Efficiency of blasting in situ depends on the strength of material to be blasted, structural geology, explosive type and blast design parameters.

Blasting performance is directly related to the characteristics and efficiency of the explosives used. Each explosive has its own chemical composition and detonation characteristics. The explosives are characterized by their properties such as density, strength, velocity of detonation, detonation pressure, critical diameter, resistance to water etc. The availability of several types of explosives provides flexibility in the explosive selection to suit a wide range of rock mass conditions and blasting applications. Therefore it is very important to select suitable explosive for different geological conditions. These basic properties of explosives must be considered to have optimum blast performance.

1.2 Statement of the Problem

One of the most important properties for selection of explosive is velocity of detonation which is the rate at which detonation wave travels through an explosive column (Hopler, 1998). Usually velocity of detonation is specified by explosive manufacturer in their product technical data sheets. The VOD values given in technical data sheets are based on the measurements carried out under laboratory conditions or calculated assuming as ideal detonation. However, the VOD of an explosive is strongly influenced both by the rock conditions and the diameter of blast hole in which the explosive is confined.

The term confinement refers to the strength or resistance of the medium surrounding the blast hole in blasting science. In other words, the confinement determines how the surrounding medium resists or deforms upon the detonation of explosive. Therefore, it is expected that the same explosive can detonate at a higher velocity when it is well confined by the medium surrounding the blast hole.

With the development of blast monitoring systems, continuous VOD monitoring systems are also recently available. The VOD measurement in the hole helps in comparing and in evaluating the relative performance of explosives under the existing rock conditions and blast hole diameter. The selection of the proper explosive for a particular blast condition and objectives depend on the ability to characterize the performance of different explosives.

A reduction in the VOD of explosive will produce a reduction in the detonation pressure as well as in the availability of the shock energy of the explosive. It is important that the explosive detonates at its optimum rate and releases sufficient detonation pressure leading to good fragmentation. Studies in the rock blasting industry show that explosives with a high VOD are well suited for blasting in competent rocks. On the other hand explosives with a low VOD are better suited for soft rocks (Jimeno and Carcedo, 1995).

Therefore the VOD of an explosive can be used as one of the most important indicators of its performance. The actual VOD of explosive depends on the chemical composition, diameter of the blast hole, degree of confinement, temperature, type and degree of priming etc (Chiappetta, 1998). VOD of the same explosive is varied in same confinement with using different blast hole diameters. Also for a given explosive composition and blast hole diameter as confinement altered the VOD of explosive differs as well (Bilgin et al., 2000). To get the best performance from the blasting it is very important to select the most suitable explosive for existing field conditions at a specific mine.

The scope of this research study is selected as the comparison and evaluation of the performance of two different explosives by means of in hole VOD measurements at two blast hole diameters and at different degree of confinements. Blasting operations in Kumtor Gold Mine are conducted at blast hole diameters of 172 mm and 215 mm. Therefore, in-situ VOD measurements were carried out at existing blast hole diameters during the study. Production is carried out not only in rock material but also in glacier. Some of the production benches are 100% ice, thus, several VOD measurements were also carried out in glacier during the study to investigate the effect of confinement on VOD of explosives.

1.3 Objective and Scope of the Study

This research study has three main objectives:

1. To investigate the performance of two different explosives by continuous VOD measurements at Kumtor open pit gold mine

2. To investigate the effect of blast hole diameter on VOD of explosives at Kumtor open pit gold mine
3. To investigate the effect of confinement on VOD of explosives within the material zones exisiting at Kumtor open pit gold mine

1.4 Research Methodology

To reach the objectives of this research study following steps were followed:

- Blasting zones (different rocks and glacier) and blast patterns were investigated, blasting parameters such as diameters, depth of holes, drilling, and initiation sequences were observed.
- Ingredients of bulk ANFO and bulk emulsion were investigated and observed to be sure that same materials were used throughout manufacture process.
- Bulk ANFO and bulk emulsion explosive trucks were calibrated.
- VOD measurements were conducted and recorded using the calibrated instruments belonging to Orica and Kumtor Gold Mine.
- Performance of bulk ANFO and bulk emulsion were tested at different blast hole diameters and confinement by means of in-situ VOD measurements, Figure 1.1.
- In order to investigate effect of confinement on VOD of both explosives, in-situ measurements were carried out in three different medium, Figure 1.1.
- Since the blast hole diameters of 215mm and 172mm are utilized for blasting practice in the mine, the effect of blast hole diameter on VOD of both explosives were investigated at two different blast hole diameters, Figure 1.1.
- Blast hole diameters vs. VOD graphs were drawn for the same and the different rock conditions to see the effect of diameter and confinement on VOD of explosives at Kumtor Open Pit Gold Mine.

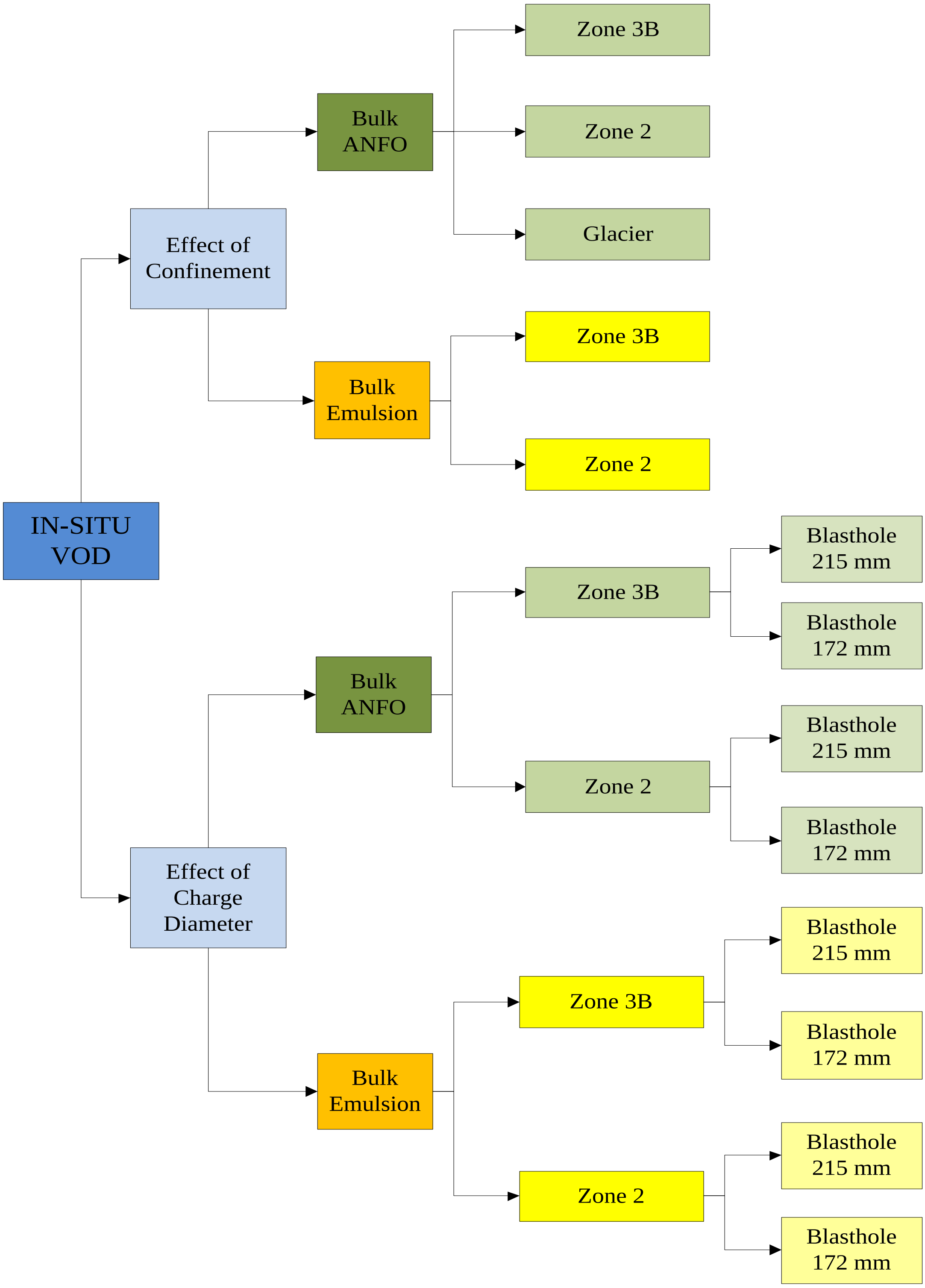

Figure 1.1 Research methodology followed during the study

1.5 Outline of the Thesis

This thesis is composed of 5 chapters.

In Chapter 2, the literature survey on the subject is given. Literature survey includes basic principles of rock breakage, detonation of commercial explosives, systems used to measure VOD of explosives and factors affecting the velocity of detonation.

Chapter 3 presents the general information about the mine site. Test method for VOD measurements is also described in the scope of this chapter.

The results presented and the discussions made are given in Chapter 4. VOD measurements taken during study are discussed and evaluated comparing with the previous studies on the subject.

Chapter 5 is devoted to the main conclusions drawn from this research and the recommendations on the suitable explosive selection for mine conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Principles of Rock Breakage

The three main phases in the fragmentation of rocks with explosives, as defined by Atlas (1987), are:

I. Detonation
II. Shock or Stress Wave Propagation (Shock energy)
III. Gas Pressure Expansion (Gas energy)

Detonation is the first stage of the fragmentation. The detonation of explosive starts with point of primer initiation. When detonation waves propagate through explosive column, the ingredients in the explosive converted into high pressure and high temperature gases, Figure 2.1 (a).

Cristopher (2011), expressed the detonation pressure as a function of the velocity detonation and the density of the explosives as,

$$P_d = 0.25 \times \rho \times VOD^2 x 10^{-6} \qquad (2.1)$$

Where:

P_d = detonation pressure (GPa)
ρ = density of explosive (g/cc)
VOD = Detonation Velocity (m/s)

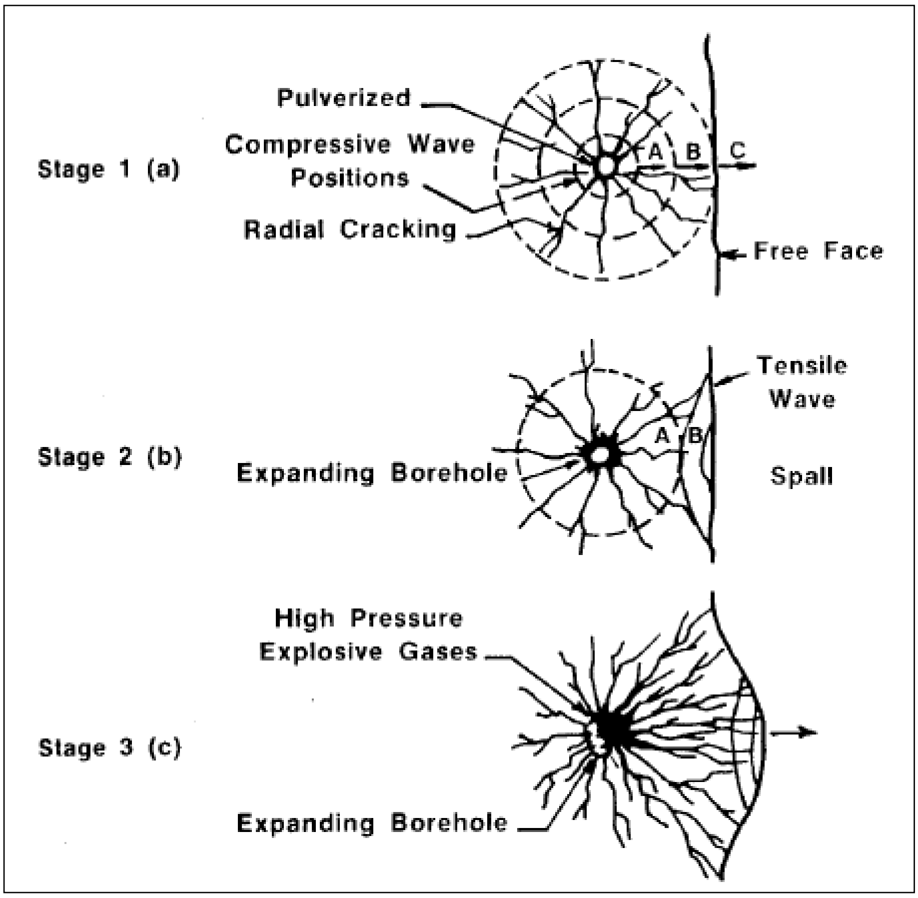

Figure 2.1 Sequences of events occurring in the rock mass after detonation of explosive (Atlas, 1987)

Field trials show that the explosives with a high VOD are best suited for competent rocks. Better blasting results are achieved in soft rocks by using explosives with a low VOD (Esen, 1996 and Bilgin et al., 2000).

The second stage is the shock or stress wave propagation. When the explosive detonates in the blasthole, an intense compressive stress wave and an indirect tensile stress wave (hoop stress) are transmitted into the rock mass. These shock waves cause rock compression, tension, and crack around the blasthole, Figure 2.1 (b). The amount of the cracks depends on the strength or stiffness of the rock (Olsson et al., 2002).

When the compressive stress wave reaches the free face a tensile wave is reflected back towards the blasthole. Spalling of the rocks at the bench face also occur by the reflected tensile waves. Shock energy should not be called as fragmentation energy. Fragmentation also occurs during subsequent stages of rock breakage and is not completely result of tensile failure of the rock (Atlas, 1987).

After stress wave propagation, the detonation product gases at high temperature and pressure enter the cracks existing between the blasthole and free face. It is during this final stage that gas pressure contributes to further fragmentation and heaves the broke rock, Figure 2.1 (c). The gas energy used during this stage of rock breakage is called heave energy (Atlas, 1987).

High pressure explosion gases eventually escape to the atmosphere and effective work on the rock mass stops at this point. The total energy liberated to this point is called the fragmentation energy (Orica, 2008).

Olsson et al. (2002) has indicated that:

- The shock wave is mainly responsible for cracks lengths in the remaining of rock walls.
- Movement of rock burden is achieved by gas pressure.
- Gasses had no effect on cracks especially for the emulsion explosives.
- An explosive having low VOD works more gently on the rock, whereas a high VOD explosive will subject the rock to high impact pulses.

2.2 Properties of Explosives

Explosives are compounds or mixture of compounds that undergoes a rapid chemical reaction by action of heat and impact, forming gases at high temperature and pressure (Sickler, 1992). Explosives are divided into two namely; military and commercial explosives.

Commercial explosives have been the primary method of breaking and loosening rock in mining industry. It is necessary to select suitable explosive for existing blast conditions to get best performance. Factors, important in the selection of best explosive for the job are as follows (Atlas, 1987):

- Velocity of detonation
- Density
- Detonation pressure
- Sensitivity
- Energy output
- Water resistance
- Safety characteristics
- Temperature stability
- Post blast fumes
- Shelf life

Velocity of detonation (VOD) is the rate at which detonation wave travels through an explosive column. As seen in equation 2.1, detonation pressure is directly proportional to the square of VOD. Hence, an explosive with a high VOD provides better fragmentation in competent rocks whereas an explosive with a low VOD are better suited for soft rocks.

The density of an explosive is its weight per unit volume and generally is expressed in grams per cubic centimeter. When blast hole contains water it is necessary to load the hole within an explosive having a density greater than 1.0 g/cm^3 (Atlas, 1987). If explosive density is lower than the water density, the explosive floats, and after primer initiation, this results in failure of full column detonation.

As seen in Equation 2.1, there is a strong relationship between explosive density and detonation pressure. Generally high density explosives produce more energy.

However, most bulk explosives become less sensitive at higher densities. The desensitization of explosive occurs because of hydrostatic pressure due to high density (Orica, 2011). If blasting is to be carried out in deep blastholes, gas bubbles, which increase the sensitivity of explosive, become unstable under high hydrostatic pressure. In order to decrease this hydrostatic pressure, explosives with a lower density are more suitable than those with a higher density in deep blast holes.

The water resistance of explosive is usually defined as its ability to detonate after its exposure to water (Orica, 2011). Emulsions have excellent water resistance; water in oil explosives has good water resistance, whereas ANFO has negligible resistance to water.

Explosives are at risk of burning or exploding at elevated temperatures as initiation sensitivity increases with temperature (Orica, 2011). At temperatures higher than the safe values, chemical reactions and decomposition may start. Some explosives can generate heat and proceed to ignition or explosion. All explosives are less sensitive at lower temperatures but the loss of sensitivity is not sufficient to cause failure to detonate.

The principle gases resulting from the detonation of explosives are CO_2, N and steam. Each of these is generally accepted as non toxic. Varying amounts of toxic or poisonous gasses are also produced; the main ones are CO and NO_x. Sometimes Hydrogen sulphide and sulphur dioxide are present after blasting in sulphide ores (Olofsson, 2011).

Over a period of time, explosives are likely to become less sensitive to initiation and after extended periods, beyond their shelf-life they can not be relied upon to detonate (Cristopher, 2011). Explosives must be consumed before their end of shelf life.

Recently, it is inevitable to develop mining equipment and consequently also explosive products including manufacturing, distribution or handling caused by large scale mining and excavation. Today most of the commercial explosives in the world used in large diameter drill holes. Therefore long time is required to load blast holes. In addition to this the safety and working environment has become most significant parameters when the overall mining operation is evaluated. All those factors have forced to handle explosives in safe conditions and load to blast holes in short time as a bulk with special charging trucks.

2.2.1 Bulk ANFO

ANFO is one of the most commonly used products in mine and quarry blasting. It is composed of Ammonium Nitrate (AN) and fuel oil. Ideal proportion of ANFO is 5.7 % (weight basis) of fuel oil and 94.3 % AN (Atlas, 1987). Maximum explosive strength and minimum fumes are obtained with this mixture rate which can be seen in Figure 2.2.

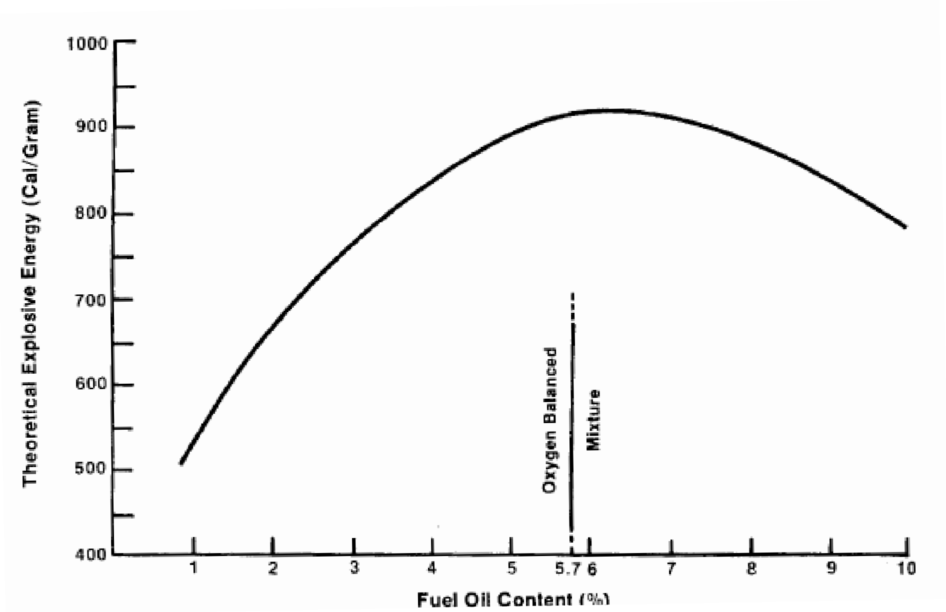

Figure 2.2 Effect of fuel oil content on explosive energy (Atlas, 1987)

VOD is a good indicator for explosive performance. Higher VOD means greater release of available energy. Maximum VOD can be obtained at an ideal proportion and under confinement (Figure 2.3).

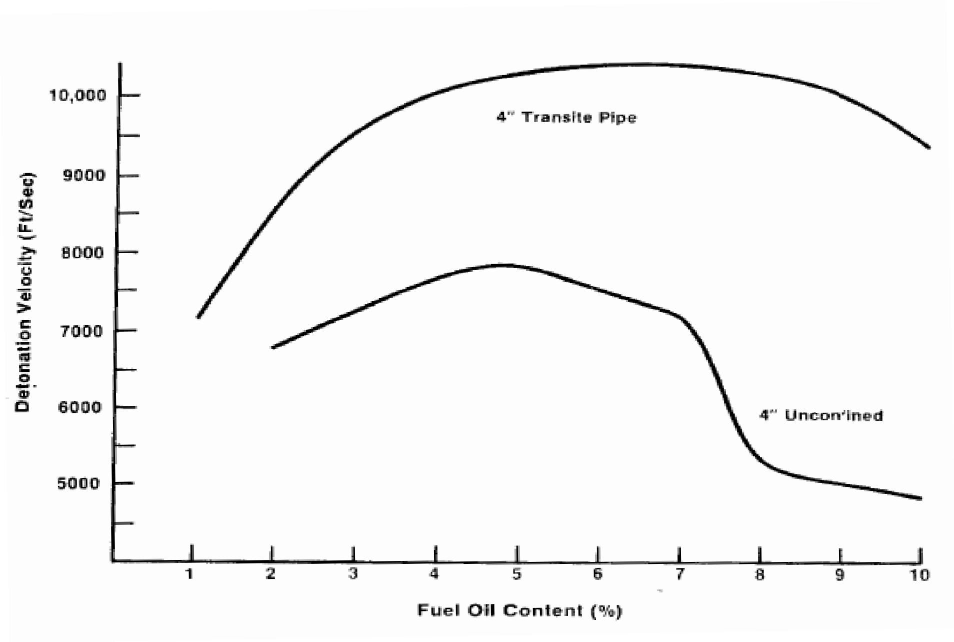

Figure 2.3 Effect of fuel oil content on VOD (Atlas, 1987)

With too much or too little distillate, energy yield falls off. As the content of Fuel oil increases in the product, it causes excess CO to be liberated in the detonation gases, whereas insufficient content encourages the generation of greater volumes of oxides of nitrogen. The appearance of distinctive reddish brown colored post detonation fumes in an ANFO blast may indicate too little fuel oil in the mixture (Orica, 2008). These fumes can also appear where ANFO has absorbed blast hole water.

ANFO either can be prepared in factory or can be manufactured in mobile equipment. In large operations quantities of correctly proportioned and mixed ANFO are charged quickly and efficiently by bulk trucks, Figure 2.4

Figure 2.4 Loading blasthole with ANFO bulk truck

Having recognized the cost effectiveness of using accurately blended ANFO, most mines prefer to use ANFO which has been mixed by bulk trucks.

2.2.2 Bulk Emulsion

Bulk emulsion system is used to provide greater safety and control of explosives in the mining. The new system was developed as a result of the specific demand for a safer and more cost effective explosives systems.

Bulk emulsion is not regarded as an explosive under the new regulation, published by International Maritime Dangerous Goods Code**.** They can be classified as an explosive until sensitized during the charging process at the blast hole. Until this process is undertaken, the emulsion is classified as an oxidizer (Hazardous Class

5.1- Oxidizing agents) and has numerous advantages with regard to safety and the handling of explosives (IMO, 2008).

2.2.2.1 Description of the Bulk Emulsion

All bulk emulsion explosives contain the following essential components (Sickler, 1992):

- Oxidizer is a chemical which provides oxygen for the reaction. Solution is prepared by solving AN prills in hot water.
- Fuel blend reacts with oxygen to produce heat. Common fuel blends include mineral oil and diesel oil.
- Sensitizer provides voids which act as hot spots and at which reaction starts during detonation. They are generally air or gas in the form of very small bubbles. Sometimes glass micro balloons are used as a sensitizer.

All these raw materials are not classified as an explosive.

Bulk Emulsion consists of small droplets of ammonium nitrate solution, tightly packed in a fuel blend, Figure 2.5, its structure resembles of honeycomb (Orica, 2008).

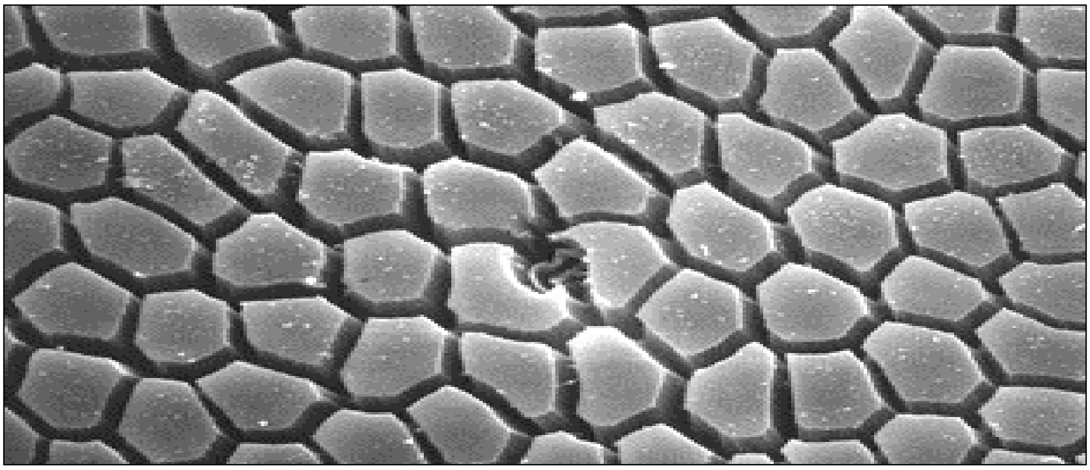

Figure 2.5 Structure of water in oil type emulsion (Orica, 2008)

The thickness of the fuel blends membranes separating the oxidizer droplets are about 1-10 micron. This increases the contact area between fuel blend and oxidizer solution. Very rapid and complete detonation is obtained by intimate mixing. The fine droplet size and detailed mixing of oxidizer and fuel enables them to react very quickly and efficiently. This produces relatively high VOD and small quantity of toxic post-blast fumes.

The water-in-oil structure of emulsion also provides excellent water resistance, as each droplet of water- soluble oxidizer solution is surrounded by oil (Sickler, 1992).

By adding special gassing solution, sensitivity of the emulsion can be increased. Gassing solution acts as density gradients in the explosive and effectively transfers shock wave energy to heat and enhance the rapid detonation of the emulsion. A simple flow sheet for bulk technology is given in Figure 2.6.

2.2.2.2 Advantages of Bulk Operation

Derya et al. (2010) summarized the main advantages of the system as follows:

- System provides reduction in blast crew.
- Product is insensitive to accidental initiation by friction or impact; detonation may occurr from heavy impact and excessive heating under confinement.
- Product is reliable in dry and wet blast holes, it has excellent water resistance.
- Blast holes can be loaded at varying densities and energies to maximize fragmentation and improve mine to mill productivity.
- It provides rapid blast hole loading.
- Complete coupled blast holes maximizes blast outcomes.
- Bottom of blast hole can be reached by bulk trucks product hose and it provides complete hole loading. System prevents gaps between charges.

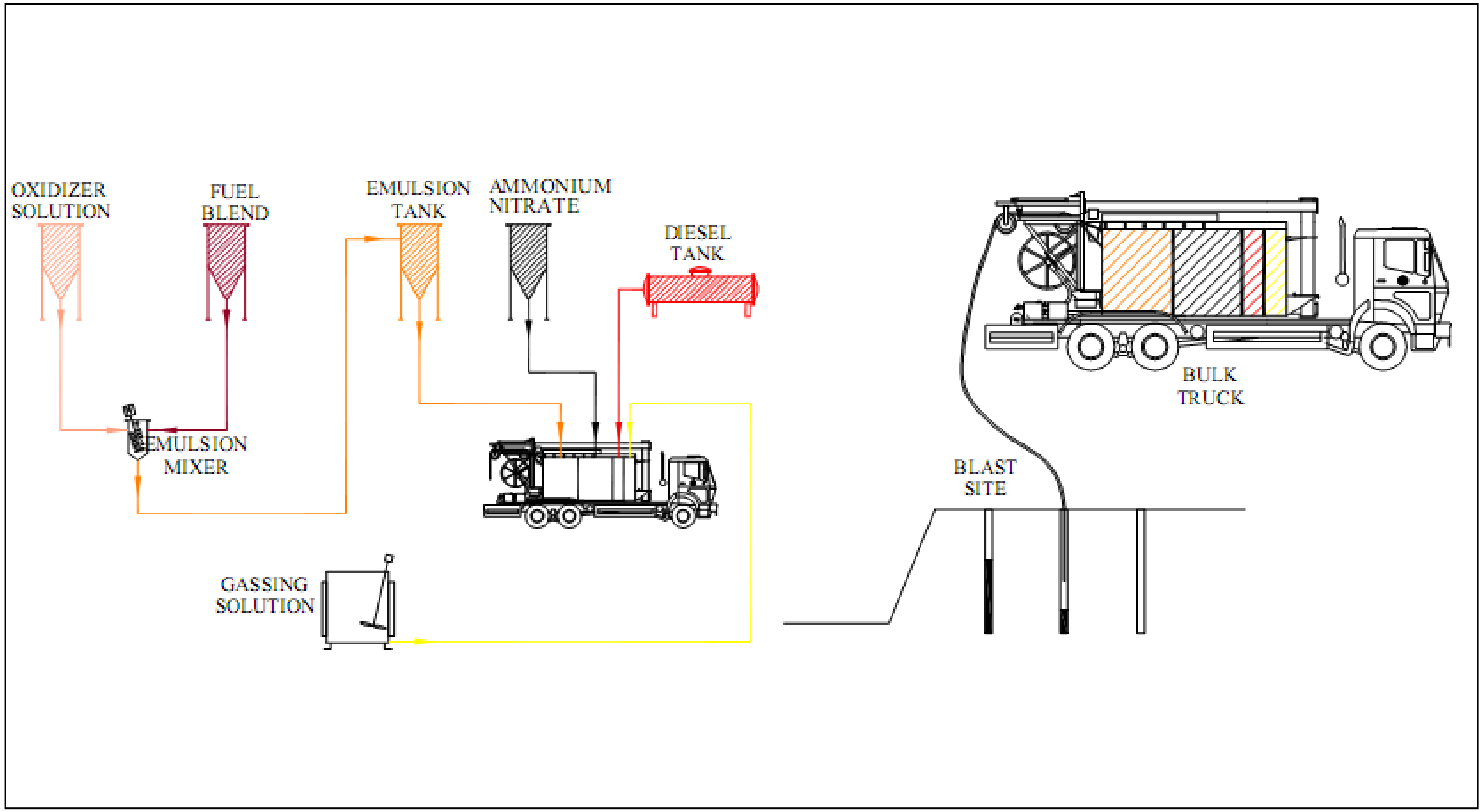

Figure 2.6 Flow sheet for bulk explosives technology

2.3 Detonation Process

A detonation is a process in which a shock-induced, supersonic combustion wave propagates through a reactive mixture or exothermic compound (Lee, 2008). The detonation wave starts at the point of primer initiation in the explosive column and travels at velocity which is faster than the speed of sound in the explosive. It can be considered as a reacting shock wave where reactants transform into products, accompanied by an energy release across it (Lee, 2008).

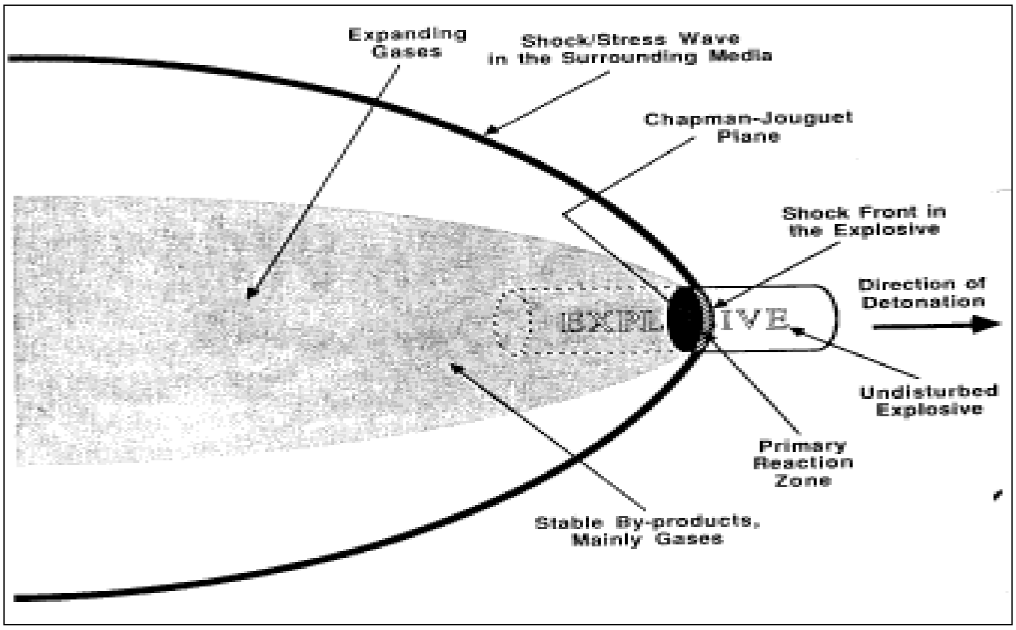

Figure 2.7 The detonation process for cylindrical explosives (Atlas, 1987)

A typical detonation process is illustrated in Figure 2.7. The chemical decomposition begins in the primary reaction zone. Reaction is bounded at the one end by shock front on the other by C-J plane. In an ideal detonation, the chemical reaction is complete at this plane (Esen, 1996).

Chapman and Jouguet classified detonation process in to two namely, ideal and non- ideal detonation (Brinkmann, 1990).

2.3.1 Ideal Detonation

The phenomenon for ideal detonation was developed by Chapman and Jouguet over a century ago. In this case detonation is supposed that the explosive is under the infinitely thick confinement and very large diameter (Brinkmann, 1990). The important components of the ideal detonation are illustrated in Figure 2.8.

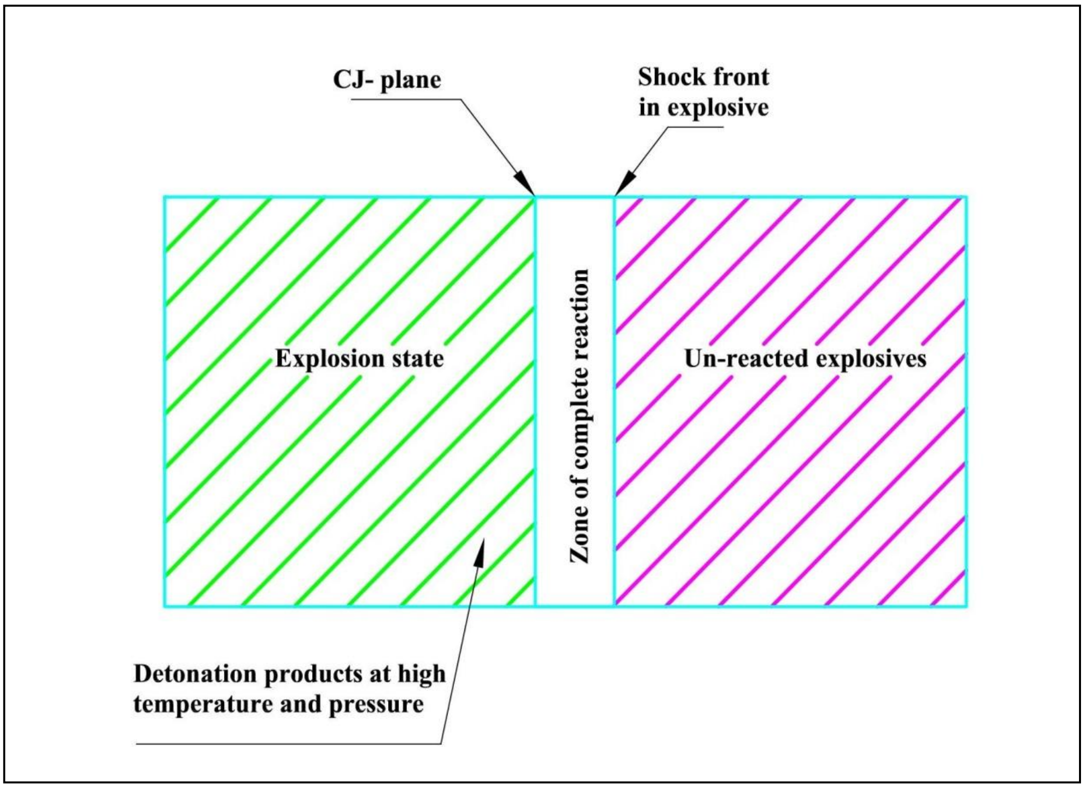

Figure 2.8 Features of ideal detonation process of explosive (Brinkmann, 1990)

The leading part of a detonation front is a strong shock wave propagating into the explosive. This shock wave heats the material by compressing it and heating causes a chemical reaction (Ficket and Davis, 2000). Reaction is complete and instantaneous. The release of energy close to the shock front results in a pressure raise in the explosive which supports the front. This allows the pressure to increase and the front to accelerate. The thickness of the reaction zone is very thin in ideal detonation and all the energy of explosive is released in this zone. This zone is bounded at the rear by C-J plane and at the front by the shock wave (Brinkmann, 1990).

2.3.2 Non-Ideal Detonation

Commercial explosives can not reach the Chapman and Jouguet detonation velocity and behave as non-ideal (Ficket and Davis, 2000).The amount of energy released by commercial explosives depends on how far their detonation velocity approaches to ideal detonation. Confinement, explosive density and blast hole diameter influence the detonation velocity of the commercial explosives (Esen, 1996).

The important features of non-ideal detonation of an explosive are illustrated in Figure 2.9. In a non-ideal detonation, some of the energy is released so far behind the shock wave and that corresponding pressure waves never reach the shock front. Shock front is curved in this detonation due to the reduced pressure and temperature near the edge of the explosion.

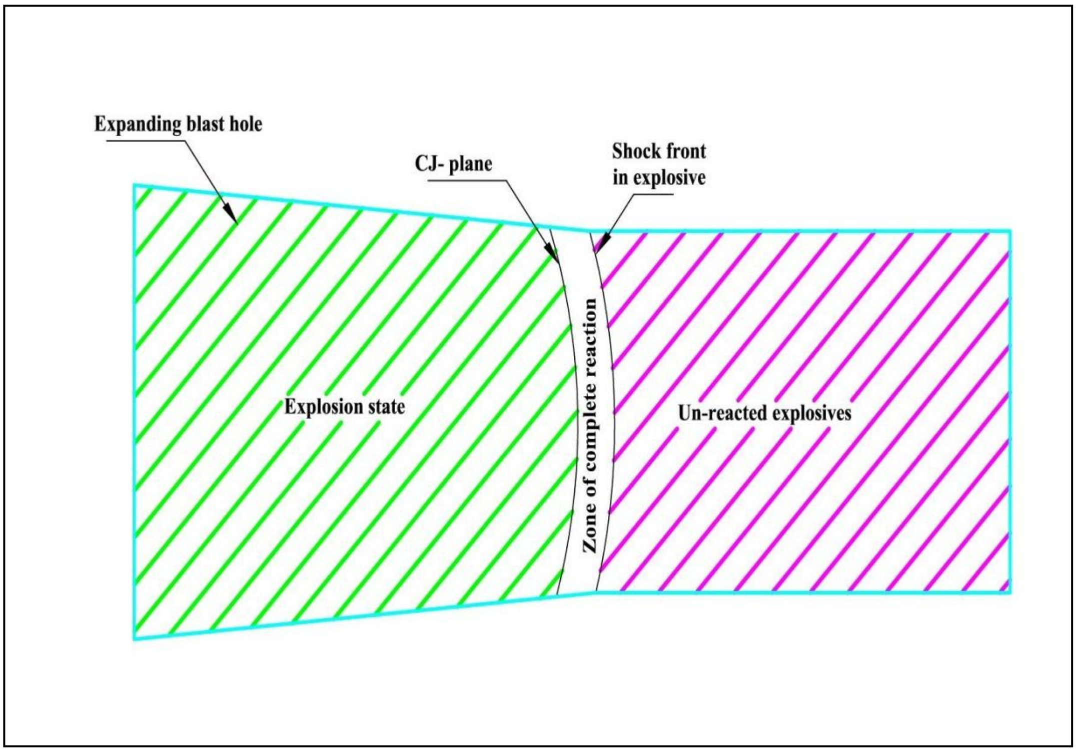

Figure 2.9 Features of non-ideal detonation process (Brinkmann, 1990)

The zone of complete reaction represents the volume where the reaction energy supports the shock wave, and is bounded at the rear by the C-J plane (Brinkmann 1990).

As the amount of released energy increases in this zone, detonation velocity of explosive increases and detonation behave towards the ideal. Reaction behind the C-J plane does not support the shock front. It can affect the explosive performance but does not influence velocity of the detonation itself (Hopler, 1998).

2.4 P and S Wave Velocities of Rock

When the explosive detonates through the charged column, two conical waves generated. One of them is P-waves (c_p) which is known as longitudinal or primary waves and the other is S-waves (c_s) known as shear or secondary waves (Daehnke and Rossmanith, 1997). Wave expansion from a detonating column charge is illustrated in Figure 2.10. P-waves propagate through the rock faster than the S-waves.

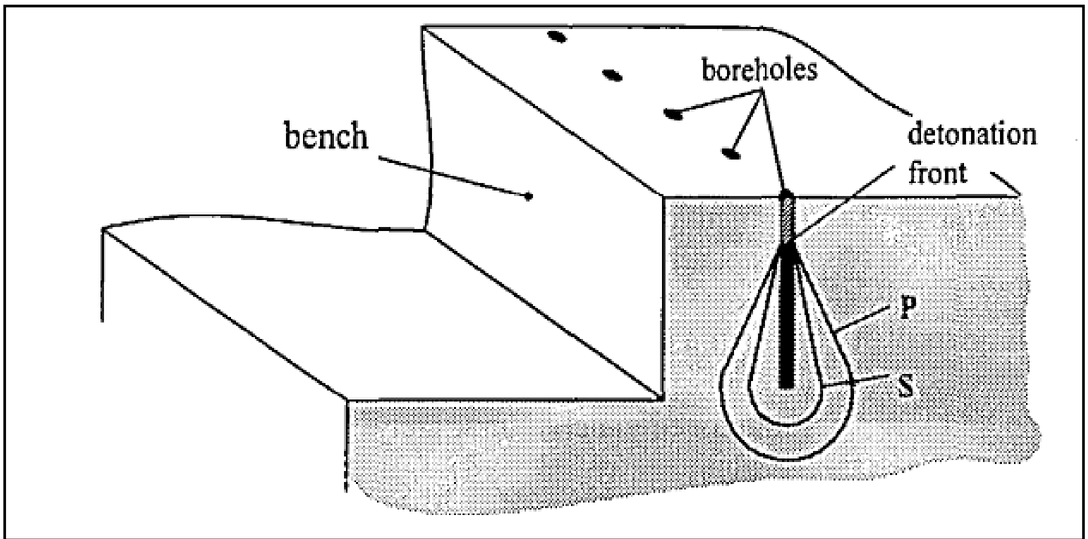

Figure 2.10 Conical waves generated upon explosive detonation (Daehnke and Rossmanith, 1997)

Rossmanith et al. (1997) pointed out the relation between VOD of an explosive and generated conical waves during detonation. Kouzniak and Rossmanith (1998) identified three fundamental cases depending on VOD of explosives and velocities of wave propagation in existing rock type. These cases are supersonic, transonic and subsonic.

In supersonic case, the VOD of explosive is greater than both P and S-wave velocities of the rock. Thus, P-wave and S-wave will be generated upon detonation. In transonic case, the VOD of explosive is larger than the S-wave velocity but smaller than the P-wave velocity. In the case where VOD is smaller than the S-wave velocity, both P and S-waves are lost which is called subsonic case (Kouzniak and Rossmanith, 1998).

Table 2.1 P and S - wave speeds in common rock types (Carmichael, 1988)

Rock Type	**P - wave (m/s)**	**S - wave (m/s)**
Gabbro	6800	3900
Quartzite	6230	4000
Marble	6060	3070
Limestone(Solenhofen)	6000	2950
Granite	5780	3420
Basalt	5410	3210
Sandstone(dry)	4040	2510

As shown in Table 2.1 each rock a type has its own P and S - wave velocities. In order to improve efficiency and productivity of blasting, the detailed mechanical and physical conditions of the rock requires better understanding (Carmichael, 1988). The explosive shock wave is better transmitted to the rock when the impedance of the explosive (the product of VOD and density) is close to the impedance of rock, which is the product of P wave velocity and density of rock to be blasted.

Hausmann et al. (2007) carried out studies on two active glaciers in the Eastern Alps. The glaciers are located at an altitude of 2300-2600 m. Displacement of glaciers was observed during 2003 to 2005. The measurements from a study conducted by Hausmann et al. (2007) indicated that the P- wave velocity of glaciers is 3300m/s on average which is below the P- wave velocity of pure ice (3700 m/s).

Another study was conducted by Rege and Godio (2011) on the Pre de Bar glacier in Aosta Valley (Italy). Their surveys were focused in estimating the P and S -wave velocities of glaciers. Analysis by Rege and Godio (2011) demonstrated that P - wave velocity changes with depth from 1500 m/s on the surface to 3600 m/s at deeper level and S - wave velocity vary from 800 m/s to 1500 m/s.

2.5 Detonation Velocity

The detonation velocity of an explosive is the speed at which detonation front travels through a column of explosive (Cristopher, 2011). Detonation velocities of commercial explosives range from 2,438-7,925 m/sec. Every explosive has its own ideal detonation velocity. VOD of explosives varies from one to another depending on the density, composition and particle size (Atlas, 1987).

Detonation velocity of an explosive can be used to indicate its performance under the existing rock conditions. Many factors influence the VOD of an explosive, including product type, degree of confinement, diameter, temperature, sleep time in borehole, degree and type of priming, nearness to critical density, and nearness to critical diameter (Chiappetta, 1998).

Despite the fact that the influences of some parameters on VOD of explosives are easily predicted, there were unexpected factors affecting the VOD of bulk explosives. Araos (2002) evaluated the effect of oxidizing phase composition, gassing solution rate, product temperature, emulsion-ANFO blend composition on VOD of bulk explosives. According to Araos VOD of bulk explosives also can be altered extensively by all those factors.

2.5.1 Effect of Confinement on VOD of Explosive

Literature on this subject shows that the greater the confinement of an explosive, the higher the detonation velocity (Olofsson, 2011; Cristopher, 2011; Esen and Bilgin, 1998; Persson et al., 1994). If we detonate a column of explosive and measure the VOD, we will find that the VOD of an explosive changes under the different confinement. The VOD increases as the confinement increases. This effect is caused by pressure rises along the side of borehole (Cristopher, 2011).

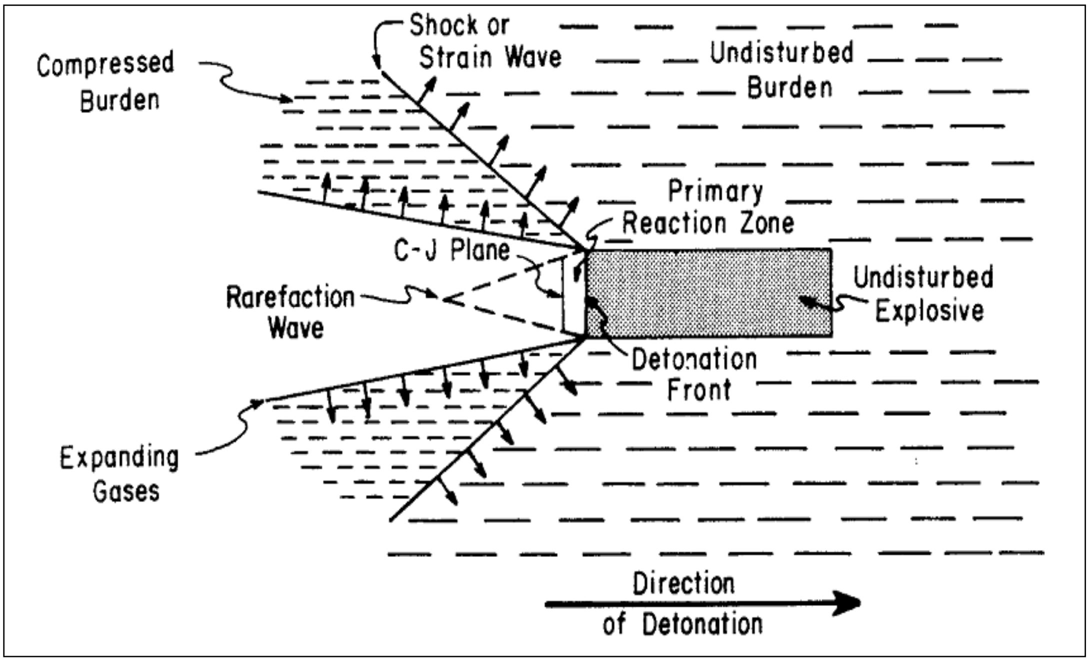

Figure 2.11 Detonation in a readily compressible medium (Cristopher, 2011)

Figure 2.11 and 2.12 are illustration of how degree of confinement effects the shock wave propagation and VOD of an explosive. Under the weak confinement as the expanding gases compress surrounding area, temperature and pressure decreases rapidly in the reaction zone. Occurrences of these losses create rarefaction waves and decrease the support on the detonation front (Cristopher, 2011).

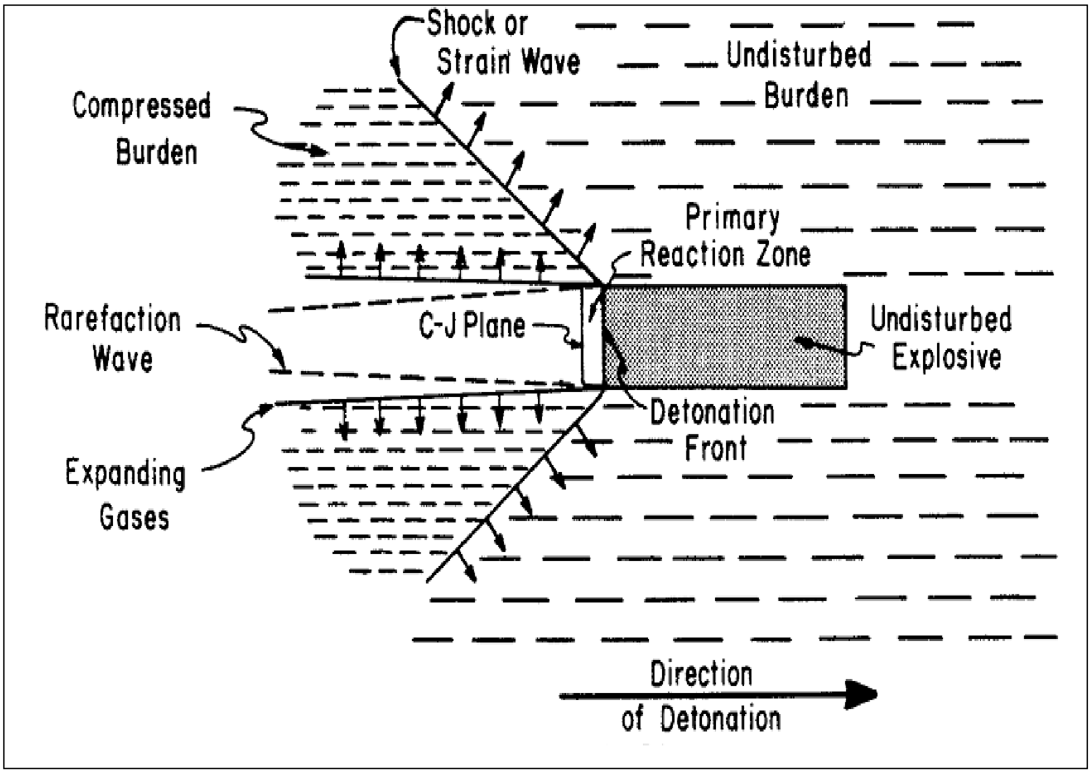

Figure 2.12 Detonation in an incompressible medium (Cristopher, 2011)

As illustrated in Figure 2.12 if the explosive is detonated in confined column the rarefaction wave becomes weaker. As the degree of confinement increases, lateral expansion near the primary reaction zone is inhibited. This maintains the temperature and pressure at greater levels resulting in support on the detonation front (Esen, 2004).

Bilgin and Esen (1999) evaluated the performance of three different explosives by means of in situ measured VOD at different rock conditions. Test results showed that the idealities of these explosives affected positively by degree of confinement. For a given explosive composition and blast hole diameter as confinement increases the VOD of explosives increases.

Bilgin et al. (2000) conducted study on use and importance of VOD measurements in blasting. VOD of three different explosives were measured in-situ. Measurements were carried out under same degree of confinement and in 159mm blast hole diameter. It was found that each explosive has different detonation velocities under same field conditions. Bilgin et al. (2000) suggested suitable explosive type to get best blast performance for existing conditions according to in –situ VOD measurements.

Bilgin et al. (2000) tested three different commercial explosives at confinements ranging in uniaxial compressive strength from 15.3 MPa to 108 MPa. The blast holes for this study varied between 89mm and 165mm. Bilgin et al. (2000) found that as the degree of confinement increases VOD of explosives increases.

Studies have showed that charges which are decoupled from the borehole wall have lower VOD than those fully coupled (Derya et al., 2010). The difference in effect could be a result of the change in confinement on the charge during detonation.

Derya et al. (2010) mentioned effect of confinement due to decoupling in their study. According to authors, charging wet holes with packaged explosives has some difficulties and disadvantages. When blast holes loaded with packaged explosives, the interaction between explosive and borehole is not fully provided which decreases degree of confinement on explosive and velocity of detonation.

As shown in Eqn 2.1, there is a positive relation between the detonation pressure and VOD of explosives. Decoupling is also common practice in commercial blasting. Decoupled holes produce less fragmentation than fully coupled holes which is caused by energy loss (Orica, 2008).

According to Sanchidrián et al. (1998), one means of reducing the shock pressure onto the rock is decreasing confinement by using decoupled holes. Sanchidrián et al. (1998) indicates that if the explosive fills the borehole, the VOD of the explosive will be high and the peak pressure in the borehole wall will be extremely high.

Persson et al. (1994) highlighted the influence of confinement on VOD of explosives. In the case of strong coupling, the products radial expansion reaches the borehole wall before the end of the reaction zone (Figure 2.12). The pressure increase from the borehole due to confinement is therefore affecting the shock front and, accordingly, the VOD is increased. This explains why the VOD of commercial explosives always increases as the degree of confinement increases (Persson et al., 1994).

2.5.2 Effect of Blast Hole Diameter on VOD of Explosives

It is found experimentally that the VOD of an explosive varies as a function of blast hole diameter (Akhavan, 2004). Esen (2006) indicates that for a cylindrical column of an explosive the VOD will increase as the diameter of the explosive column increases. The velocity decreases as the diameter of the column decreases. According to author, VOD of an explosive is influenced by the pressure difference at the side of the blast hole column.

The detonation shock front for a cylindrical column of explosive is not flat. On the contrary, it is convex as shown in Figure 2.9. It can be seen that the VOD gradually decreases from the center of column to its sides. For large diameter charges, the influence of blast hole diameter on VOD of an explosive is not as same degree as for small diameter charges (Akhavan, 2004). The typical relationship between VOD and blast hole diameter is illustrated by Sun et al. (2001) as shown in Figure 2.13.

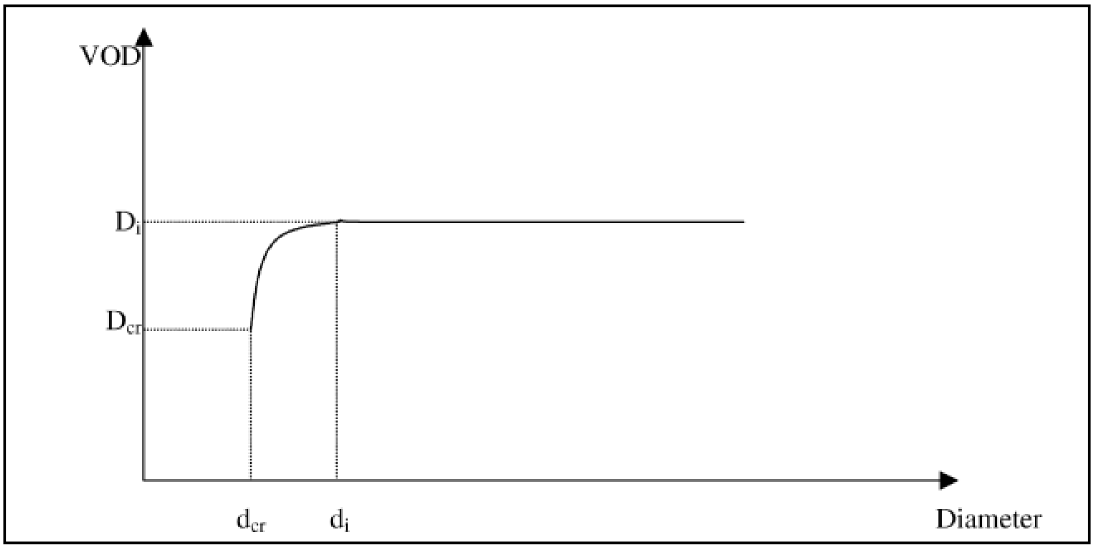

Figure 2.13 Effect of blast hole diameter on VOD of an explosive (Sun et al., 2001)

In Figure 2.13 D_i is the ideal detonation velocity in which the diameter of charge assumed as infinite and d_i is the ideal blast hole diameter. It can be seen from the figure that VOD reaches the ideal value when its blast hole diameter is equal ideal or greater than the ideal. The figure also indicates that when the blast hole diameter is d_{cr} which is critical diameter, VOD is at the critical detonation velocity and expressed by $D_{cr.}$ When the blast hole diameter is below the critical value the explosive column fails to detonate.

According to the results of tests that carried out by Bilgin and Esen (1999), as the blast hole diameter increases, VOD of explosives become greater. The VOD of an explosive (ELBAR 5C) is 2947m/s at 89mm blast hole diameter. On the other hand, the VOD of the same explosive is increased to 4227 at 165mm blast hole diameter under the same confinement.

Increase in blast hole diameter has therefore the same effect as an increase in degree of confinement (Esen and Bilgin, 1998; Bilgin and Esen, 1999; Bilgin et al., 2000).

2.6 Test Methods of Measuring VOD of Explosives

The methods for the detonation velocity determination may be classified into several groups. Suceska (1995) generally classified the experimental methods to measure VOD of explosives into four.

This simplest method is Dautriche method and it does not require any special device (Chiappetta, 1998). It can be applied for the rough estimation of detonation velocity. The principle of Dautriche method is based on the propagation of the two processes, which are at different linear velocities, traveling different distances at the same time. The simple illustration of the method can be seen in Figure 2.14.

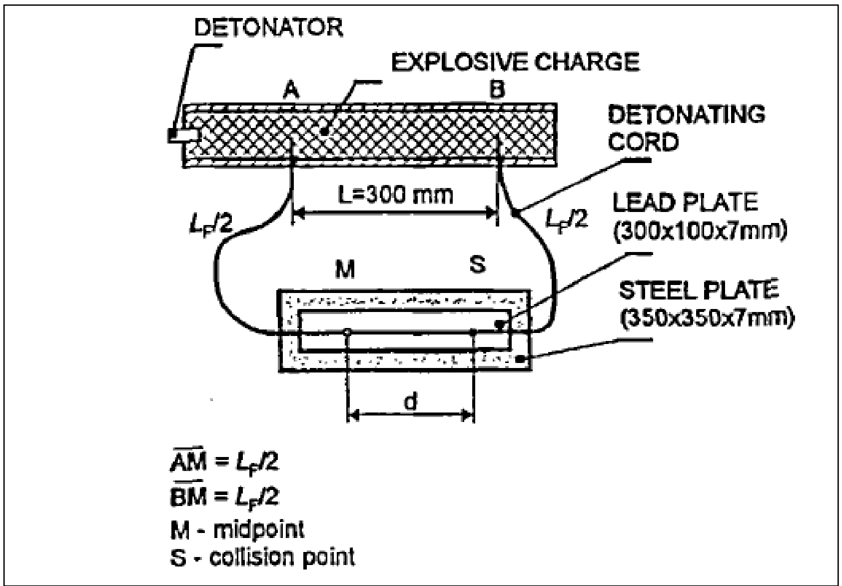

Figure 2.14 Determination of detonation velocity by Dautriché's method (Suceska, 1995)

After the explosive is initiated, its detonation waves propagate the detonating cord starting from point A and B. The marks on the lead plate indicate collision point of two detonation waves. Since the VOD of detonating cord is known, detonation velocity of the explosive can be calculated by comparing the distance between point M and S (Suceska, 1995).

$$\frac{V_{exp} = V_{Det} \times L}{2d} \qquad (2.2)$$

V_{exp}: Detonation velocity of explosive to be measured

V_{det}: Detonation velocity of detonating cord

L: Distance between points A and B

d: Distance between points M and S

The principle of determination of the detonation velocity of explosives by optical methods is continuous viewing of detonation wave which propagates through the explosive column (Suceska, 1997). After the detonation wave is viewed by high speed cameras, detonation velocity can be calculated from the obtained graph detonation wave – distance curve. Several type cameras are used to view process. But the way the curve is obtained is basically same for all types (Suceska, 1997).

The measuring system that uses an electronic counter- velocity probes technique depends on their operating principle either ionization type probes or electro contact type probes can be used in this method (Suceska, 1995). When the explosive initiated, detonation wave front produces products which are highly ionized. Thus, detonating products are capable of conducting electric current. In this method two probes are inserted into an explosive at a known distance. When the detonation wave arrive the first probe, assembly start collecting data until the wave reaches the second probe. The time required for detonation wave to propagate between first and second probe is recorded by assembly. Therefore, VOD of explosive can be calculated from the ratio between distance and time.

As mentioned by Suceska (1995) detonation velocity of explosives can be also measured by optical fibers. Optical fiber detects and transmits a light signal accompanying the detonation wave front and this light signal may be recorded by optical methods or may be transformed into an electrical signal which is then recorded by suitable signal recording technique (Suceska, 1997).

The continuous resistance wire type VOD measurement method, which is used in this research investigation, is presented in Chapter 3.4.

CHAPTER 3

MINE SITE AND VOD MEASUREMENT SYSTEM

3.1 Mine Site

The Kumtor Gold Project, operated by Kumtor Operating Company (KOC), is located in the administrative territory of the Dzety Oguz district of the Issyk-Kul region, eastern Kyrgyzstan (Figure 3.1). The Kumtor mine site (Figure 3.2) is located on the northwest slope of the Ak-Shyirak mountain range of the Tian-Shan Mountains, approximately 350 km to the southeast of Bishkek (Kyrgyz capital), and about 60 kilometers to the north of the international boundary with China, at 41º 52' N and 78º 11' E(Elliott et al, 2009).

The Kumtor processing plant is situated in alpine terrain at an elevation of 4016 m, while the highest waste and glacier mining occurs above 4400 m. The main camp, administration and maintenance facilities are at about 3600 m. Local valleys are occupied by active glaciers that extend down to elevations of 3800 to 3900 m, and undisturbed permafrost in the area can reach a depth of 250 m (Elliott et al, 2009).

The climate is continental with a mean annual temperature of minus 8°C. Extreme recorded temperatures vary from plus 23°C to minus 49°C, with short summers that last from June to September. Precipitation is low at around 300 mm per annum, with the majority falling in the summer months, and snow accumulations of 600 mm. Kumtor operates 365 days per year and there have been no significant interruptions to Kumtor operations because of climatic conditions (Elliott et al, 2009).

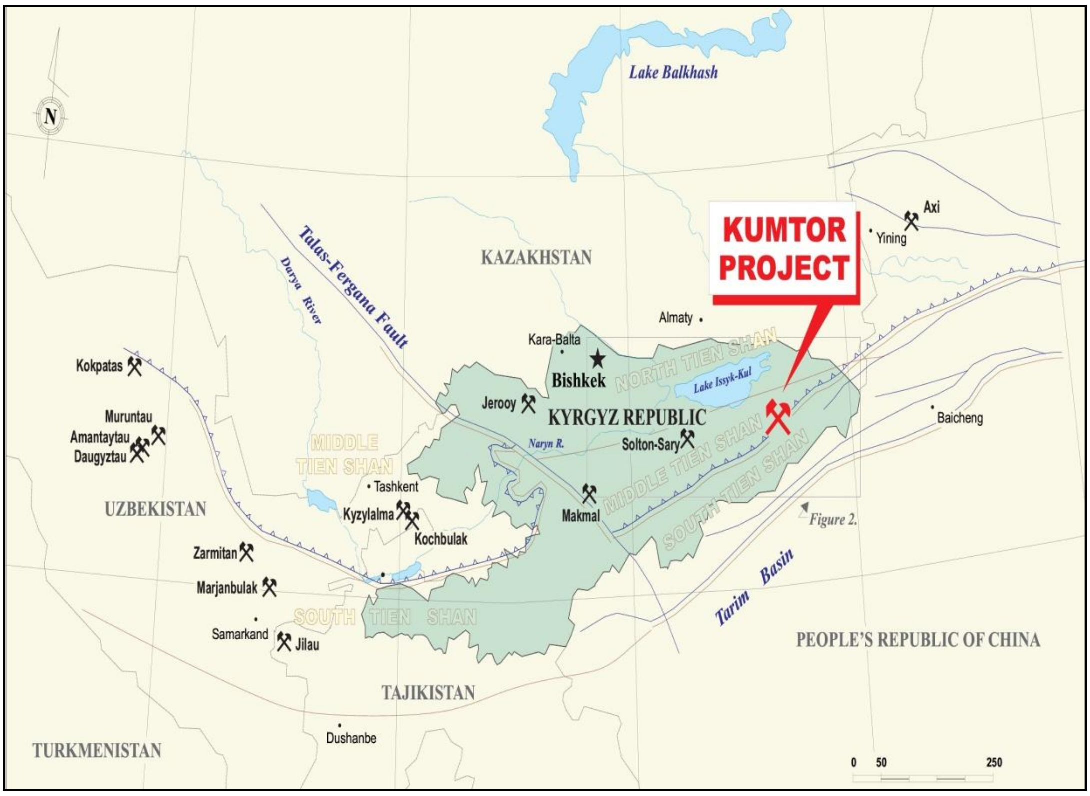

Figure 3.1 Location of mine site (Elliott et al, 2009)

Supplies are transported by rail to the Kumtor marshalling yard in Balykchy at the west end of Lake Issyk-Kul, and then trucked 250 km to the mine site. A helicopter pad is available at the mine site for emergency use.

It is the largest gold mine operated in Central Asia by a Western-based company, having produced more than 7.8 million ounces of gold between 1997 and the end of 2010.In 2010 Kumtor's gold production was 567,802 ounces. Ore processed via crushing, grinding, pyrite flotation, regrinding, CIL recovery and electrowinning.

Figure 3.2 General view of Kumtor Open Pit Gold Mine from dispatcher

3.2 Geology

3.2.1 Introduction

The Kumtor gold deposit occurs in the southern Tien Shan Metallogenic Belt, a Hercynian fold and thrust belt that traverses Central Asia, from Uzbekistan in the west through Tajikistan and the Kyrgyz Republic into north-western China, a distance of more than 1500 kilometres. Along this belt, described by Cole (1992) as "a major metallogenic province which contains many world-class mesothermal-type gold deposits", occur a number of important gold deposits including Muruntau (one of the largest gold deposits in the world), Zarmitan, Jilau and Kumtor. "The Tien Shan itself is an extremely complex fold and fault belt in which various components represent different orogenetic events that span the Phanerozoic and were later overprinted by Alpine-Himalayan deformation". This belt is located at "the margin of Palaeozoic Asia (Baltica and Siberia) [to the north] and the Palaeo-Turkestan Ocean" (Cole, 1992).

Gold mineralization has been observed over a distance of more than 12 km, with the Kumtor deposit itself located in what is called the centre block, with a length of 1,900 m, a vertical range of 1000 m and a width of up to 300 m.

3.2.2 Geological & Structural Setting

Kumtor open pit consists of four main zones, namely; Zone0, Zone1, Zone2 and Zone3 (Figure 3.3). Zone 3 is further sub- divided on structural grounds into 3 sub-zones A, B and C. Each sub-zone exhibits diagnostic structural characteristics. Zones 3A, 3B and 3C are separated by major SE dipping thrust faults (Elliott et al, 2009).

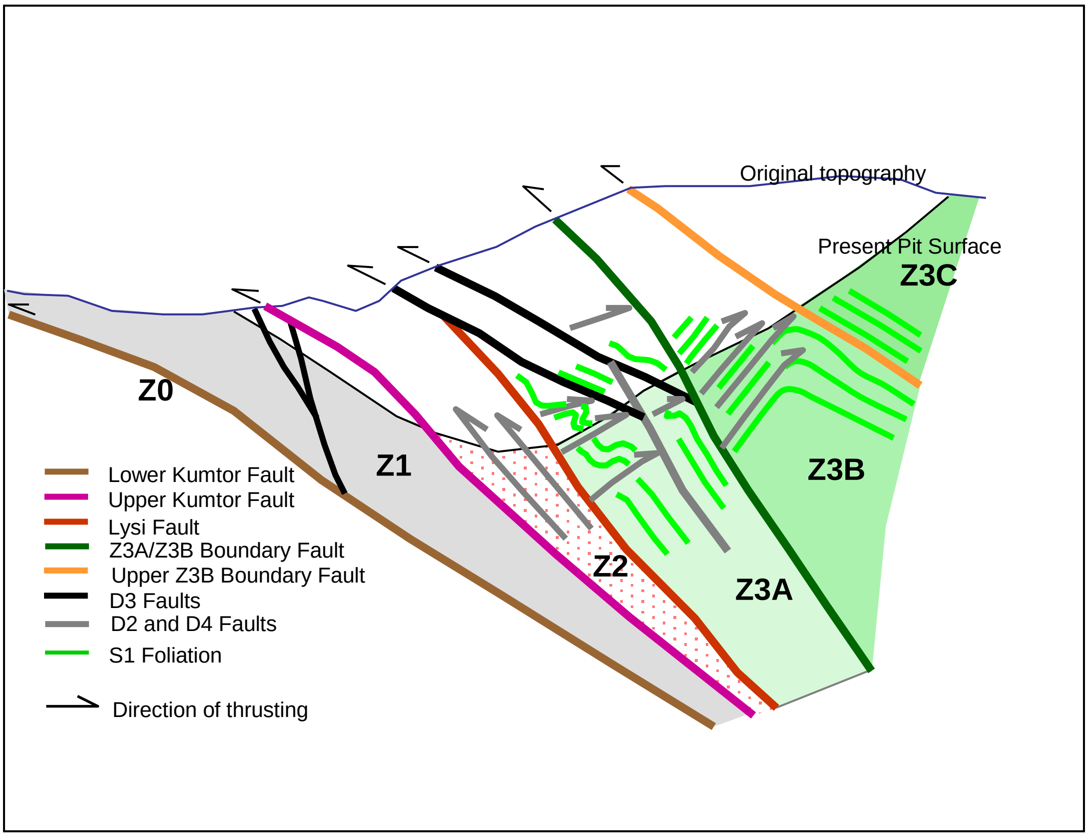

Figure 3.3 Generalized sketch representing the overall structure of the central pit area

Zone 0 is situated in the footwall to the Lower Kumtor Fault (LKF) and consists of a folded and repeated sequence of Carboniferous to Palaeocene strata.

Zone 1 constitutes the Kumtor Fault Zone (KFZ), whose upper limit is the Upper Kumtor Fault (UKF). The KFZ is generally a dark-grey to black, graphitic gouge zone, up to 600 m wide. The KFZ strikes north-easterly, dips to the SE at moderate angles and has a width of up to several hundred meters. The adjacent rocks in its hanging wall are strongly affected by shearing and faulting for a distance of up to several hundred meters (Elliott et al, 2009).

Zone 2 is situated in the hanging wall to the UKF and the footwall to the Lysi Fault (LF) as can be seen in Figure 3.4. Zone 2 composed of both phyllites and metasomatised rock or mineralized stock-work and hosts the main ore-bearing rocks of the region. Zone 2 is also referred to as the mineralized stock-work zone.

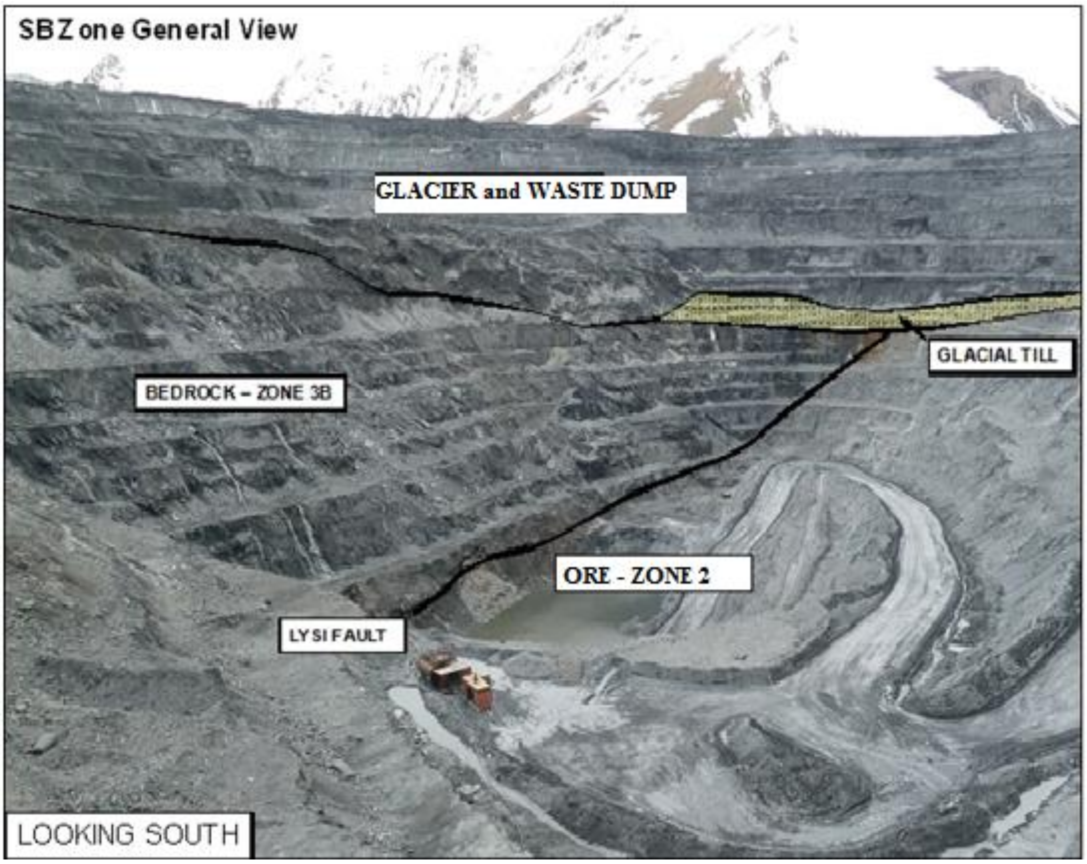

Figure 3.4 SB zone general view

Zone 3 consists of phyllites, also of Vendian age, that show several phases of folding. The dip of the schistosity is shallow to steep to the northwest or shallow to towards to the southeast. The subsequent brittle deformation is less strongly developed as in Slices 1 and 2. Slice 3 is sub-divided into three units based on the orientation of the foliation (Elliott et al, 2009).

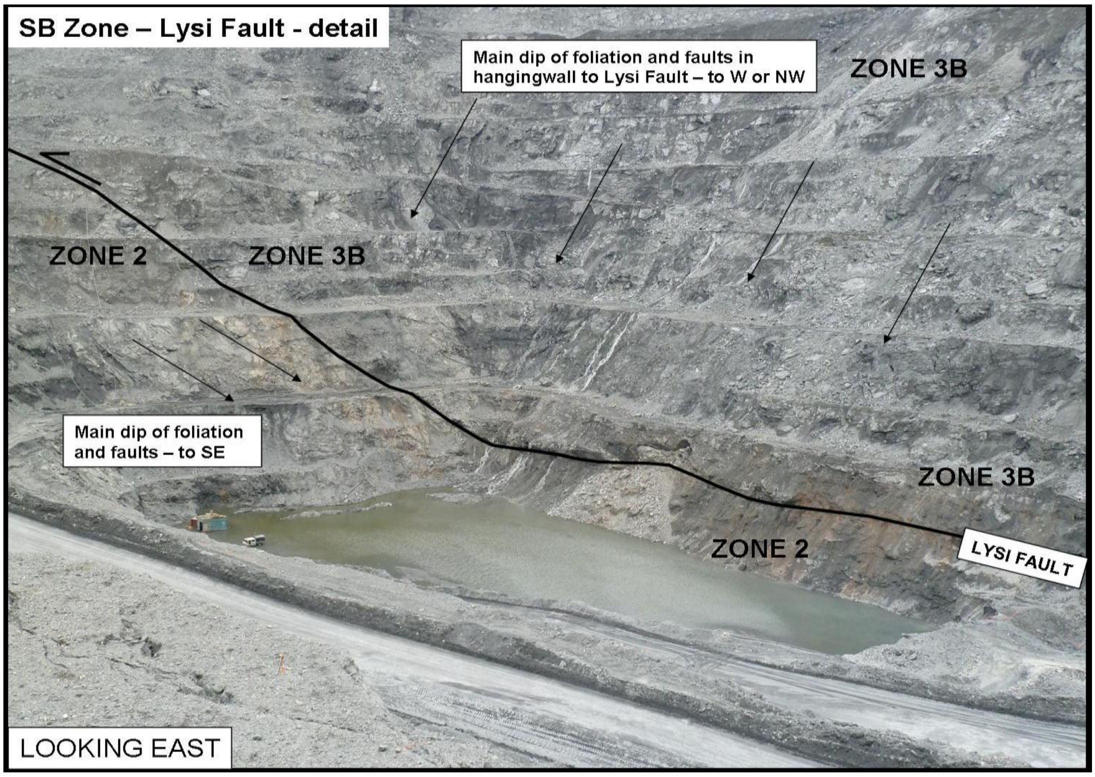

Figure 3.5 Zone 2 general view

Zone 3 is further sub- divided on structural grounds into 3 sub-zones A, B and C. Each sub-zone exhibits diagnostic structural characteristics. Zones 3A and B are separated by a major SE dipping fault. Zone 3B is represented by phyllite and carbonate-containing phyllite of dark-grey, locally hosting horizons of carbon-containing phyllite (Elliott et al, 2009).

3.2.3 Rock Mass Properties

3.2.3.1 Zone 1 (Foot Wall of Kumtor Fault Zone)

This zone characterizes the bottom of an extensive tectonic structure (overthrust). The zone's thickness is not consistent. In the south pit area it gets to 30-50 m wide whereas in the north pit area - up to 200-250 m. The zone is mainly composed by black carbonaceous phyllites. The rocks are considerably displaced, boudinaged and graphitized. Locally this zone's rocks contain considerable amounts of rock inclusions from other structural zones as boudinages, lenses and thin tectonic plates (Elliott et al, 2009). Rock mass properties supplied by Kumtor engineering department are given below:

- Rock density: 2.6 g/cm^3
- Uniaxial compressive strength of rock material (UCS): 15 MPa
- Rock Quality Designation (*RQD*) : 15 %
- Spacing of discontinuities: < 60 mm
- Condition of discontinuities: Slicken sided surfaces, or gouge less than 5 mm thick.
- Groundwater conditions: Between none to 25 l/meter of tunnel length
- Orientation of discontinuities: Zone 1-dip to SE, (at 50-60 deg);

3.2.3.2 Zone 2 (Ore Bearing Zone)

Zone 2 is highly sheared and consists of numerous parallel faults. The main rock type is ore metasomatite. Table 3.1 represents the rock mass classification of Zone 2. Rock mass properties supplied by Kumtor engineering department are given below are given as follows:

- Rock density: 2.92 g/cm^3
- Uniaxial compressive strength of rock material (UCS): 40 MPa
- Rock Quality Designation (*RQD*) : 40 %
- Spacing of discontinuities: 60 - 100 mm
- Condition of discontinuities: slightly rough surfaces, separation < 1 mm, highly weathered walls.
- Groundwater conditions: Between none to 25 l/meter of tunnel length
- Orientation of discontinuities: Zone 2-dip to SE, (at 50-60 deg)
- Shear Modulus (G) : 18 GPa

- Bulk Modulus (K) : 26 GPa
- Poisson's ratio : 0.22
- Modulus of Elasticity (E)   : 56 GPa
- Ultrasound P-wave velocity : 4513 m/s
- Ultrasound S-wave velocity: 2685 m/s

Table 3.1 Classification Parameters and Ratings for Zone 2

Parameter	**Zone 2**	**Rating**
UCS	40 MPa	4.5
RQD	40 %	8
Spacing of discontinuities	60-100 mm	5.5-6.5
Condition of discontinuities	Slightly rough surfaces , separation<1mm,highly weathered walls	20
Ground water conditions	Between none to 25 l/m of tunnel length	15-0
Orientation of discontinuities	Dip to SE at 50-60 deg.	-5
Total ratings	RMR	48-34

3.2.3.3 Zone 3 (Hanging Wall Zone)

Zone 3 is dominated by sediments metamorphosed to green schist facies which produces a sequence of phyllites and slates - phyllites being the most common rock unit in Zone 3. Main rock type for Zone 3B is carbonate-containing phyllite of dark-grey. Rock mass classification of Zone 3B is represented in Table 3.2. General rock mass properties supplied by Kumtor engineering department are given below:

- Rock density: 2.88 g/cm^3
- Uniaxial compressive strength of rock material (UCS): 50-70 MPa
- Rock Quality Designation (*RQD*) : 50-60 %
- Spacing of discontinuities: 100- 200 mm

- Condition of discontinuities: slightly rough surfaces, separation < 1 mm, highly weathered walls
- Groundwater conditions: Between none to 25 l/meter of tunnel length
- Orientation of discontinuities Zone 3A-dip to SE, Zone 3B – dip to NW (at 50-60 deg)
- Shear Modulus (G) : 19 GPa
- Bulk Modulus (K) : 36 GPa
- Poisson's ratio : 0.23
- Modulus of Elasticity (E) : 58 GPa
- Ultrasound P-wave velocity : 4943 m/s
- Ultrasound S-wave velocity : 2829 m/s

Table 3.2 Classification Parameters and Ratings for Zone 3

Parameter	Zone 3B	Rating
UCS	50-70 MPa	5.5-7
RQD	50-60 %	10- 12
Spacing of discontinuities	100-200mm	6.5-8
Condition of discontinuities	Slightly rough surfaces , separation<1mm,highly weathered walls	20
Ground water conditions	Between none to 25l/m of tunnel length	15-0
Orientation of discontinuities	Dip to SE at 50-60 deg. Dip to NW at 50-60 deg.	-5
Total ratings	RMR	52- 57

3.3 Blasting Method

The Kumtor deposit is mined by using conventional open pit methods. Benches on both bedrock and ore body are drilled and blasted. Blasted material is excavated by hydraulic shovels and hauled by mine trucks. Blast design (Shotplus) software is used at Kumtor mine. Blast survey files from Gemcom are exported in AutoCad (.dxf) format and imported into Shotplus. The survey points are converted to holes within Shotplus and then used for the blast initiation design (Figure 3.6).

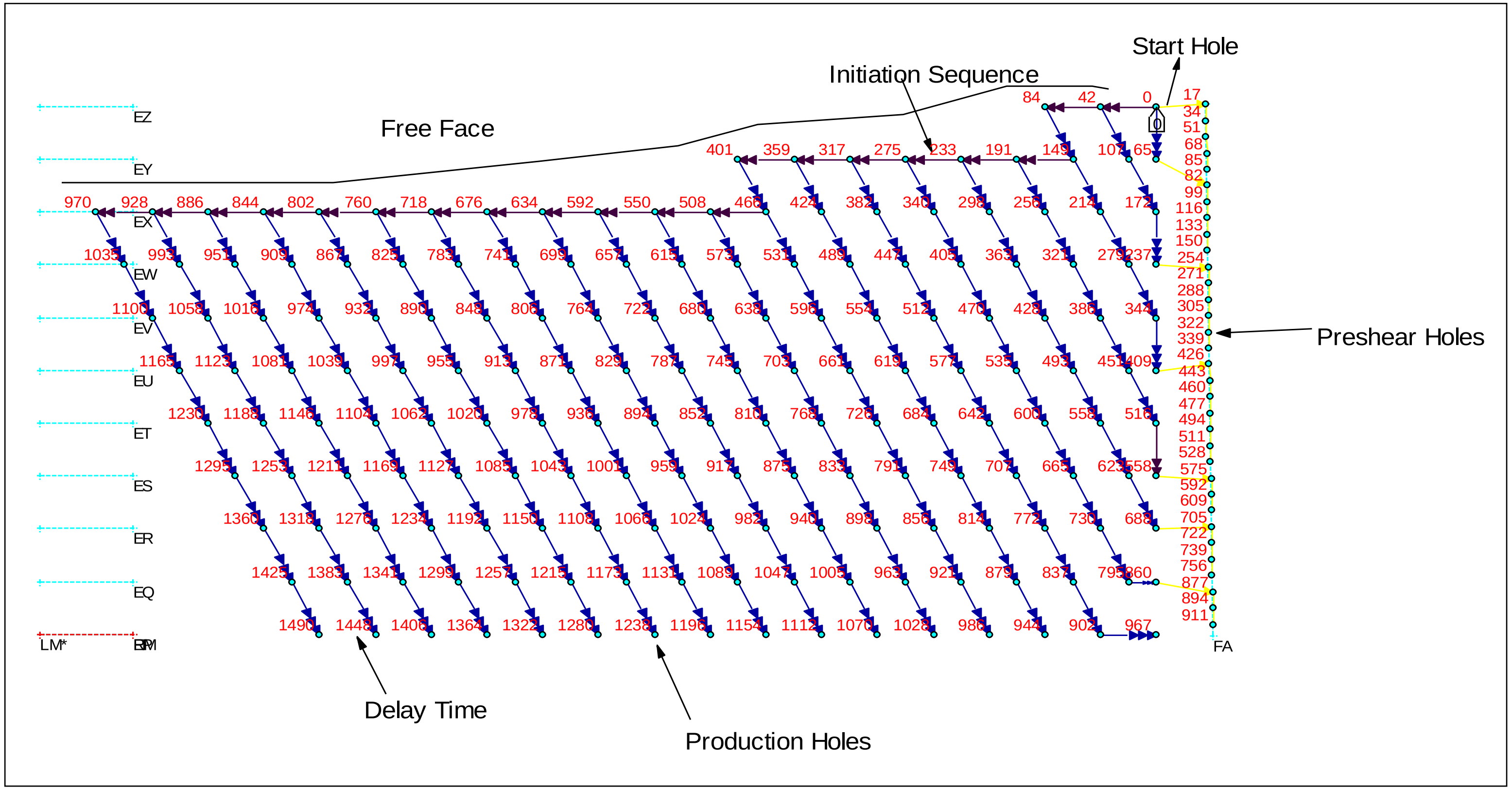

Figure 3.6 Plan view of blast pattern designed by the software

The blast parameters are determined according to existing pattern location. Bench height is 9 m and depth of the production holes varies between 9 m-11 m. Blast holes diameter depends on the area. They are 215 mm (8.5 in) in bedrock and 172 mm (6.8 in) in ore rock. Safety berms are being left every 24 meters. The preshear is being drilled at a depth of 8m with the 172 mm diameter hole. As illustrated in Figure 3.7, there are buffer holes between production and preshear holes. The depth of the buffer holes is 8.5 m. Loading practices for production holes is shown in Figure 3.8. The practice of preshear blasting improves the stability of final wall.

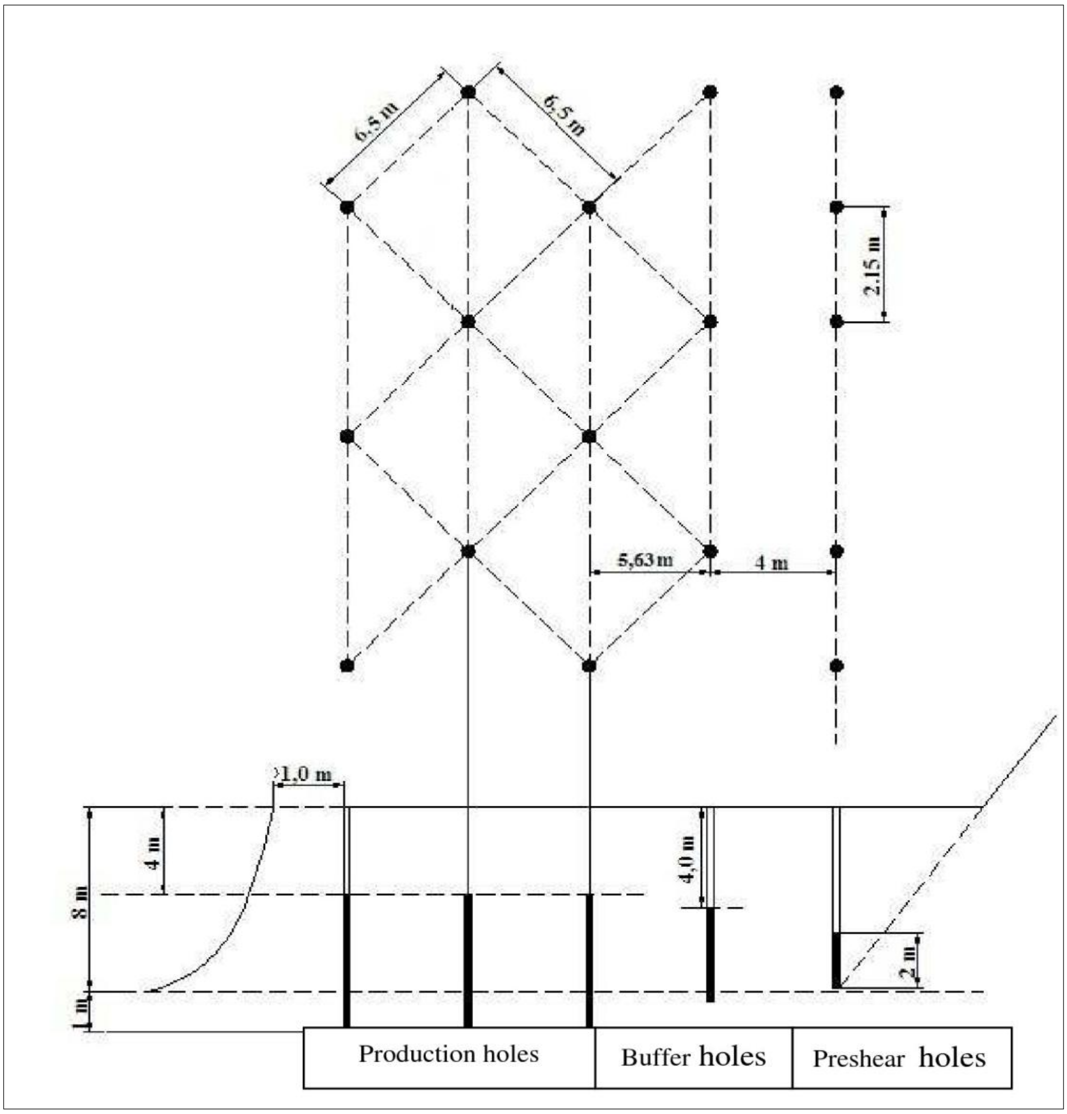

Figure 3.7 Blast pattern design in production bench (Zone 3B)

Bulk emulsion and bulk ANFO are used as blasting agents. Technical specifications for ANFO and bulk emulsion are given in Table 3.3 and Table 3.4. Wet holes and blast holes drilled in ore zone are charged by bulk emulsion. Bulk ANFO is used to load dry holes. The burden and spacing of the blast patterns change from 4.33 x 5 meters to 6.5 x 7.5 meters.

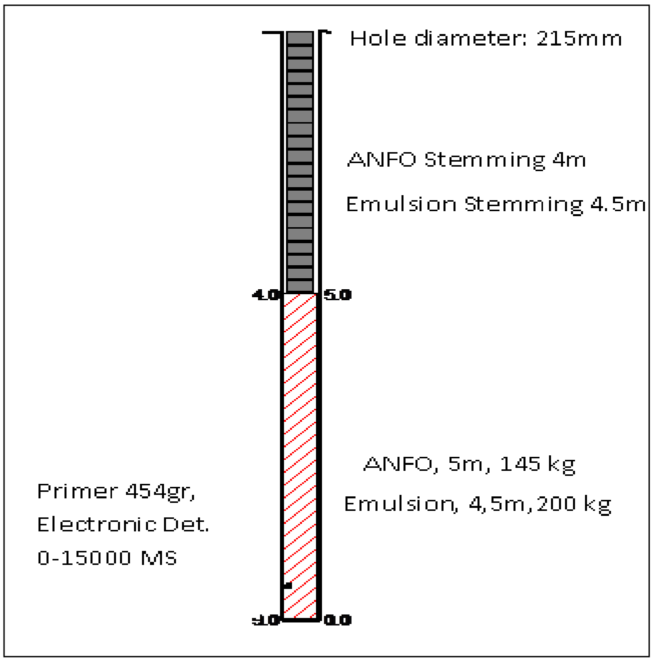

Figure 3.8 Loading practice for 215 mm blast hole

Cap sensitive 454 gr primers are used in each blast hole. Either nonelectric or electronic detonators are used to initiate primer and to tie holes. Electronic detonators are used to blast hard rock. Delay times can be varied up to 15000 ms with electronic detonators. 17 ms, 25 ms, 42 ms, 65 ms and 100 ms delay times can be given to holes by nonelectric detonators. Remote blasting system is used to initiate for both nonelectric and electronic blast patterns.

Gravel materials are used as stemming material. The diameter of the stemming material is between 15 mm - 25 mm. In order to get better confinement gravels are loaded as stemming material instead of drill cuttings.

Table 3.3 Technical specifications of bulk ANFO (Orica Mining Service website)

Property	ANFO
Density (g/cm^3)	0.8
Minimum Blasthole Diameter (mm)	76
Maximum Blasthole Depth (m)	80
Maximum Charge Length (m)	75
Water Content in Hole	Dry
Ideal VOD (km/s)	2.50 - 4.80
Relative Weight Energy	100
Relative Bulk Strength	100
Sleep Time (day)	42
CO_2 Output (kg/tonne)	182

Table 3.4 Technical specifications of bulk emulsion (Orica Mining Service website)

Property	Bulk Emulsion
Density (g/cm^3)	1.10 - 1.25
Minimum Blasthole Diameter (mm)	89
Maximum Blasthole Depth (m)	30
Maximum Charge Length (m)	25
Water Content in Hole	Dry, Wet or Dewatered
Ideal VOD (km/s)	3.9 - 6.5
Relative Weight Energy	101 - 110
Relative Bulk Strength	139 - 172
Sleep Time (day)	21
CO_2 Output (kg/tonne)	150 - 158

3.4 VOD Measurement System

The continuous resistance wire method is used during the study to measure VOD of explosives. Operation is based on the basic Ohm's law;

$$E = R \times I \qquad (3.1)$$

In Equation 3.1, where E is the voltage, R is the resistance of cable and I is the current (Chiappetta, 1998). Probecable of known linear resistance is placed axially in the explosive sample or explosive column. As the detonation front of the explosive consumes the probecable, the resistance of the circuit will decrease in proportion to the reduction in length of the probecable. The HandiTrap II records the resulting decrease in voltage across the probecable versus time. Recorded data is automatically converted into a graph of distance versus time. The slope of this graph at any position is the VOD of the explosive at that particular position.

3.4.1 Monitoring Procedure

HandiTrap II continuous VOD recorder which is developed by MREL group of companies is used to measure in blasthole velocity of detonation of explosives in this study. The Software is used to retrieve, display, analyze, print and export VOD data. The HandiTrap II is capable of monitoring the continuous VOD profile along the entire length of an explosives column. Components of the system include HandiTrap II, VOD probecable-HT and coaxial cable as shown in Figure 3.9.

Figure 3.9 HandiTrap II instrument and accessories

Preparation of probecable for single blasthole VOD recording is schematically represented in Figure 3.10.

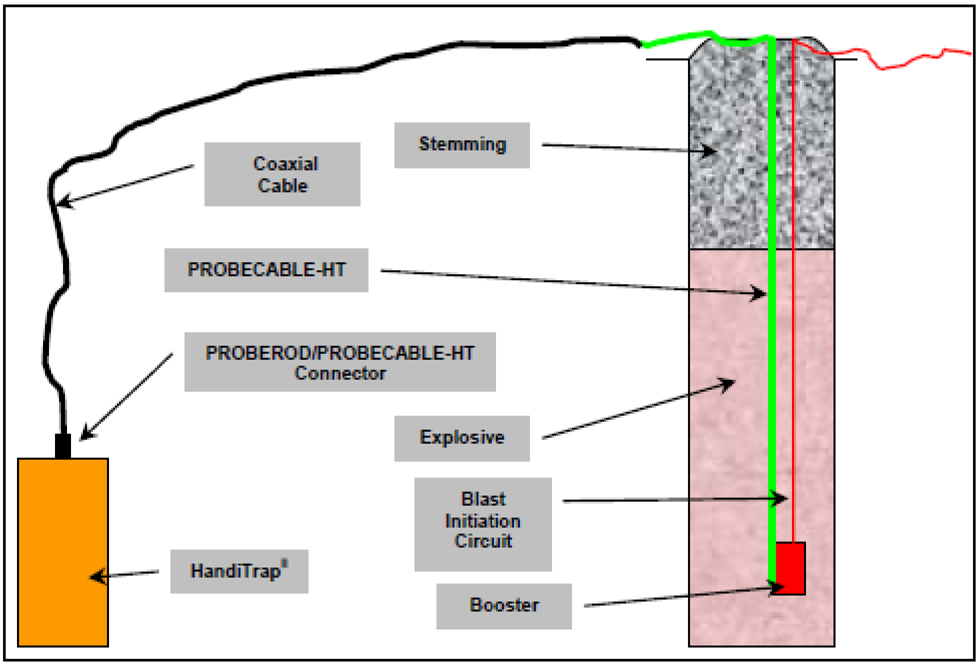

Figure 3.10 Schematic illustration of VOD measurement in a blasthole

Main steps of installing probecable to measure VOD of explosives in blasthole are shown in Figure 3.11 and listed as follows.

a. Make one end of the probecable short circuit and attach this end of the cable to a rock or primer and lower it on the side of the hole opposite to shock tube down line. Shock tube can damage the probecable during initiation and prevents to get proper record during detonation of explosive. It can be taped to cable of electronic detonator, Figure 3.11 (a).

b. After loading check the resistance of probecable using galvanometer. The resistance of the probecable should be approximately 320 ohms +/- 6 ohms, Figure 3.11 (a).

c. The hole can now be loaded with explosives and stemming per usual procedure. Hold the probecable taut during the loading of explosive to avoid slack in the hole, Figure 3.11 (b).
d. Connect the probecable to the coaxial cable using the wire cutters and electrical tape.
e. Run the coaxial cable from the probecable to the HandiTrap II. Place the HandiTrap II in a protective shelter, Figure 3.11 (c).
f. The equipment now ready to measure VOD of explosive, Figure 3.11 (d).

Figure 3.11 Setting equipments to measure in hole VOD

Do not attach probe cable to the primer as a weight to lower it in the wet hole. It may float during the loading. To make sure that it is taut, wrap leftover wire around the rock and tie the probecable to that. It is important to hold probecable during loading to prevent extra cable to get pulled into the hole while loading.

3.4.2 Applications of the HandiTrap II

The main applications of the HandiTrap II to test explosives in a blasthole include (MREL, 2010):

- Measurement of VOD in any hole diameter, wet or dry holes, and in any type of rock.
- Prediction of whether full detonation, low order detonation or failure occurred, and where in the explosive column it happened.
- Prediction of the minimum primer size for any explosive by measuring run-up velocities in full scale blasting environments.
- Measurement of the timing accuracy of detonators in a decked hole in full scale blasting environments.
- Measurement of the effects of water, drill cuttings, and rocks, etc. trapped within the explosive mass.
- Determination of the length of explosive column to use in decking operations to evaluate the effect of stemming and drill cutting dilution, water pick-up, on the explosive run-up requirements.
- Delay time between blast holes can be determined.

3.4.3 HandiTrap II Technical Specifications

The specifications of the HandiTrap II continuous VOD recorder are summarized below (MREL, 2010):

- The HandiTrap II is a portable, 1 channel, high resolution, and explosives continuous VOD recorder.
- It mainly consists of VOD recorder (HandiTrap II), coaxial cable and probecable. Components provided by HandiTrap II are 120 or 230 VAC Battery Charger, serial port Communications Cable, USB Cable, color Operations Manual, HandiTrap II Advanced Analytical Software for Windows, HandiTrap II Software for the PalmTM Operating System.

– Pre trigger time of the instrument is 32.8 milliseconds (32,768 data points), total recording time is 131 milliseconds (131,072 data points).
– Vertical resolution of the HandiTrap II is 12 bits, 1 part in 4,096 and recording rate is 1 MHz.
– HandiTrap II can be triggered internally, automatically on the VOD signal from the blast. Can be triggered externally from a break-wire, which also allows multiple HandiTraps to be time synchronized for determining delay times between holes.
– The Battery Charger is either 120 VAC or 230 VAC and can be charged overnight which provides 8 hours of active operation.
– Size of the HandiTrap II is 12 x 6.5 x 4 cm and weight is 0.3kg.
– It operates at -40 to +80 C (-40 to +185 F). Snow, rain, dust and sand proof. Drop proof from at least a 1 m (3 ft) height.

The Software allows unlimited graphical zoom on graphs, creation of annotated sub-graphs and VOD analyses of any parts of the VOD graph and determination of delay times between decks of explosives. The user can select metric (m/s) or imperial (ft/sec) units. Figure 3.12 shows a line plot of distance versus time for the complete duration of a VOD test.

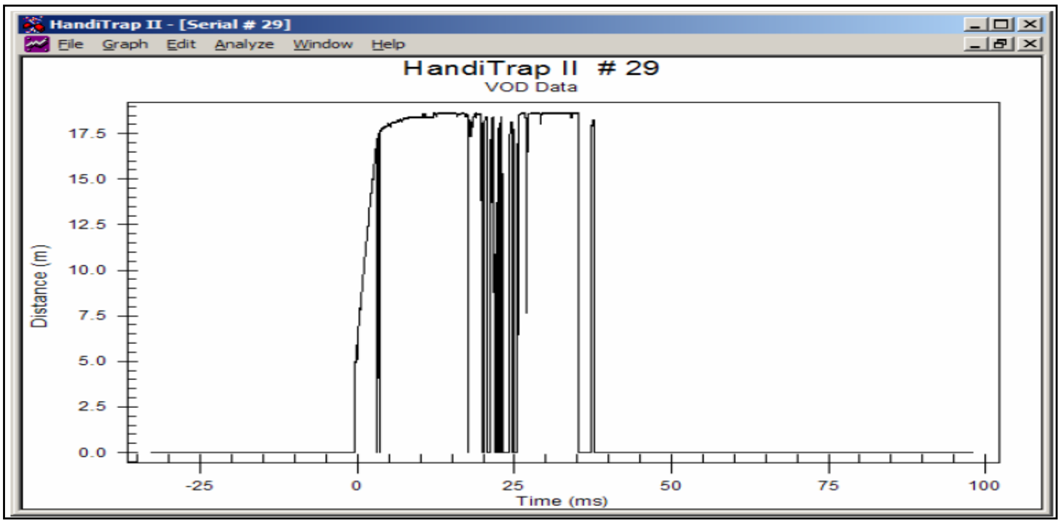

Figure 3.12 Line plot for the complete duration of VOD test

Using the zoom tool the user can focus on the area of the explosives detonating in the blasthole.

Figure 3.13 shows results from zooming in on the data of interest. The Software calculates the VOD by conducting a linear regression on the data contained between two data points chosen by the user.

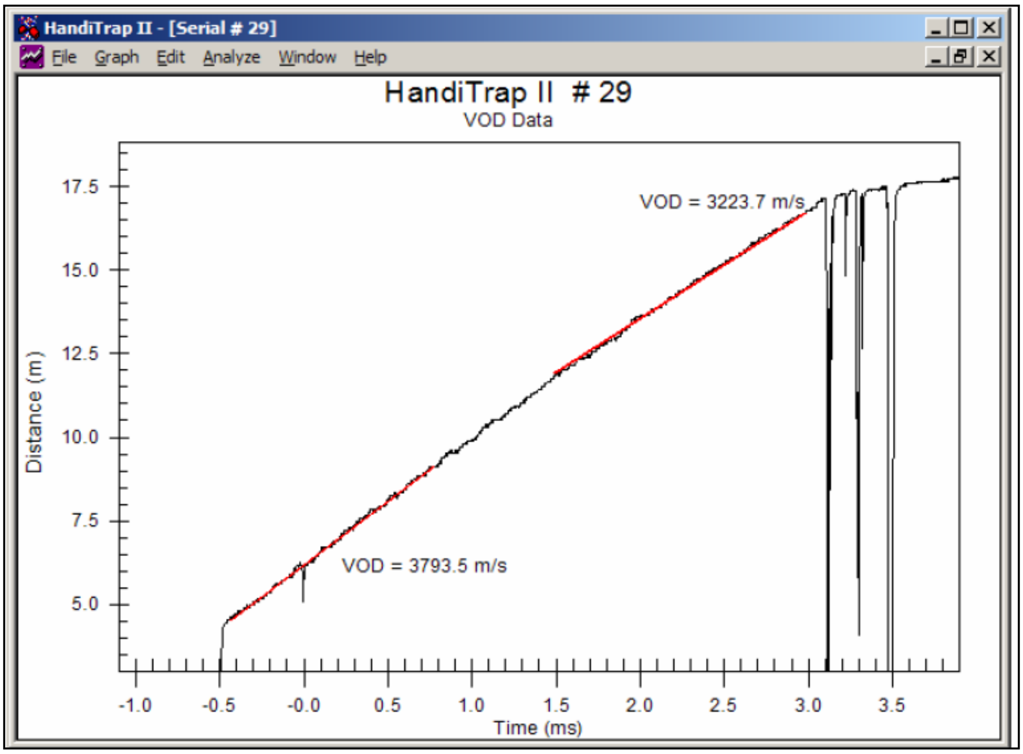

Figure 3.13 Final VOD plot drawn by the help of Software

3.5 Mobile Manufacturing Units

ANFO and emulsion based blasting agents now dominate the market because of their high efficiency and moderately price (Persson et al, 1994). A Mobile Manufacturing Unit (MMU-Bulk Trucks) mixes emulsion with the ANFO and then loads emulsion directly at the blast site and sensitizes the final product with the gassing solution during pumping.

Ratio of the ANFO and emulsion in the blend can be adjusted according to rock properties to be blasted. Explosives with a high VOD are well suited for blasting in competent rocks. On the other hand explosives with a low VOD are better suited for soft rocks. As seen in Figure 3.14 the more the percentage of emulsion, the more VOD of explosive. Consequently, to blast competent rock, it is better to increase percentage of the emulsion in the blend. Percentage of the emulsion can be decreased to blast soft rocks.

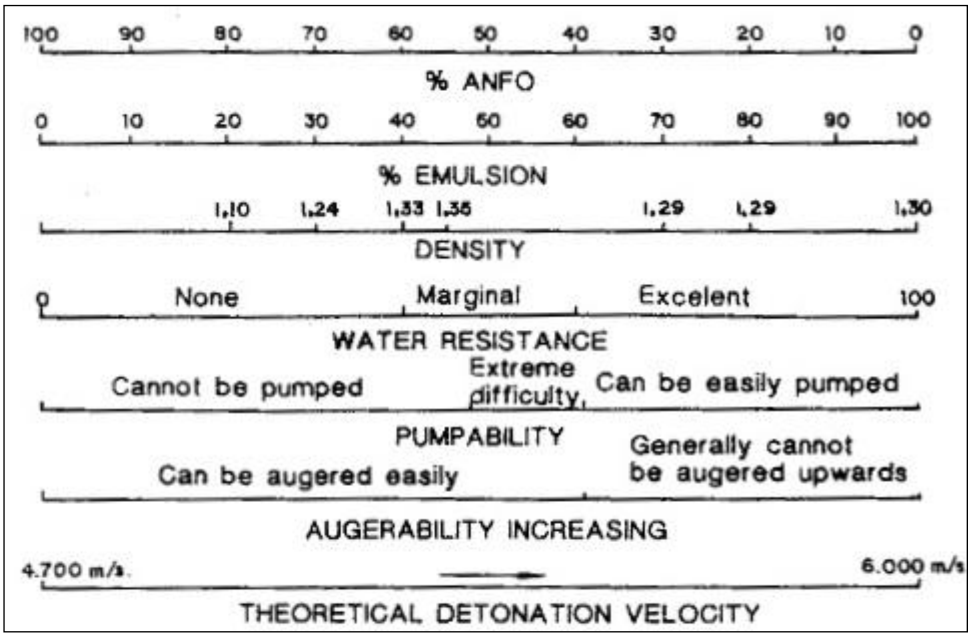

Figure 3.14 Charging and main charachteristics of different types of blends (Jimeno and Carcedo, 1995)

Three different bulk trucks were used as explosive charging equipment throughout the study. Bulk emulsion was charged with two different types of MMUs (Figure 3.15). Calibration of one type of this equipment was carried out manually and other one was calibrated automatically. Manual calibration is conducted by a valve which adjusts the proportion of ANFO and matrix in bulk emulsion.

Figure 3.15 Bulk emulsion trucks

Automatic calibration follows a certain procedure which can be summarized below:

- First, the CLEAR/BLEND/ANFO selector is moved to the "ANFO" position so that matrix flow is prevented.
- Then 100 kg of ANFO sample is taken according electronic box reading (EBR) to be weighed.
- Measured weight is compared with electronic box record.
- According to difference between measurements calibration factor is calculated as in equation 3.2;

$$Calibration\ Factor = \frac{Scale\ Reading}{EBR} \qquad (3.2)$$

- This factor is used as an input in electronic box prior to second reading.
- Same procedure is followed until EBR equals scale reading.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Measurement of In-situ Detonation Velocity

The continuous resistance wire method is employed to measure in hole detonation velocity of explosives. VOD measurements were carried out for two different bulk explosives which are ANFO and Emulsion. In order to study how blast hole diameter effect detonation velocity of an explosive measurements were carried out at two different diameters. Hole diameters were 172 mm and 215 mm. The effect of confinement on detonation velocity was also evaluated for a given explosive and blast hole diameter.

Start hole of each blast round was used as VOD measurement. The purpose of selecting the first hole as the test hole is to prevent damage on probe and coaxial cable due to fly rock. All blast holes were bottom initiated and cap sensitive 454 gr primers were used to initiate explosive in each blast hole. Both non electric and electronic initiation systems are utilized for the initiation of primer.

In general, VOD measurements for explosives were made along 4-5 meters length of explosive column as shown in Figure 4.1. A line plot of distance versus time is shown in the graph. The hole depth was 9m, 5m was charged with bulk ANFO and the stemming was 4m. The primer was loaded into the hole at a distance of approximately 1m from the bottom of the blast hole. As seen in the Figure 4.1 when the primer was initiated it immediately cut off 1m of probe cable. The remainder of the explosive column above the primer position consumes the probecable. When the stemming position is met the rate of change of length of probecable changes dramatically as can be expected.

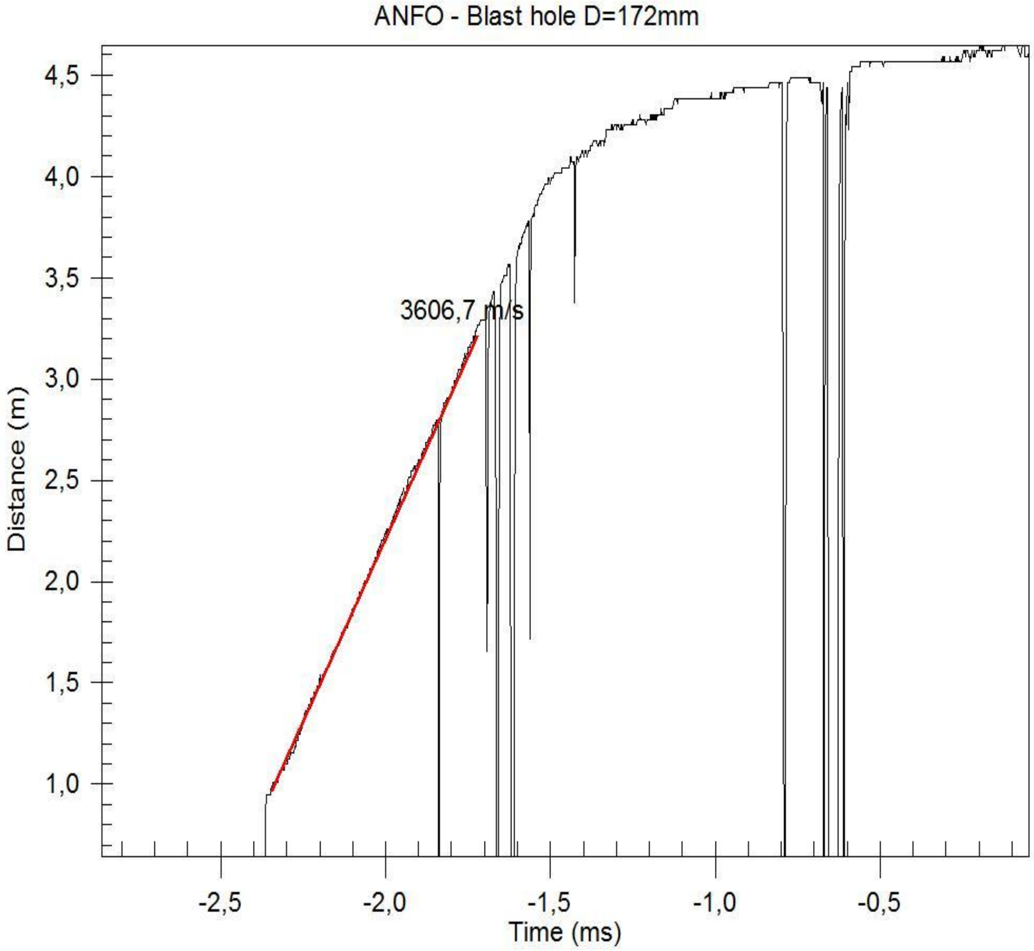

Figure 4.1 VOD result for bulk ANFO in blast pattern 3834-45a

Table 4.1 gives details of the experimental holes and the corresponding VOD results. In table; blast hole no, blast hole condition, blast pattern no, hole diameter, hole length, burden, spacing, stemming length, explosive type, explosive column length, explosive column weight, primer weight, blast hole location, P and S wave velocities of rock, VOD of explosives, and rock type are given.

Table 4.1 Summary of VOD results

Test #	Test Hole	Date	Blast Ref	Hole Diameter (mm)	Hole Length (m)	Burden (m)	Spacing (m)	Stemming Length (m)	Explosive Type	Explosive Column Length (m)	Explosive Column Weight (Kg)	Primer Weight (gr)	Blast Hole Location Type	P waves (m/s)	S Waves (m/s)	VOD (m/s)	Rock Type
1	Dry	18.06.2010	3834-45a	172	9	5.20	6	4	ANFO	5	93	454	Zone 3B	4943	2829	3606	carbonate-containing phyllites
2	Wet	16.06.2010	3834-45	172	9	5.20	6	4	Emulsion	5	140	454	Zone 3B	4943	2829	5356	carbonate-containing phyllites
3	Dry	30.09.2010	3810-59a	215	9	5.20	6	4	ANFO	5	145	454	Zone 3B	4943	2829	4102	carbonate-containing phyllites
4	Wet	26.09.2010	3810-59	215	9.2	5.20	6	4.2	Emulsion	5	220	454	Zone 3B	4943	2829	5894	carbonate-containing phyllites
5	Wet	28.09.2010	3810-60a	215	9.2	5.20	6	4.2	ANFO	5	145	454	Zone 3B	4943	2829	3544	carbonate-containing phyllites
6	Wet	01.12.2010	3754-11	172	8	4.33	5	4	Emulsion	4	112	454	Zone 2	4513	2683	5181	Ore Metasomatite
7	Wet	26.11.2010	3746-11	215	8	4.33	5	4	Emulsion	4	174	454	Zone 2	4513	2683	5518	Ore Metasomatite
8	Wet	28.11.2010	3746-9	215	8	4.33	5	4	Emulsion	4	174	454	zone 2	4513	2683	5500	Ore Metasomatite
9	Wet	02.01.2011	3706-2	215	8	4.33	5	4	Uncalibrated Emulsion	4	174	454	zone 2	4513	2683	6300	Ore Metasomatite
10	Wet	08.01.2011	3746-13	172	8	4.33	5	4	Emulsion	4	112	454	Zone 2	4513	2683	5131	Ore Metasomatite

Table 4.1 continued

Test #	**Test Hole**	**Date**	**Blast Ref**	**Hole Diameter (mm)**	**Hole Length (m)**	**Burden (m)**	**Spacing (m)**	**Stemming Length (m)**	**Explosive Type**	**Explosive Column Length (m)**	**Explosive Column Weight (Kg)**	**Primer Weight (gr)**	**Blast Hole Location Type**	**P waves (m/s)**	**S Waves (m/s)**	**VOD (m/s)**	**Rock Type**
11	wet	15.01.2011	3706-1	172	9.5	4.33	5	4	Emulsion	5.5	154	454	zone 2	4513	2683	5160	Ore Metasomatite
12	Dry	02.03.2011	3906-347	215	9	5.20	6	4	ANFO	5	145	454	Zone 3B	4943	2829	4038	carbonate-containing phyllites
13	Ice 1	09.03.2011	3898-328	215	10	5.20	6	4	ANFO	6	174	454	Ice Bench	3300-3600	800-1500	3297	Glacier
14	Wet	11.03.2011	4098-200b	172	8	5.20	6.0	4	Emulsion	4	112	454	Zone 3B	4943	2829	5331	carbonate-containing phyllites
15	Ice 2	17.03.2011	3890-322	215	9	5.20	6	3	ANFO	6	174	454	Ice Bench	3300-3600	800-1500	3267	Glacier
16	Dry	19.03.2011	4002-308	215	10	5.20	6	4	Uncalibrated Emulsion	6	245	454	Zone 3B	4943	2829	6769	carbonate-containing phyllites
17	Ice 3	23.03.2011	3890-333	215	9	5.20	6	4	ANFO	5	140	454	Ice Bench	3300-3600	800-1500	3197	Glacier
18	Wet	25.03.2011	3882-262	215	9	4.33	5	4	Emulsion	5	220	454	Zone 2	4513	2683	5504	Ore Metasomatite
19	Dry	29.03.2011	3882-264a	215	9	4.33	5	4	ANFO	5	140	454	Zone 2	4513	2683	3810	Ore Metasomatite
20	Dry	30.03.2011	3750-112	172	9	4.33	5	3	ANFO	6	174	454	Zone 2	4513	2683	3430	Ore Metasomatite

Table 4.1 continued

Test #	Test Hole	Date	Blast Ref	Hole Diameter (mm)	Hole Length (m)	Burden (m)	Spacing (m)	Stemming Length (m)	Explosive Type	Explosive Column Length (m)	Explosive Column Weight (Kg)	Primer Weight (gr)	Blast Hole Location Type	P waves (m/s)	S Waves (m/s)	VOD (m/s)	Rock Type
21	Dry	07.04.2011	4082-299	215	9	4.33	5	3	ANFO	6	174	454	Zone 3B	4943	2829	4126	carbonate-containing phyllites
22	Ice 4	30.04.2011	3858-177	215	6.5	4.33	5	3	ANFO	3.5	98	454	Ice Bench	3300-3600	800-1500	3206	Glacier
23	Wet	02.05.2011	3850-99a	172	9	5.63	6.5	4	Emulsion	5	140	454	Zone 3B	4943	2829	5365	carbonate-containing phyllites
24	Dry	04.05.2011	3746-35	215	9	5	5	4	ANFO	4	140	454	Zone 2	4513	2683	3819	Ore Metasomatite
25	Wet	07.05.2011	3842-145	172	9	5.63	6.5	4	Emulsion	5	140	454	Zone 3B	4943	2829	5305	carbonate-containing phyllites
26	Dry	09.05.2011	3842-145a	215	9	5.63	6.5	4	ANFO	5	140	454	Zone 3B	4943	2829	4150	carbonate-containing phyllites
27	Dry	10.05.2011	3834-107	172	9	5.63	6.5	3	ANFO	5	174	454	Zone 3B	4943	2829	3572	carbonate-containing phyllites
28	Dry	13.05.2011	3834-110	215	10	5.63	6.5	4	ANFO	6	208	454	Zone 3B	4943	2829	4035	carbonate-containing phyllites
29	Wet	17.05.2011	3834-300a	215	9	5.63	6.5	4	Emulsion	5	220	454	Zone 3B	4943	2829	5751	carbonate-containing phyllites
30	Dry	20.05.2011	3746-116	172	9	4.33	5	4	ANFO	5	174	454	Zone 2	4513	2683	3413	Ore Metasomatite

Table 4.1 continued

Test #	Test Hole	Date	Blast Ref	Hole Diameter (mm)	Hole Length (m)	Burden (m)	Spacing (m)	Stemming Length (m)	Explosive Type	Explosive Column Length (m)	Explosive Column Weight (Kg)	Primer Weight (gr)	Blast Hole Location Type	P waves (m/s)	S Waves (m/s)	VOD (m/s)	Rock Type
31	Dry	21.05.2011	4002-394	215	9	5.63	6.5	4	ANFO	5	174	454	Zone 3B	4943	2829	4139	carbonate-containing phyllites
32	Wet	02.07.2011	3802-60	215	9	4.33	5	5	Emulsion	4	176	454	Zone 2	4513	2683	5536	Ore Metasomatite
33	Wet	04.07.2011	4040-6b-7b	172	11	5.63	6.5	5	Emulsion	6	200	454	Zone 3B	4943	2829	5351	carbonate-containing phyllites
34	Dry	05.07.2011	3794-55a	172	10	4.33	5	5	ANFO	5	150	454	Zone 2	4513	2683	3400	Ore Metasomatite
35	Dry	11.07.2011	3794-63	215	9	4.33	5	5	ANFO	4	140	454	Zone 2	4513	2683	3834	Ore Metasomatite
36	Wet	15.07.2011	3786-53	215	11	5.20	6	5	Emulsion	6	246	454	Zone 2	4513	2683	5545	Ore Metasomatite
37	Wet	16.07.2011	3786-52	215	9.8	6.50	7.5	4	Emulsion	5.8	237	454	Zone 3B	4943	2829	5820	carbonate-containing phyllites
38	Wet	19.07.2011	3754-57	172	9	5.20	6	4	Emulsion	5	140	454	Zone 2	4513	2683	5137	Ore Metasomatite
39	Dry	21.07.2011	3778-62	172	9	5.20	6	4	ANFO	5	150	454	Zone 3B	4943	2829	3635	carbonate-containing phyllites

65 VOD measurements test were carried out during the study. 26 of them were not successfully evaluated. Following mistakes that were observed during measurements should be considered by researches for future studies:

- If probe cable is attached to primer, it must be sure that tape is wrapped around primer to keep the probe cable from sliding off
- It should be checked whether the holes are filled from the top or the bottom. The primer may be floating during loading. This is an extra reason to attach the probe cable to a very heavy rock before anything else is placed in the hole.
- The probe cable should be held in place or wrapped around a stick in the ground so that it does not get pulled extra into the hole while loading.
- Connection points between coaxial cable and probe cable should be regularly checked using continuity mode to make sure it is not damaged. If it has been pulled with a lot of force or bent sideways strongly, it can become unreliable.
- Always avoid placing probe cable close to surface initiators and shock tubes.

4.2 Influence of Explosive Type on VOD of an Explosive

In order to study effect of explosive type on detonation velocity, several experiments were conducted at Kumtor gold open pit mine. The main explosives used for VOD measurements were bulk ANFO and Bulk Emulsion. The detonation velocities of two explosives were evaluated in different rocks that are under different confinement. In situ measured average VOD of explosives in Phyllite and Ore Metasomatite are given in Table 4.2. All test results are presented graphically in Figure 4.2 and Figure 4.3.

Table 4.2 Effect of explosive type on VOD in phyllite and ore metasomatite

Blast hole diameter (mm)	Average VOD in Phyllite (m/s)	Average VOD in Ore Metasomatite (m/s)	Explosive Type
172	3604	3414	Bulk ANFO
215	4098	3821	Bulk ANFO
172	5341	5152	Bulk Emulsion
215	5821	5520	Bulk Emulsion

Detonation velocity measurements for each explosive are carried out at the equivalent confinement. Average VOD of bulk ANFO in 172 mm diameter blast hole is found to be 3604m/s in phyllite out of three measurements. On the other hand for the same blast hole diameter the average VOD of Bulk emulsion is determined as 5341m/s under the same confinement out of five records. It is understood that VOD of bulk emulsion is greater than that of bulk ANFO under the same test conditions such as the blast hole diameter and rock type.

VOD of Bulk ANFO in 215 mm hole is 4098m/s on average and VOD of bulk emulsion is 5821 m/s on average under the same confinement and blast hole diameter. It is understood once more that the average VOD of bulk emulsion is greater than that of bulk ANFO in the same rock, phyllite, but at a larger blast hole diameter.

Similarly, the VOD of bulk ANFO is always smaller than the VOD of bulk emulsion in ore metasomatite for the given blast hole diameters as shown in Table 4.2. As it is seen in Table 4.2, bulk ANFO had a VOD of 3821 m/s on average in ore metasomatite at blast hole diameter of 215mm, whereas VODs of bulk emulsion is 5520 m/s on average at same blast hole diameter. VOD values of explosives drops down to 3414 m/s on average for bulk ANFO and to 5152 m/s for bulk emulsion. Another finding is that although the rock type is the same as phyllite and ore metasomatite, the average VOD values increases, as the blast hole diameter increases for both explosive types.

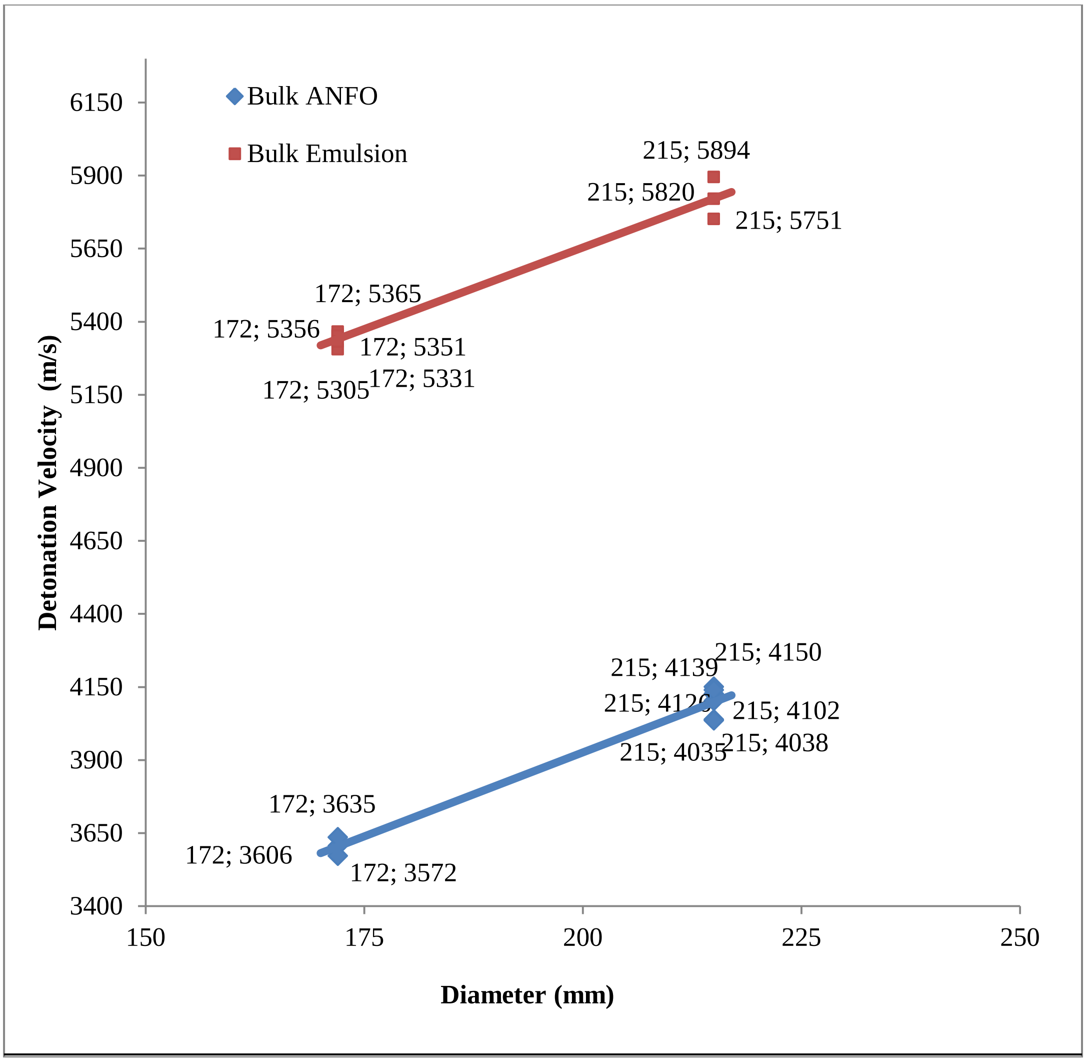

Figure 4.2 Effect of explosive type on VOD in Phyllite

As seen in Figure 4.2 and Figure 4.3 VOD of bulk emulsion is always greater than the VOD of bulk ANFO under same confinement and at same blast hole diameter.

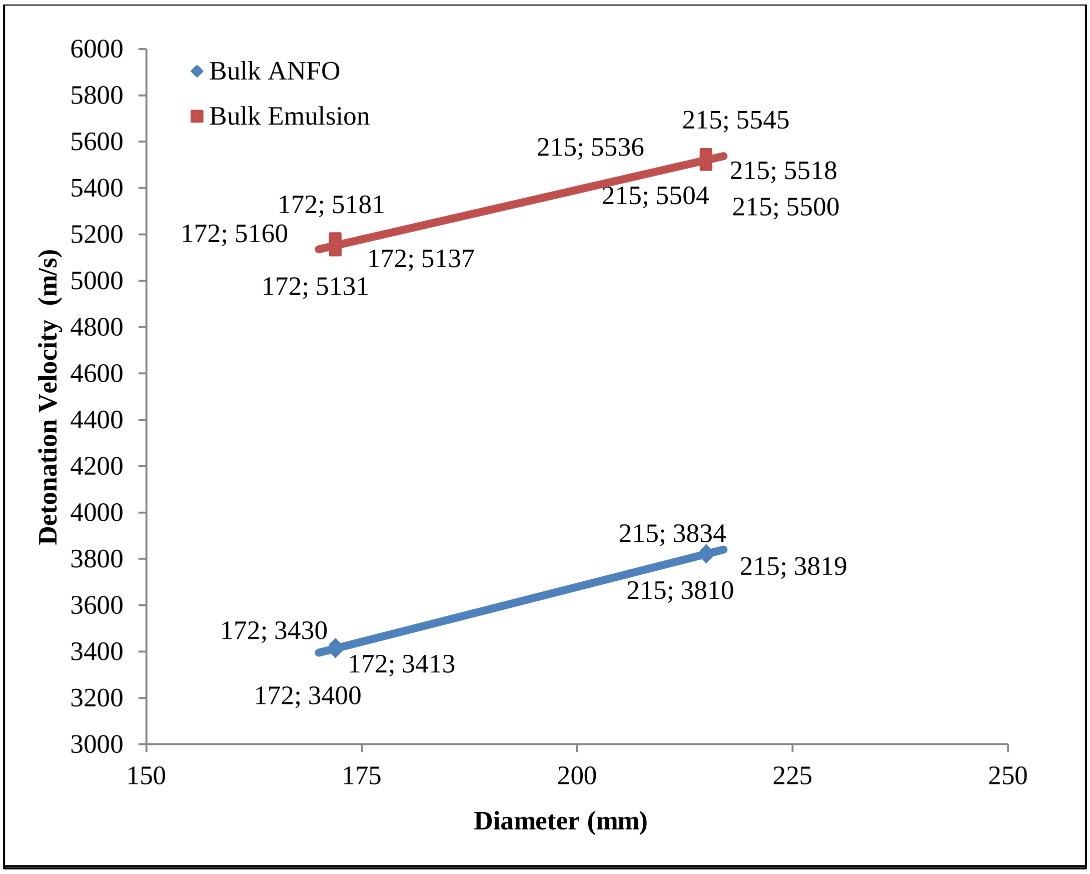

Figure 4.3 Effect of explosive type on VOD in ore metasomatite

The VOD of both bulk emulsion and bulk ANFO increases as the diameter of charge increases as it is seen from Figure 4.2 and 4.3. Another, probably most impressive finding is that bulk emulsion has always higher VOD compared to bulk ANFO for all charge sizes and for all degrees of confinement.

The higher VOD of bulk emulsion can be attributed to the following facts;

a. Density of bulk emulsion is much higher than bulk ANFO.
b. Size of explosive ingredients, such as oxidizer droplets, fuel membrane covering oxidizer droplets in bulk emulsion are smaller than bulk ANFO.
c. Gassing solution is added to bulk emulsion before loading blast hole which increases the sensitivity of explosive.

Bulk ANFO is the mixture of AN and fuel oil in comparatively bigger particle size. The size of AN particles in Bulk ANFO is 1000-3500µm. It is known that VOD of an explosive increases as the size of particles in the mixture becomes smaller. Bulk Emulsion consists of small droplets of ammonium nitrate solution, tightly packed in a fuel blend. The thickness of the fuel blends membranes separating the oxidizer droplets are about 1-10 µm. It is such a big contact surface between fuel and oxidizer that detonation velocity of a bulk emulsion becomes greater than that of bulk ANFO. The gas bubbles in the bulk emulsion also have a positive effect on VOD of explosive. They act as hot spots in the explosive which supports detonation through the explosive column.

4.3 Influence of Water on VOD of Bulk ANFO

As can be seen from the Table 4.1 VOD of bulk ANFO in test No.5 is measured as 3544m/s, in spite of the fact that the average VOD of bulk ANFO under same confinement and blast hole diameter is 4098m/s. Difference in the VOD of test No.5 is 554m/s. This difference is due to the fact that, bulk ANFO loaded into hole in a frozen ground in test No.5 and slept one day in hole, see Figure 4.4. The blast round including test hole No.5 is initiated 30 hours after the charging meanwhile the frozen ground is melted and the water wetted the bulk ANFO. Since the test hole No.5 was already stemmed, it could not be possible to take some sample and determine the percentage of water in bulk ANFO. However it is sure that the bulk ANFO was wetted, as evidenced by the emission of reddish brown colored fumes observed after the blast.

Figure 4.4 Wet hole loaded by bulk ANFO

There are some downwards pointing spikes in the VOD graph of wet hole which is shown in Figure 4.5. When wetted bulk ANFO reacts slower, there may be inefficient shorting of the probe cable. Although there are many downward spikes, the trend of VOD is apparent and can be determined.

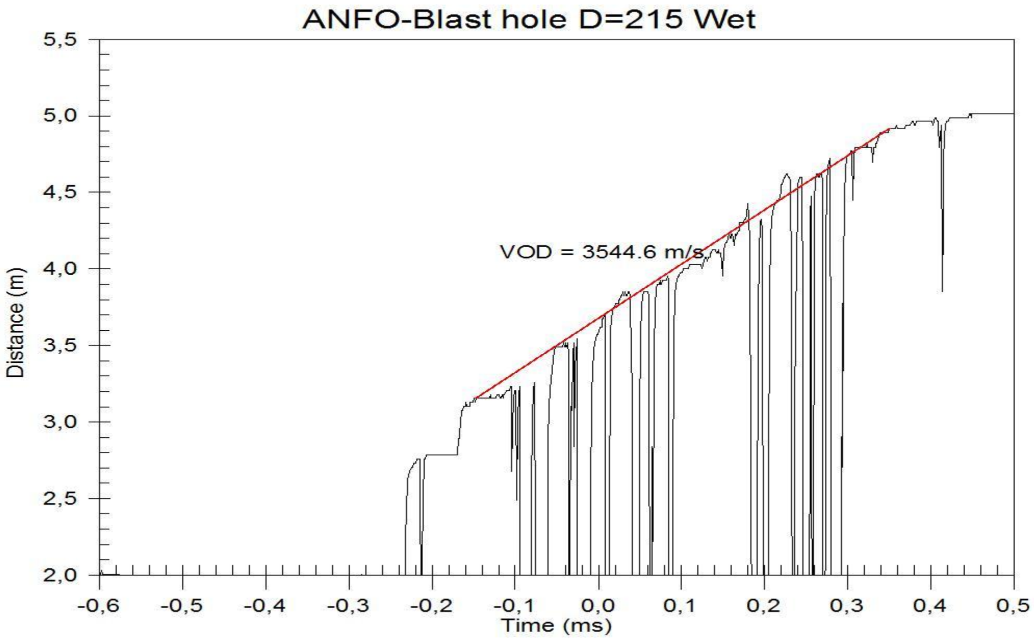

Figure 4.5 VOD result of test No. 5 in blast pattern 3810-60a

4.4 Influence of Confinement on VOD of an Explosive

It is known from the test results and the literature that there is a direct proportion between confinement of an explosive and its VOD. The effect of confinement on VOD of an explosive is evaluated under three different strata conditions in this study. The VOD measurements of bulk ANFO were carried out in phyllite, ore metasomatite and glacier. In situ VOD of bulk emulsion is measured in phyllite and ore metasomatite. The confinement provided by the medium surrounding the blast hole can be represented by the material strength and the mass strength of the medium.

The material strength properties of the medium around the blast hole can be described by density, P-wave or S-wave velocities, and UCS. P-wave and S-wave velocities of each medium are summarized in Table 4.3.

Table 4.3 P and S wave velocities of phyllite, ore metasomatite and glacier

Rock Type	P-wave Velocity (m/s)	S-wave Velocity (m/s)
Phyllite	4943	2829
Ore Metasomatite	4513	2685
Glacier	3300-3600	800-1500

Increase of P-wave velocity of the medium is directly proportional to its material strength and mass strength. As it is seen in Figure 4.6 VOD of both explosives decreases as the P-wave velocity of the surrounding medium decreases.

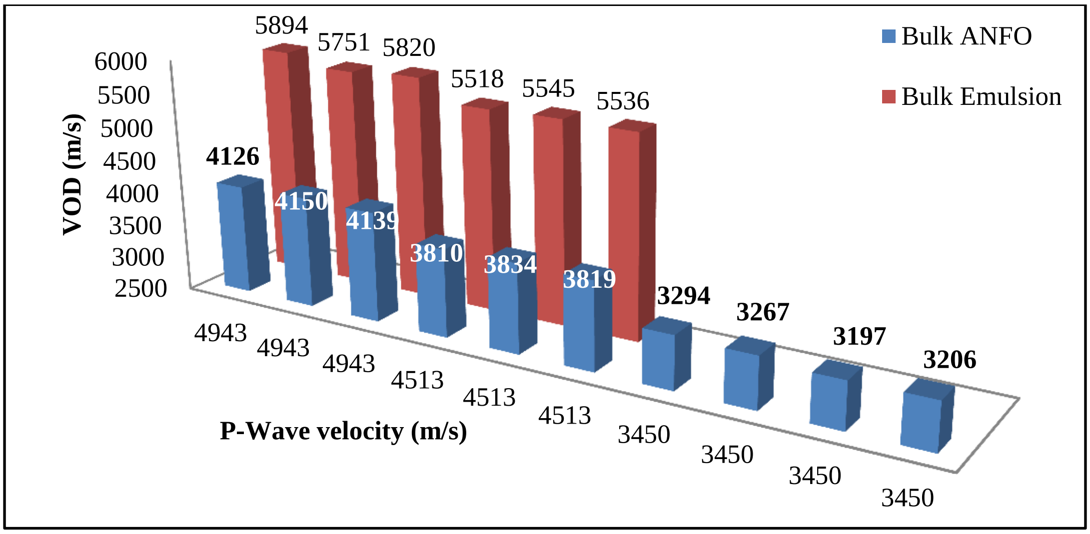

Figure 4.6 VOD vs. P-wave velocity of confining medium at 215 mm blast hole diameter

As the material strength of the confining medium around the blast hole increases, the VOD of explosives increases. Figure 4.7 illustrates that the VOD of both explosives increases as UCS of confining medium such as, glacier, ore metasomatite, and phyllite increases.

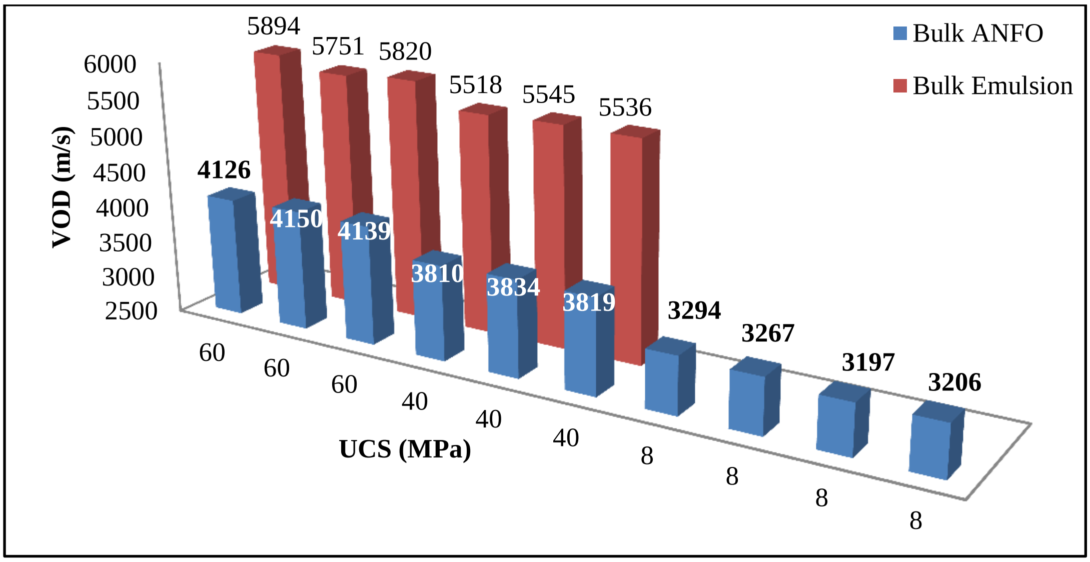

Figure 4.7 VOD vs. UCS of confining medium at 215 mm blast hole diameter

The mass strength of confining medium can be described by RMR in total or by considering individual parameter such as average spacing of discontunities. Spacing of discontunities can be compared with VOD of explosives to investigate and emphasis the effect of confinement on VOD of both explosives. As it is seen from Figure 4.8, when the spacing of discontunities gets closer, the medium gets weaker and the VOD decreases for both bulk ANFO and bulk emulsion.

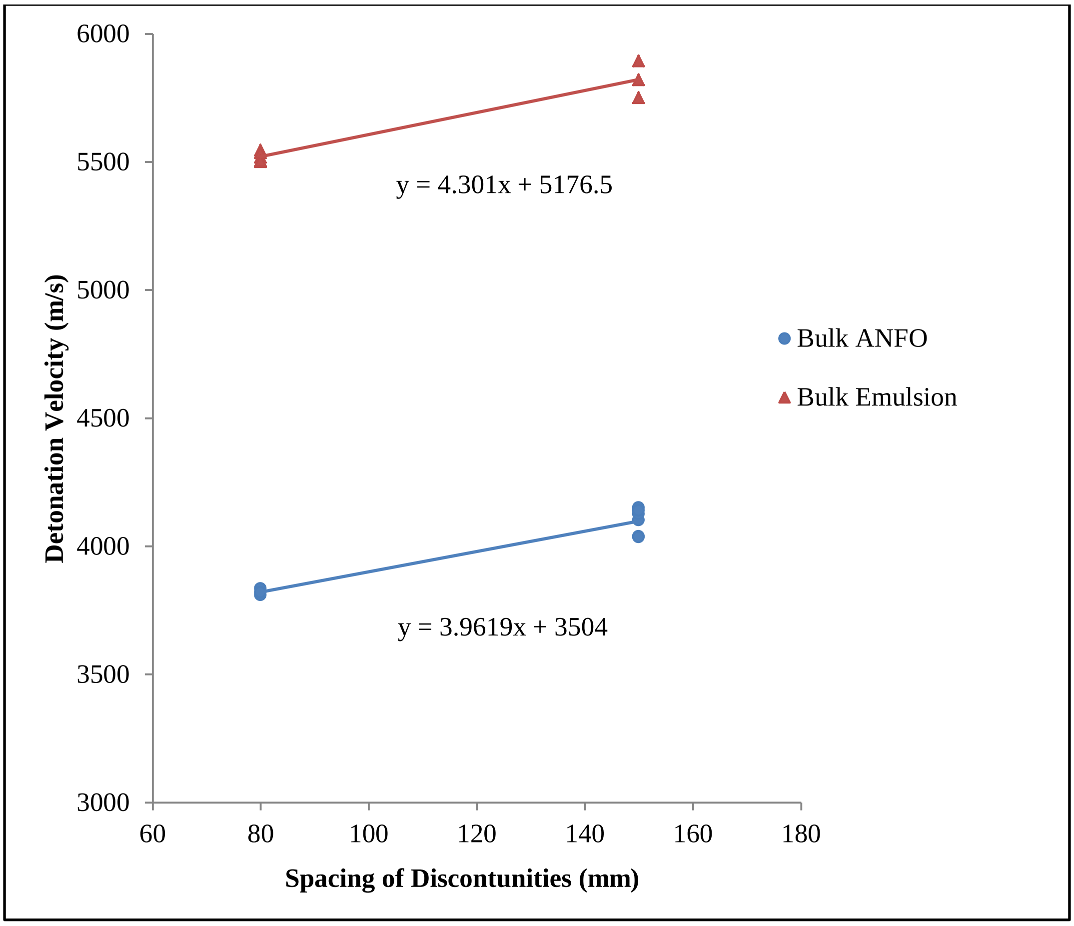

Figure 4.8 VOD vs. Spacing of discontunities of confining medium at 215 mm blast hole diameter

The relation between the VOD of both explosives and RMR of surrounding medium at blast hole diameter of 215 mm was investigated in order to point out the effect of confinement on VOD. The variation of the VOD according to RMR of confining medium can be observed in Figure 4.9 for bulk emulsion and bulk ANFO. The VOD of both explosives decreases as the RMR of confining medium decreases. In other words, mass strength properties of phyllite and ore metasomatite directly affected VOD of both explosives in 215 mm diameter blast holes.

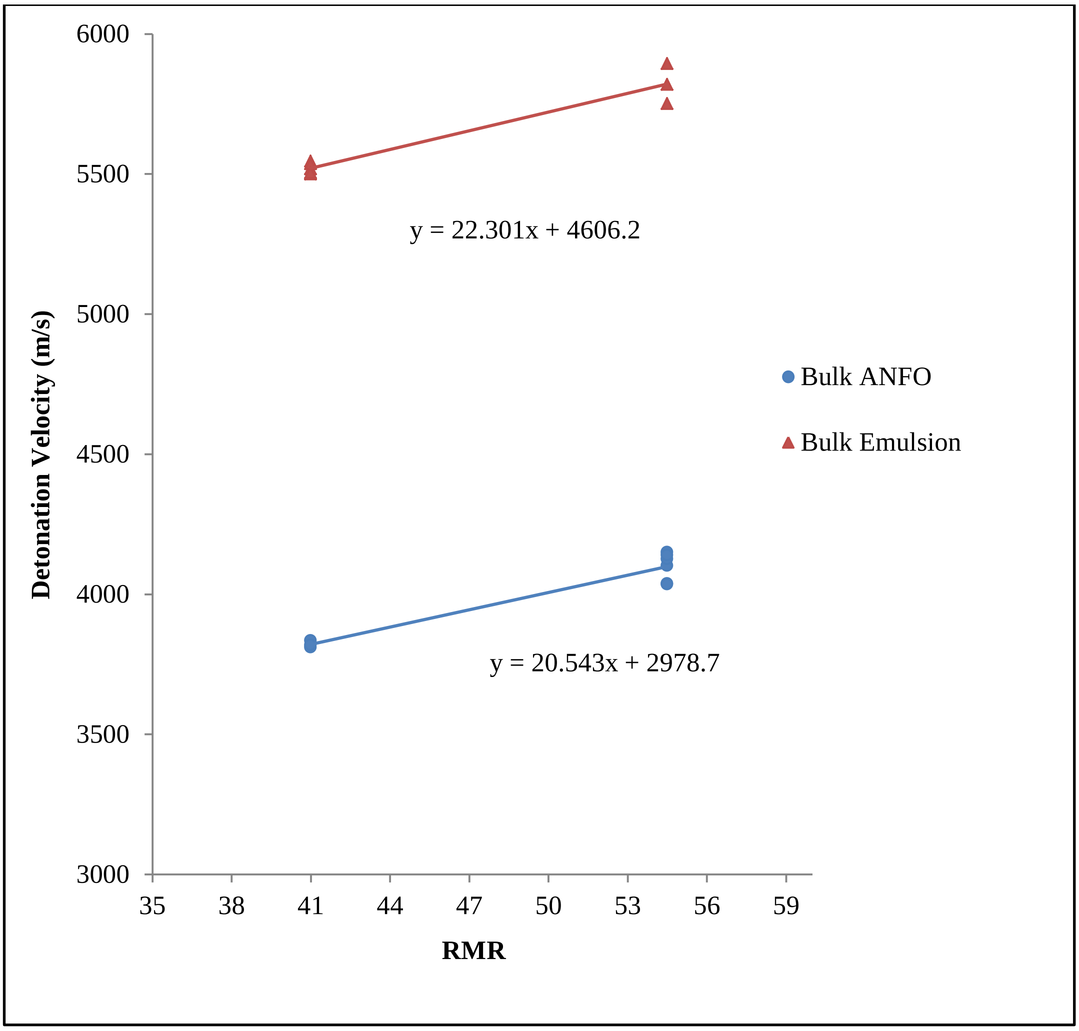

Figure 4.9 VOD vs. RMR of confining medium at 215 mm blast hole diameter

Table 4.4 and Table 4.5 summarizes mass and material properties of the medium surrounding the blast hole together with average VOD values and their standard deviation at blast hole diameter of 215 mm and 172 mm.

Table 4.4 Properties of confining medium at 215 mm blast hole diameter

Confining Medium	RMR	RQD (%)	UCS (Mpa)	Spacing of Dis. (mm)	P wave (m/s)	S wave (m/s)	Average VOD Bulk ANFO (m/s)	Average VOD Bulk Emulsion (m/s)	Standard Deviation Bulk ANFO (m/s)	Standard Deviation Bulk Emulsion (m/s)
Phyllite	52-57	50-60	50-70	100-200	4943	2829	3604	5341	31	24
Ore Metasomatite	34-48	40	40	60-100	4513	2685	3415	5152	21	23
Glacier	_	_	8	_	3300-3600	800-1500	_	_	_	_

Table 4.5 Properties of confining medium at 172 mm blast hole diameter

Confining Medium	RMR	RQD (%)	UCS (Mpa)	Spacing of Dis. (mm)	P wave (m/s)	S wave (m/s)	Average VOD Bulk ANFO (m/s)	Average VOD Bulk Emulsion (m/s)	Standard Deviation Bulk ANFO (m/s)	Standard Deviation Bulk Emulsion (m/s)
Phyllite	52-57	50-60	50-70	100-200	4943	2829	4098	5821	50	71
Ore Metasomatite	34-48	40	40	60-100	4513	2685	3821	5520	12	19
Glacier	_	_	8	_	3300-3600	800-1500	3241	_	47	_

Alternatively, the degree of confinement in each area can be demonstrated by comparing the drilling rates. Drilling rate of phyllite, ore metasomatite and glacier are represented in Table 4.6. All data was collected under the same conditions with similar drill rig type, drill bit type, blast hole diameter, and drill operator. As it can be seen in Appendix D in detail, blast hole length changes from 10 m to 11.2 m. Drilling speed average in phyllite is 0.60 m/min, whereas it is 1.13m/min in ore metasomatite and 2.08 m/min in glacier (Table 4.6). Drilling rate increases while degree of confinement decreases from phyllite to ore metasomatite, and glacier.

Table 4.6 Average drill rates in phyllite, ore metasomatite and glacier at 215 mm blast hole

Drill Id	Rock Type	Average Drill Rate (m/min)
1108	Phyllite	0.60
1108	Ore Metasomatite	1.13
1108	Glacier	2.08

Although benches in glacier are not drilled and blasted regularly in Kumtor Open Pit Mine, several experiments were carried out in glacier benches only to demonstrate the prominent influence of confinement on VOD of explosives. When VOD measurements were carried out in glacier, the average temperature in Kumtor mine site was -20. To prevent melting of glacier it was aimed to conduct VOD measurements in cold times. 215 mm diameter blast holes were drilled and charged by bulk ANFO. Since the drill cuttings are ice, sand and gravels were used as stemming material as shown in Figure 4.10.

Figure 4.10 VOD measurements in glacier benches

It was not possible to measure VOD of bulk emulsion in blast holes in glacier. Since temperature of product was changing from 50 to 70 °C, shape of the blast hole tended to deform after charging due to melting of ice. Accordingly, evaluation of VOD results could not be conducted as blast hole diameter was not measurable.

Table 4.7 Effect of confinement on VOD of bulk ANFO

Blast hole diameter (mm)	Rock Type	Average VOD (m/s)	Explosive Type
172	Phyllite*	3604	Bulk ANFO
172	Ore Metasomatite **	3414	Bulk ANFO
215	Phyllite *	4098	Bulk ANFO
215	Ore Metasomatite **	3821	Bulk ANFO
215	Glacier	3241	Bulk ANFO

* Higher confinement
** Lower confinement

The VOD measurements of bulk ANFO that was carried out in phyllite, ore metasomatite and glacier were tabulated in Table 4.7. As the degree of confinement decreases, VOD of bulk ANFO has the tendency to reduce. As it is seen in Table

4.7, bulk ANFO had a VOD of 4098m/s on average in phyllite, whereas it drops down to 3821m/s in ore metasomatite and 3241m/s in glacier at a blast hole diameter of 215 mm. Similarly, VOD of bulk ANFO measured at a blast hole diameter of 172 mm as shown in Figure 4.11 was observed to be lower in ore metasomatite compared to phyllite. The measurements revealed that the average VOD of bulk ANFO in phyllite is 3604m/s and 3414m/s in ore metasomatite. VOD graphs for bulk ANFO in phyllite and ore metasomatite are presented in Appendix A. VOD measurements in glacier are presented in Appendix C.

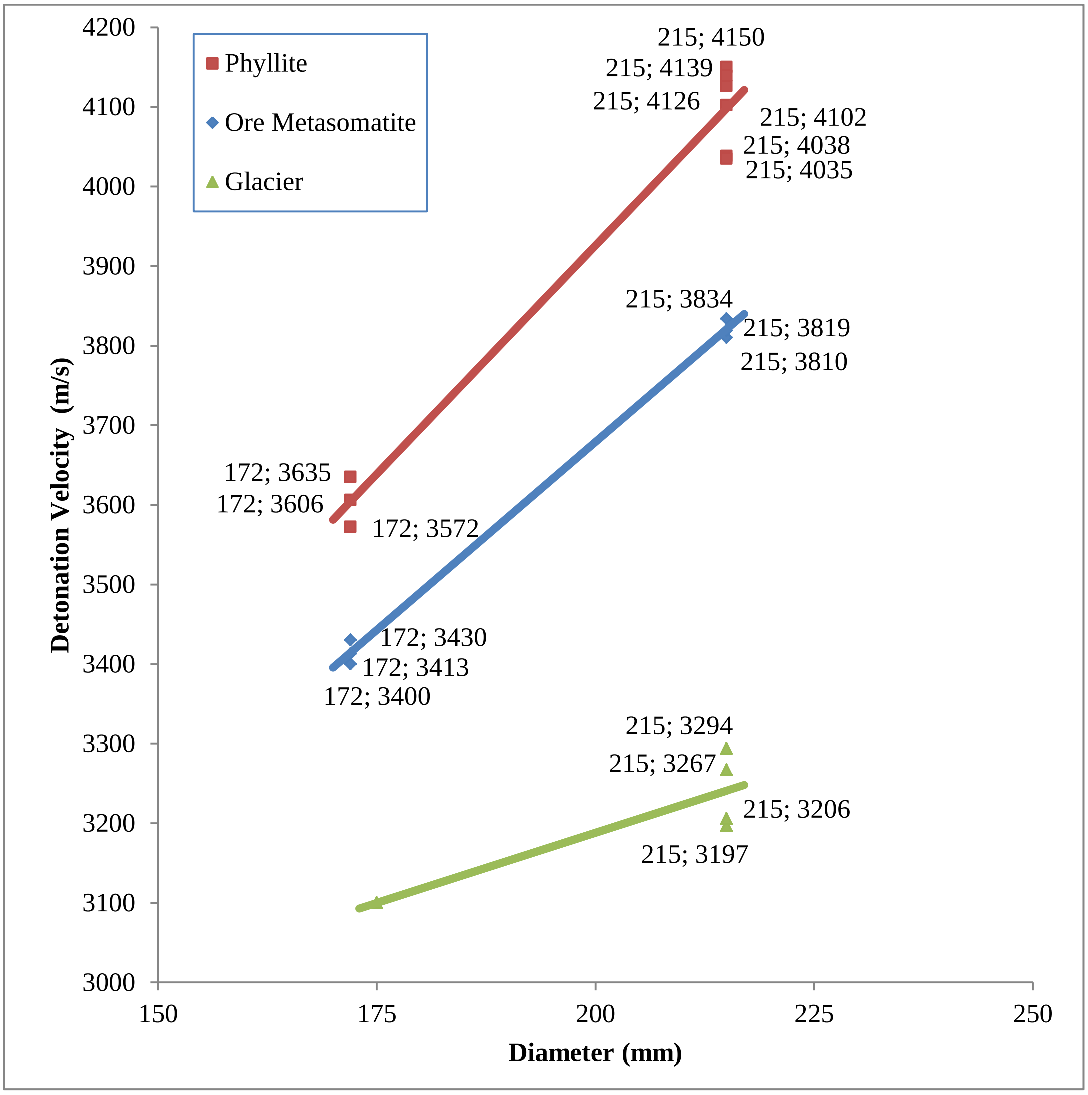

Figure 4.11 Effect of confinement on VOD of bulk ANFO

17 VOD measurements were taken to demonstrate influence of confinement on VOD of bulk emulsion. Graphs generated from measured VOD for bulk emulsion are presented in Appendix B. Test results shown in Table 4.8 indicate that the VOD of bulk emulsion decreases while the degree of confinement decreases as expected. Measurements of VOD of bulk emulsion under different confinement are presented in a different graph in Figure 4.12. Average VOD was recorded in phyllite at a blast hole diameter of 215 mm as 5821 m/s. VOD of bulk emulsion in ore metasomatite at same blast hole diameter was measured as 5520 m/s on average.

Table 4.8 Effect of confinement on VOD of bulk emulsion

Blast hole diameter (mm)	Rock Type	Average VOD (m/s)	Explosive Type
172	Phyllite *	5341	Bulk Emulsion
172	Ore Metasomatite**	5152	Bulk Emulsion
215	Phyllite *	5821	Bulk Emulsion
215	Ore Metasomatite **	5520	Bulk Emulsion

* Higher confinement
** Lower confinement

In addition to results obtained from measurements at 215 mm blast hole diameter, effect of confinement on VOD of bulk emulsion was also recorded at blast hole diameter of 172 mm (Figure 4.12). VOD of bulk emulsion at 172 mm blast hole diameter is 5341 m/s on average in phyllite. On the other hand, the VOD decreases to 5152 m/s on average in ore metasomatite at same blast hole diameter as shown in Table 4.8.

Two VOD measurements represented by green triangles in Figure 4.12, are made using an old type of bulk emulsion charging truck (MMU). The blend percentages for matrix, AN-prills, diesel oil, and gassing solution could not be regulated accurately with this MMU. Therefore, unexpectedly high VOD values are determined during two tests. Remaining tests were carried out with automatically calibrated MMU.

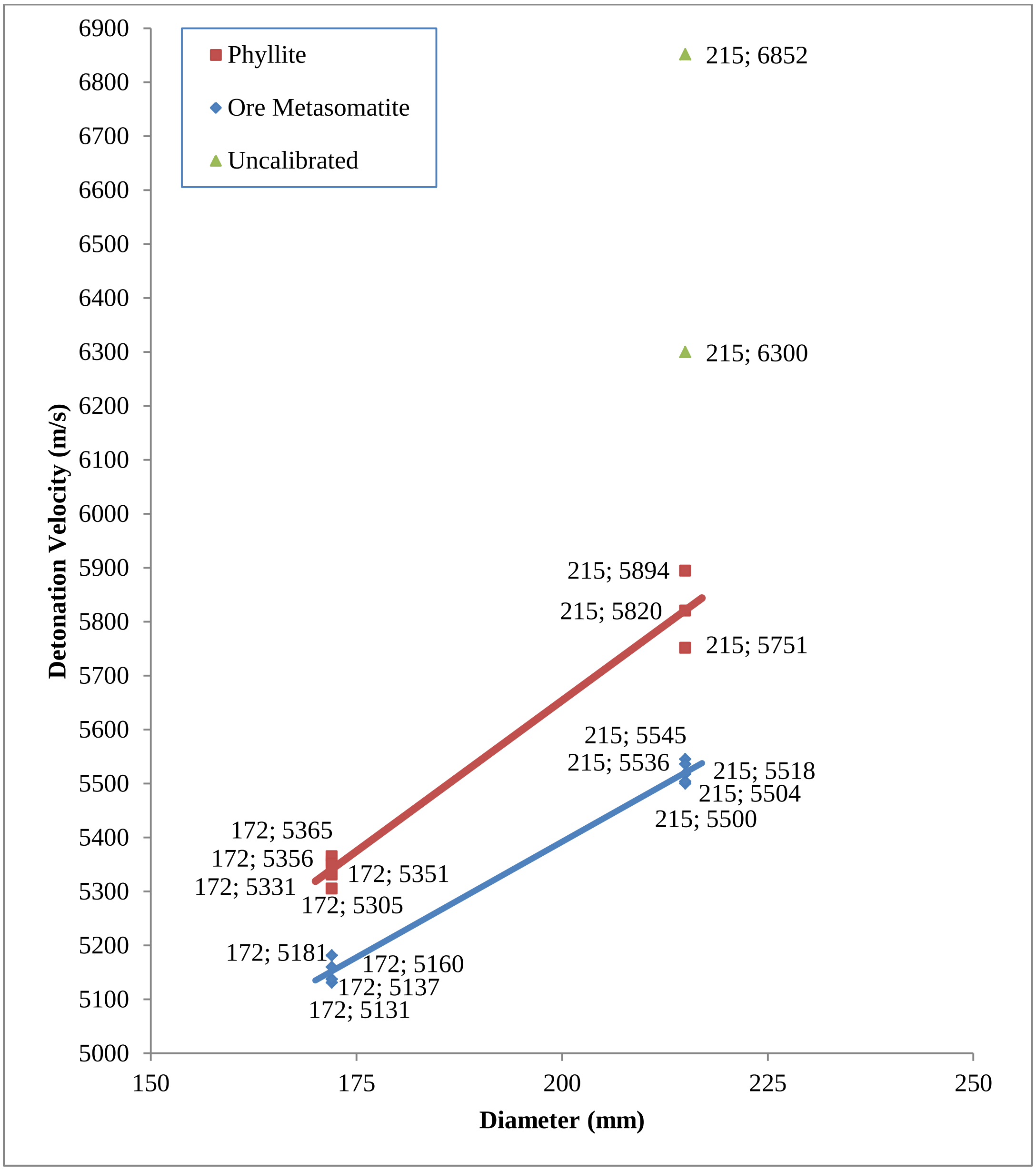

Figure 4.12 Effect of confinement on VOD of bulk emulsion

It can be concluded that the same type of explosive performs better, that is, detonates at higher velocity, under higher confinement, even though the blast hole diameter, primer type and detonator type are the same. In other word, the higher confinement which means higher material and mass strength for the rock, leads to higher detonation pressure due to higher VOD and helps fragmentation.

4.5 Influence of Blast Hole Diameter on VOD of an Explosive

In Kumtor open pit gold mine, blast hole diameters selected and used currently are 172 mm and 215 mm which are both quite above critical diameter of bulk ANFO and bulk emulsion. Since blast holes are not too deep, stable detonation could be sustained along the explosive column. It is known from literature that higher detonation velocity can be obtained in larger hole diameters.

Differences between measurements of VOD in 172 mm and 215 mm diameter holes were evaluated for existing rock conditions. 38 in hole VODs were measured to analyze the effect of borehole diameter on VOD of both bulk ANFO and bulk emulsion. The VOD records are given in Appendix A and Appendix B respectively.

The VOD of bulk ANFO in 215 mm diameter hole at phyllite was recorded 4098 m/s on average, whereas it was measured as 3604 m/s on average in 172 mm hole diameter (Figure 4.13).

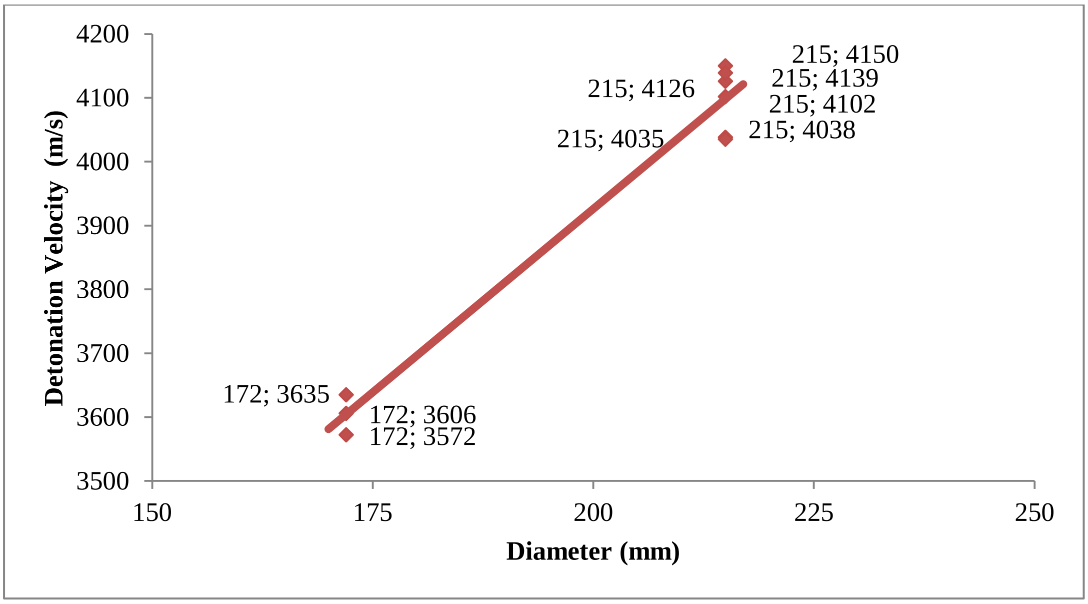

Figure 4.13 Effect of blast hole diameter on bulk ANFO in phyllite

Alternatively, several VOD measurements of bulk ANFO were carried out at ore metasomatite in both 172 mm and 215 mm diameter holes. As it can be seen in Figure 4.14, the VOD of bulk ANFO is 3821 m/s on average in 215 mm blast hole diameter while it decreases to 3414 m/s on average in 172 mm diameter holes.

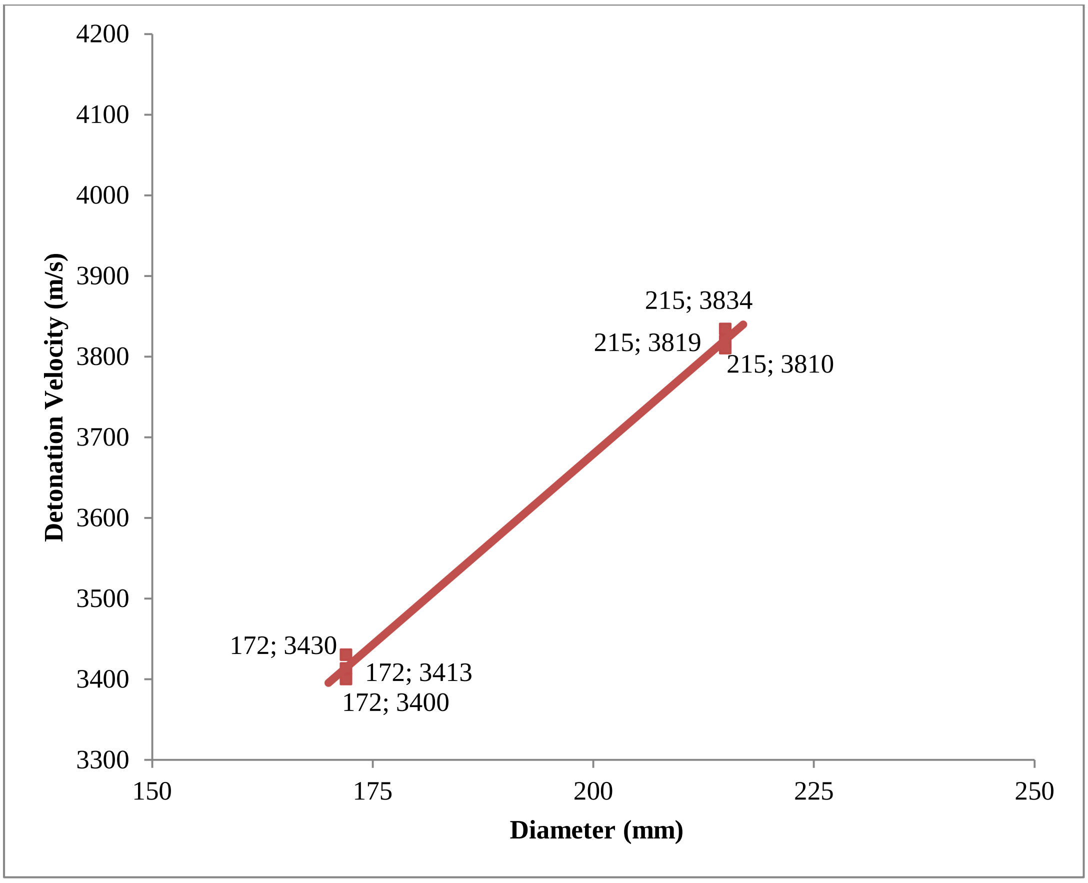

Figure 4.14 Effect of blast hole diameter on bulk ANFO in ore metasomatite

Under the same degree of confinement, the VOD values of bulk ANFO in 215 mm diameter hole is always higher than the 172 mm diameter holes which can be seen in Figure 4.13 and Figure 4.14. It can be concluded from all in-situ VOD measurements that detonation velocity increases with the blast hole diameter of bulk ANFO.

Increase in VOD of the bulk ANFO due to the increase in blast hole diameter under a lower confinement is lower (12%) when compared to that of the same type of explosive (14%) under a higher confinement.

Detonation velocity measurements for bulk emulsion were carried out at the equivalent blend ratio and density using electronically calibrated MMU. A summary of measured VODs for bulk emulsion are given in Figure 4.15 and 4.16.

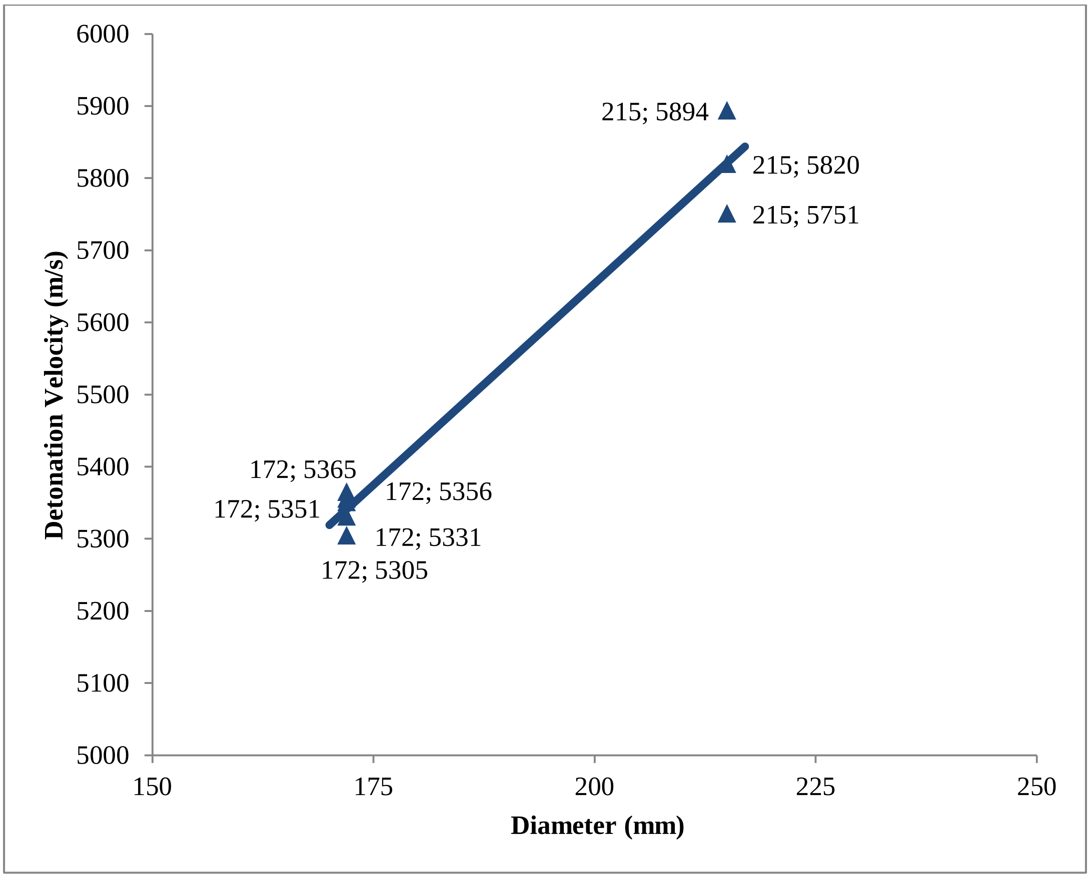

Figure 4.15 Effect of blast hole diameter on bulk emulsion in phyllite

VOD values of bulk emulsion increases when charged in larger diameter holes as in the case of bulk ANFO. The VOD of bulk emulsion in 215 mm diameter hole at phyllite was recorded as 5821 m/s on average, whereas it is 5341 m/s on average in 172 mm hole diameter (Figure 4.15). Graphical representations of VOD records of bulk emulsion are presented in Appendix B. The effect of borehole size on VODs of bulk emulsion is also demonstrated in Figure 4.16 for ore metasomatite. As it can be seen from Figure 4.16, the VOD value is 5520 m/s on average in 215 mm diameter hole. On the other hand, it decreases to 5152m/s on average in 172 mm diameter hole. In Table 4.1, all VOD records are tabulated in detail and related graphs are presented in Appendix B.

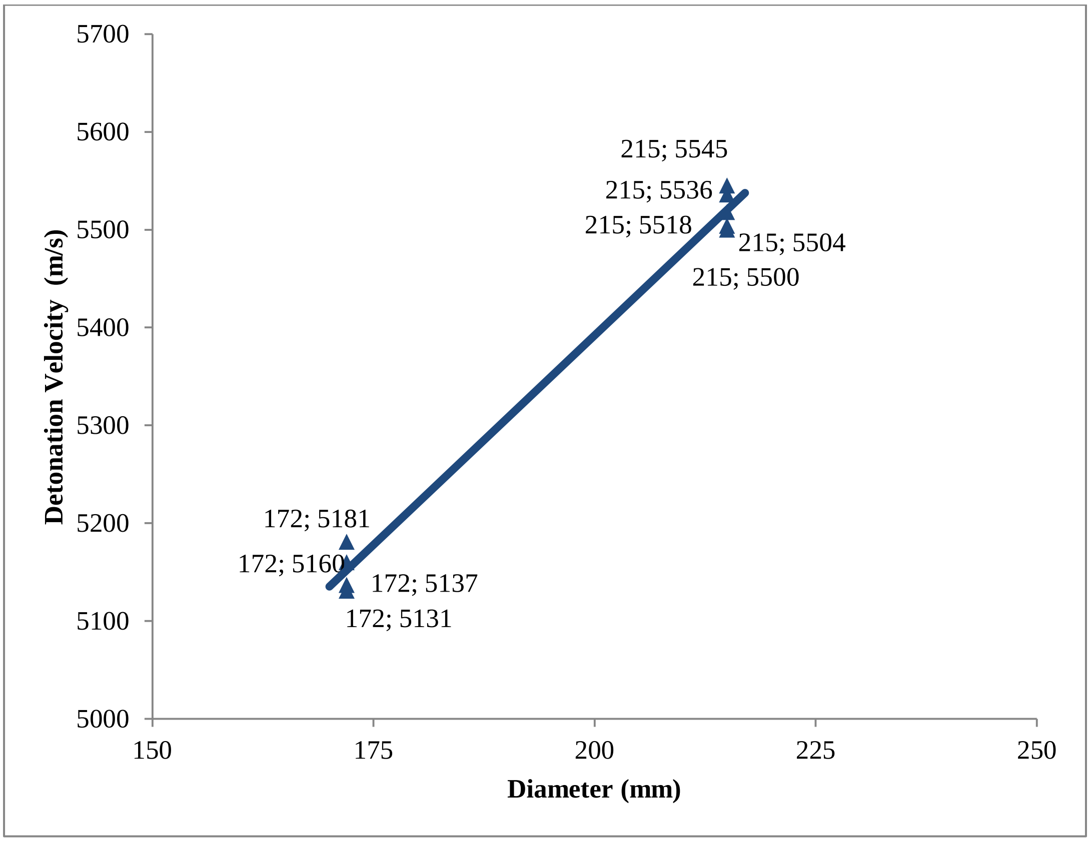

Figure 4.16 Effect of blast hole diameter on bulk emulsion in ore metasomatite

VOD of bulk emulsion increases 9% as blast hole diameter increases from 172 mm to 215 mm in phyllite. Under the lower confinement, ore metasomatite, an increase of 7% was observed. Since the bulk emulsion is a more sensitive explosive than bulk ANFO, increase in the VOD of bulk emulsion was less than that of bulk ANFO under the same conditions.

4.6 Ideality of Explosives at Different Blast Hole Diameter and Confinement

The degree of non-ideality of explosives can be defined by the difference in VOD values of ideal and non-ideal detonation. The ideal detonation of commercial explosives is the recorded VOD of that explosive by one dimensional detonation model (Orica, 2011). On the other hand, the non-ideal detonation of an explosive is actual VOD of that explosive in existing rock conditions and hole diameter (Orica, 2011).

In the course of this study, ideality of bulk ANFO and bulk emulsion in Kumtor open pit gold mine is evaluated for 172 mm and 215 mm hole diameter and existing rock and blast medium conditions. As it is listed in Table 4.9 and Table 4.10, bulk emulsion approaches to ideal detonation more than bulk ANFO in phyllite. The ideal VOD values presented in Table 4.9, 4.10, 4.11, and 4.12 are taken from the technical data sheets of explosive manufacturer company. Ideality of both explosives improves under same confinement in case the diameter of holes is increased.

Table 4.9 Ideality of bulk emulsion and bulk ANFO in phyllite – 172 mm blast hole

Explosive Type	Measured VOD (m/sec)	Ideal VOD (m/sec)	% Ideality
Bulk ANFO	3604	4800	75
Bulk Emulsion	5341	6500	82

The ideality of bulk ANFO and bulk emulsion in phyllite at a hole diameter of 172 mm is calculated as 75% and 82% respectively. Larger hole diameter resulted in an increase in ideality. It is calculated as 85% for bulk ANFO and 90% for bulk emulsion at 215 mm hole diameter.

Table 4.10 Ideality of bulk emulsion and bulk ANFO in phyllite – 215 mm blast hole

Explosive Type	Measured VOD (m/sec)	Ideal VOD (m/sec)	% Ideality
Bulk ANFO	4098	4800	85
Bulk Emulsion	5821	6500	90

The ideality of both explosives is evaluated also in ore metasomatite (Table 4.11 and Table 4.12). As the degree of confinement decreases, ideality of bulk ANFO and bulk emulsion also decreases. Both explosives approach the ideal detonation in larger diameter holes in ore metasomatite.

Table 4.11 Ideality of bulk emulsion and bulk ANFO in ore metasomatite – 172 mm blast hole

Explosive Type	Measured VOD (m/sec)	Ideal VOD (m/sec)	% Ideality
Bulk ANFO	3414	4800	71
Bulk Emulsion	5152	6500	79

The ideality of bulk ANFO and bulk emulsion in ore metasomatite at a hole diameter of 172 mm is calculated as 71% and 79% respectively. As in case of phyllite, ideality increases with larger hole diameter. It is calculated as 80% for bulk ANFO and 85% for bulk emulsion at 215 mm hole diameter.

Table 4.12 Ideality of bulk emulsion and bulk ANFO in ore metasomatite – 215 mm blast hole

Explosive Type	Measured VOD (m/sec)	Ideal VOD (m/sec)	% Ideality
Bulk ANFO	3821	4800	80
Bulk Emulsion	5520	6500	85

The ideality of bulk ANFO is calculated as 68% in glacier benches at a blast hole diameter of 215 mm. Ideality of bulk ANFO decreased from 85% in ore metasomatite to 80% in ore metasomatite and further to 68% in glacier. This difference points out the influence of degree of confinement on ideality of bulk ANFO.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In-situ VOD measurements were carried out to investigate effect of explosive type, confinement, and blast hole diameter on detonation velocity of explosives during the study in Kumtor Gold Mine. The conclusions and the recommendations drawn from this investigation are given below;

1) A total of 65 in-situ detonations were monitored of which 40 events successfully recorded were analyzed. The reasons for unsuccessful recordings are given in Section 4.1.
2) Detonation velocity is affected by explosive type. The higher the density of explosive results in higher VOD up to dead density.
3) As the size of the ingredients in the mixture of explosive decreases the VOD of that explosive increases.
4) Gassing solution in bulk emulsion has positive effect on its VOD. It acts as hot spots during detonation which increases detonation velocity.
5) It has been shown that VOD of bulk ANFO under same confinement and blast hole diameter decreases when it is wet. Wetted bulk ANFO reacts slower and stable detonation could not be reached.
6) In accordance with rewieved literature, the VOD of both bulk ANFO and bulk emulsion increases when the degree of confinement increases, provided that the blast hole diameter, primer type, and detonator type are the same.
7) As the proportion of matrix increases in the mixture of bulk emulsion the VOD of the blend increases.

8) It has been shown from all in-situ VOD measurements that detonation velocity increases with the blast hole diameter of bulk ANFO and bulk emulsion.
9) Increase in the VOD of the bulk ANFO due to the increase in blast hole diameter under a higher degree of confinement gets greater (14%) when compared to that of the same type of explosive (12%) under a lower degree of confinement.
10) VOD of bulk emulsion increases 9% as blast hole diameter increases under higher degree of confinement, phyllite, whereas under the lower degree of confinement, ore metasomatite, an increase of 7% was observed in the VOD of bulk emulsion with the increase in blast hole diameter.
11) The VOD of bulk ANFO is more sensitive to its blast hole diameter and confinement compared to that of bulk emulsion.
12) It was found that the ideality of both explosives decreases as the blast hole diameter decreases as it is also stated in former studies focusing on the effect of confinement on VOD of explosives. On the other hand, both explosives approach the ideal detonation under higher degree of confinement.
13) Another impressive finding is that the ideality of bulk ANFO decreases from 85% in phyllite to 80% in ore metasomatite and further to 68% in glacier which points out the influence of degree of confinement on ideality of bulk ANFO.
14) It can be recommended that the blast holes in frozen ground charged by bulk ANFO should be initiated as soon as possible to prevent melting of ice, and the wetting of bulk ANFO in the hole. As a result of which the stable detonation is not sustained.
15) Since the VOD of bulk emulsion is always greater than that of bulk ANFO, it can be recommended that the blast holes drilled in a ground which represents higher confinement should be charged with bulk emulsion to get better blast performance because higher VOD means higher detonation pressure.

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APPENDIX A

VOD GRAPHS OF BULK ANFO

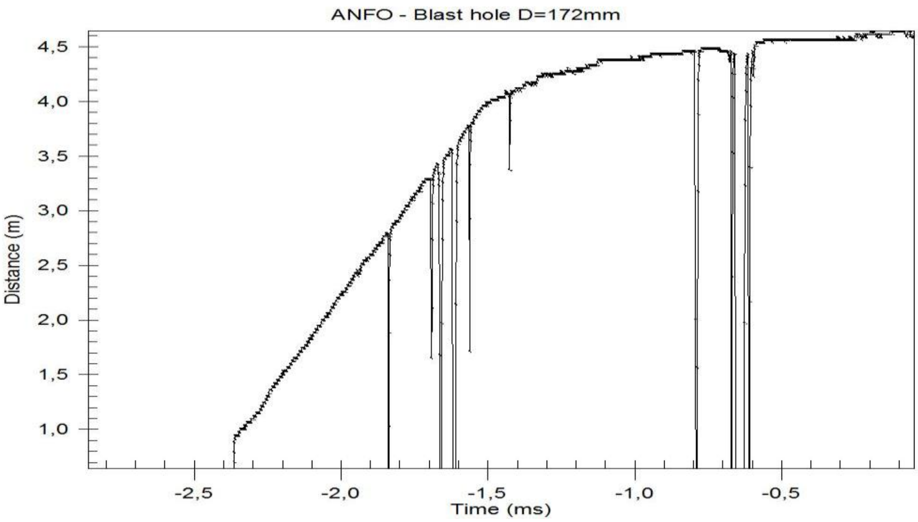

Figure A.1 The original VOD graph for blast pattern 3834-45a

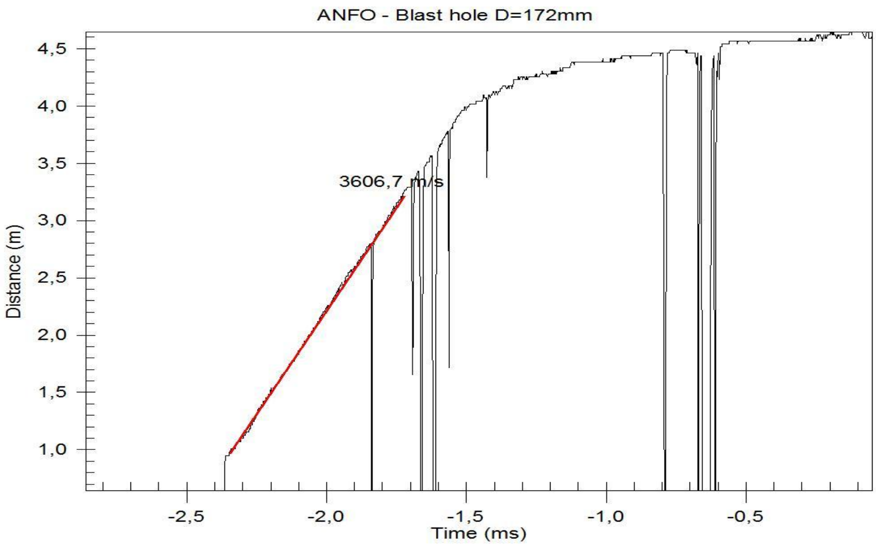

Figure A.2 VOD result for blast pattern 3834-45a

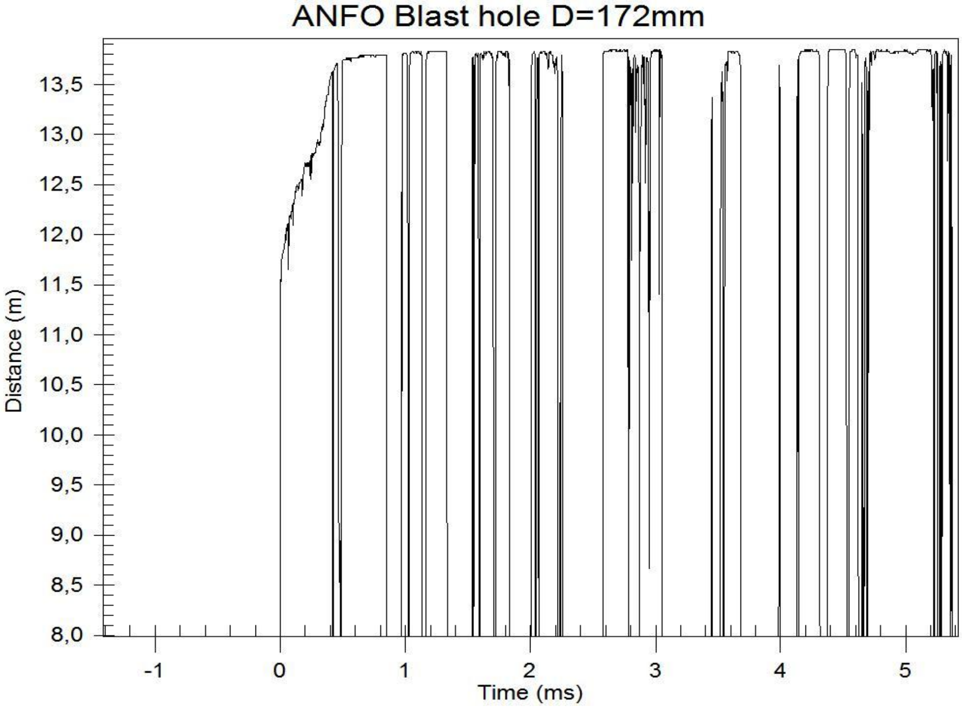

Figure A.3 The original VOD graph for blast pattern 3834-107

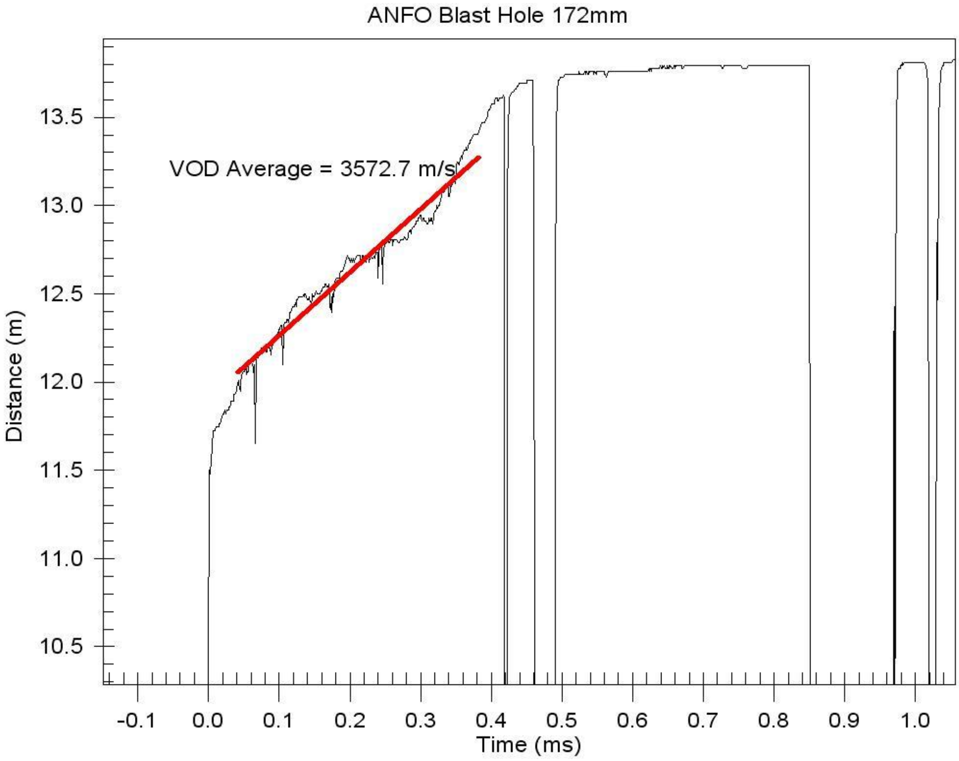

Figure A.4 VOD result for blast pattern 3834-107

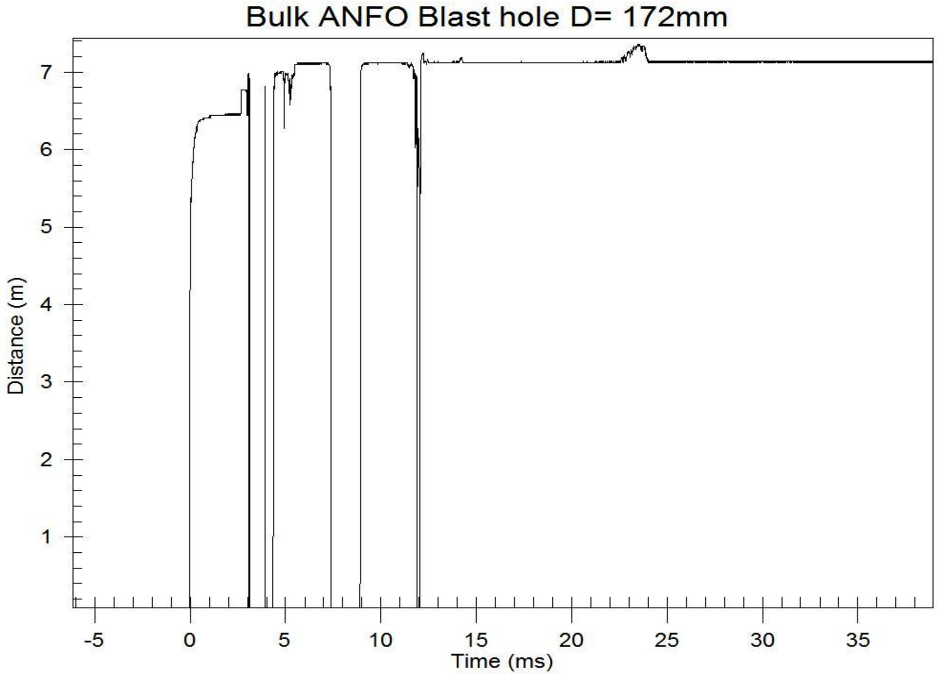

Figure A.5 The original VOD graph for blast pattern 3778-62

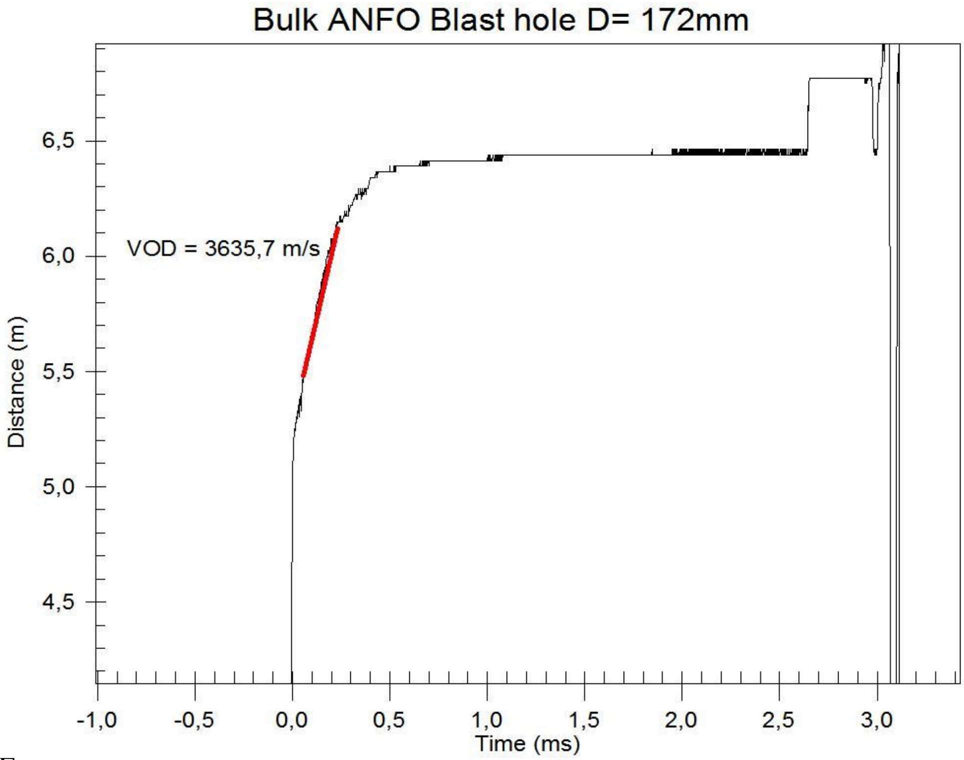

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Figure A.6 VOD result for blast pattern 3778-62

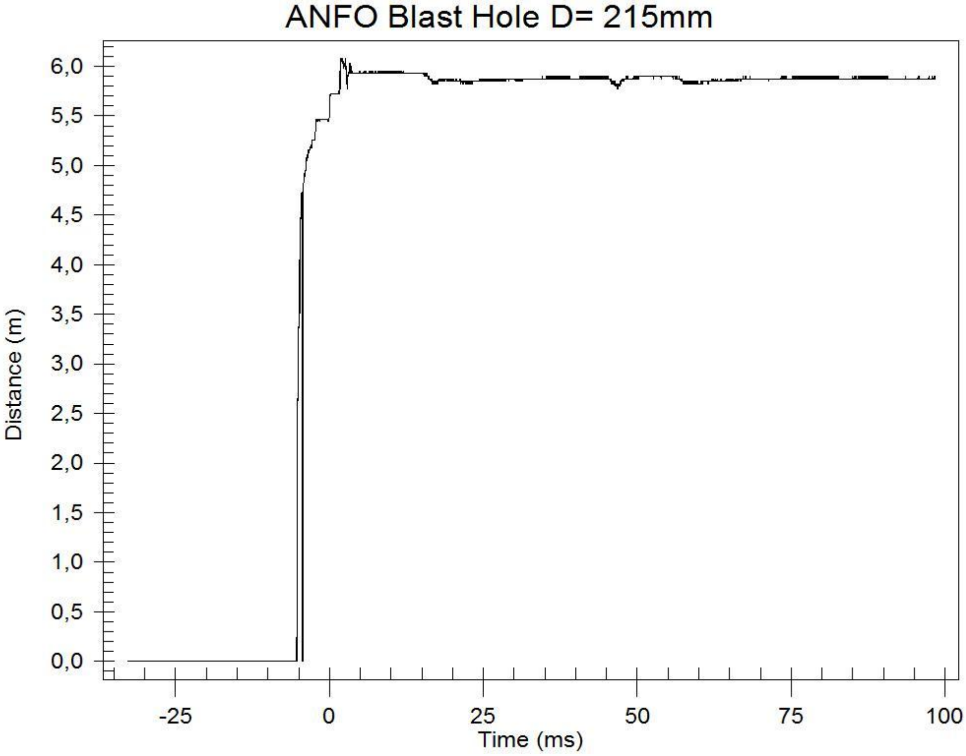

Figure A.7 The original VOD graph for blast pattern 3810-59a

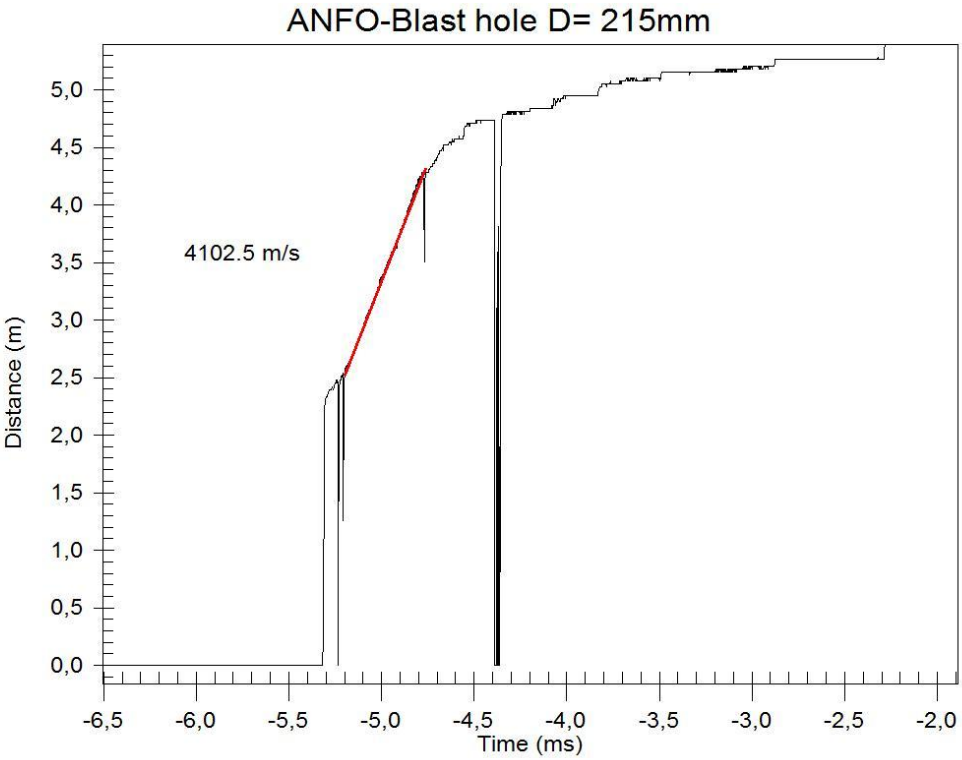

Figure A.8 VOD result for blast pattern 3810-59a

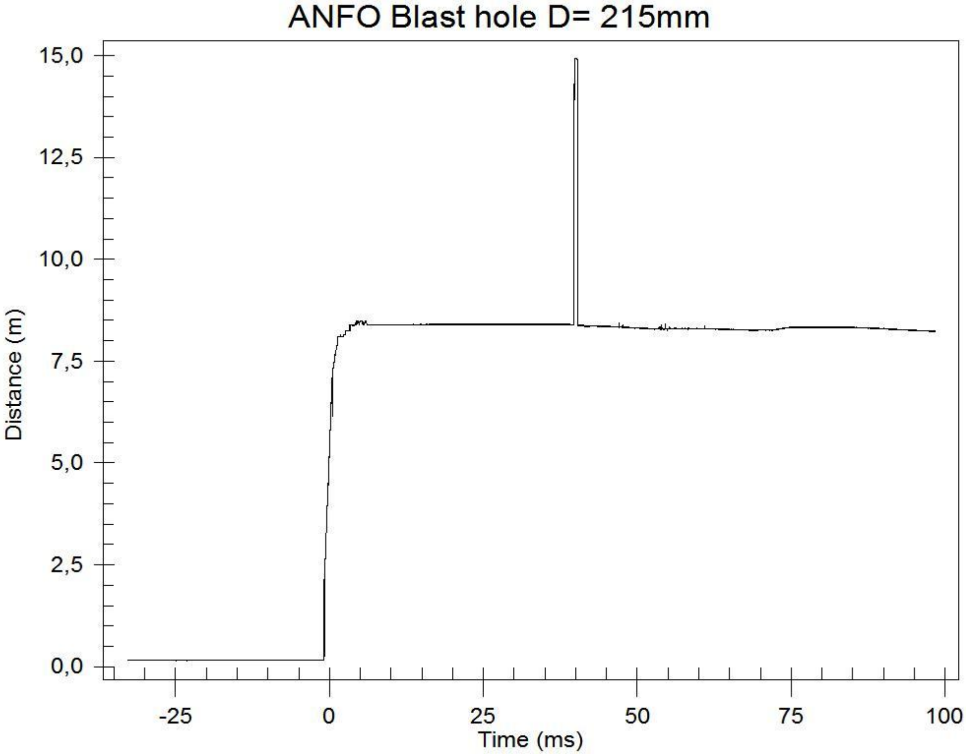

Figure A.9 The original VOD graph for blast pattern 3906-347

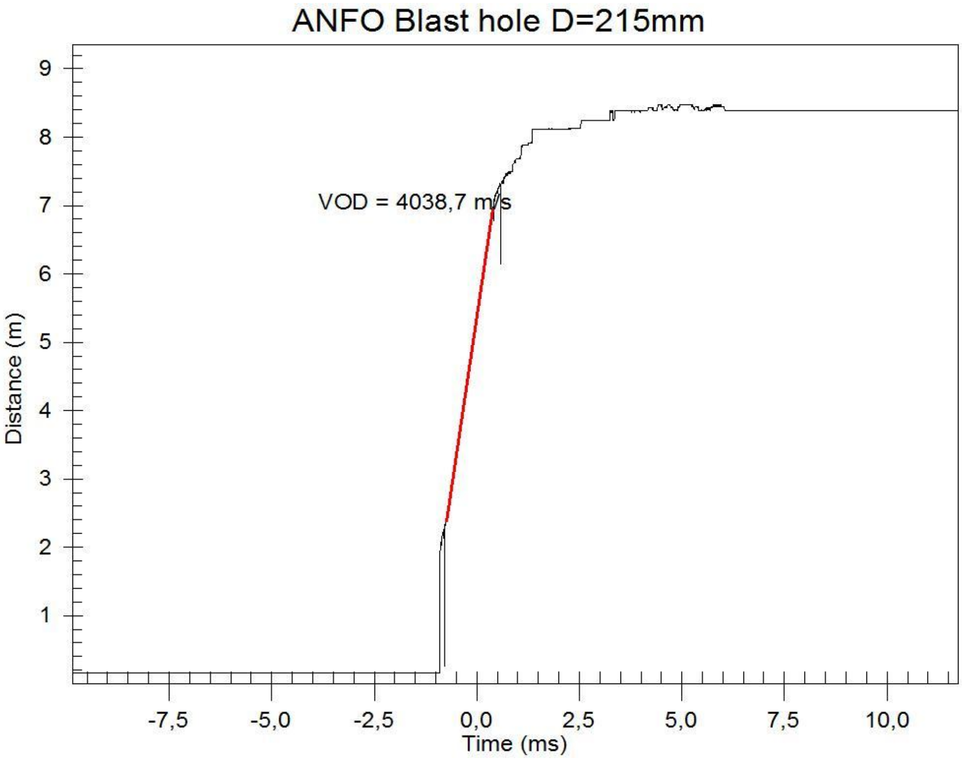

Figure A.10 VOD result for blast pattern 3906-347

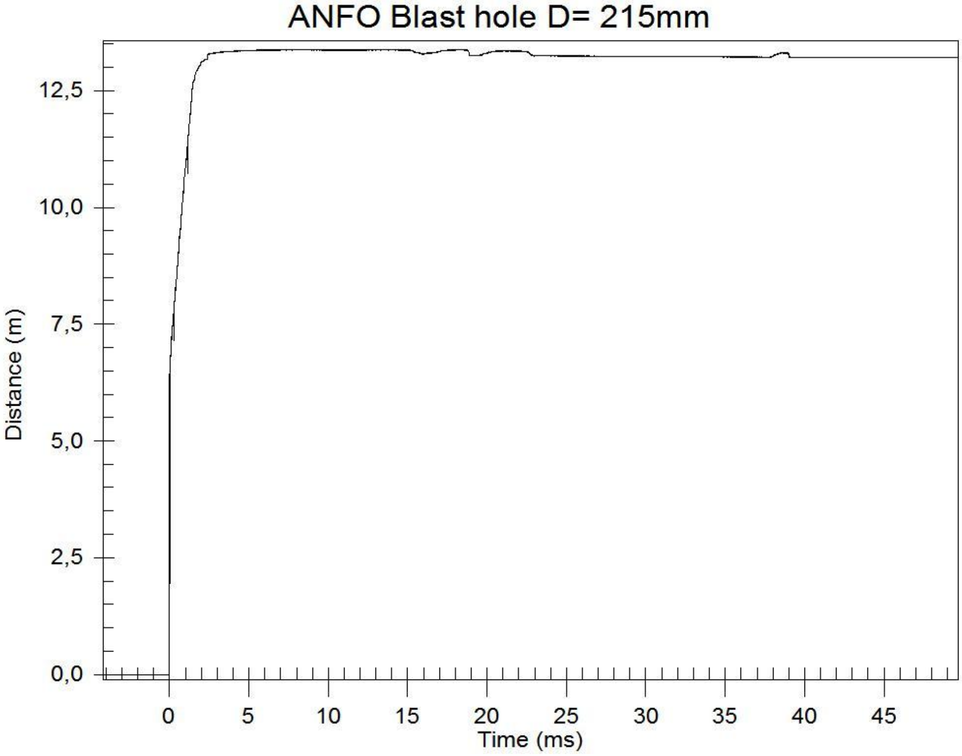

Figure A.11 The original VOD graph for blast pattern 4082-299

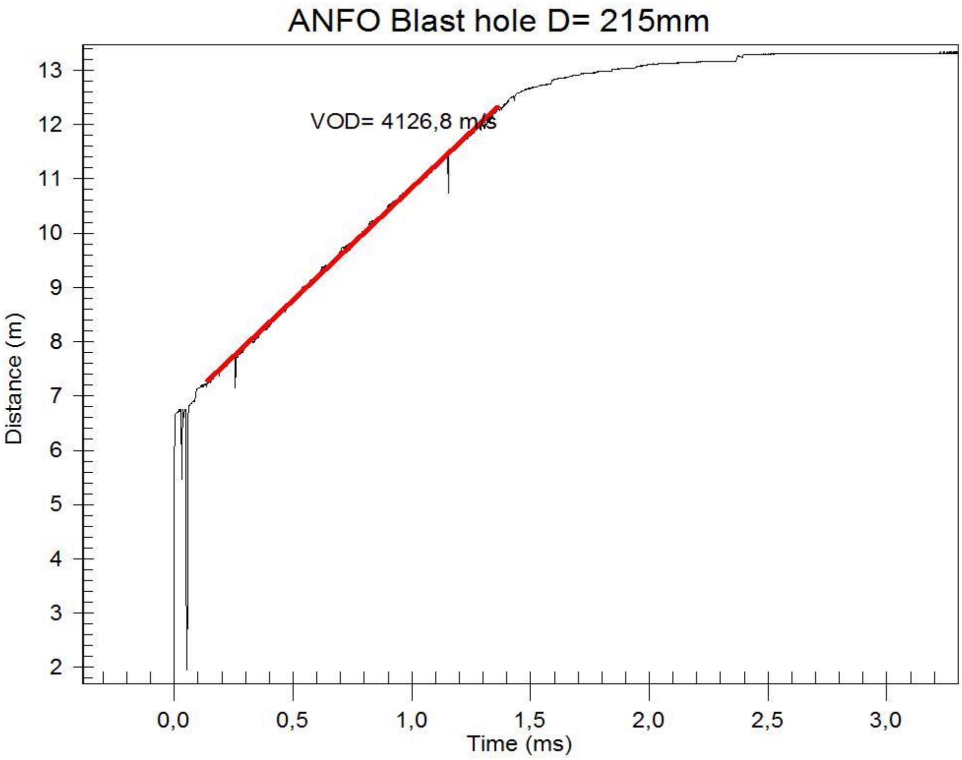

Figure A.12 VOD result for blast pattern 4082-299

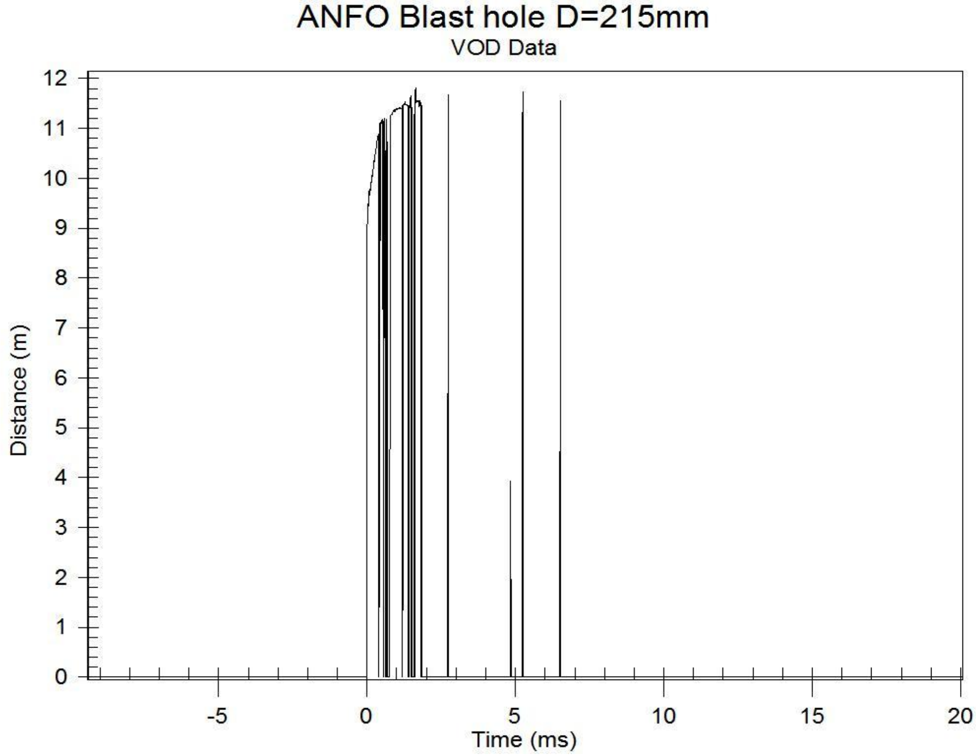

Figure A.13 The original VOD graph for blast pattern 3842-145a

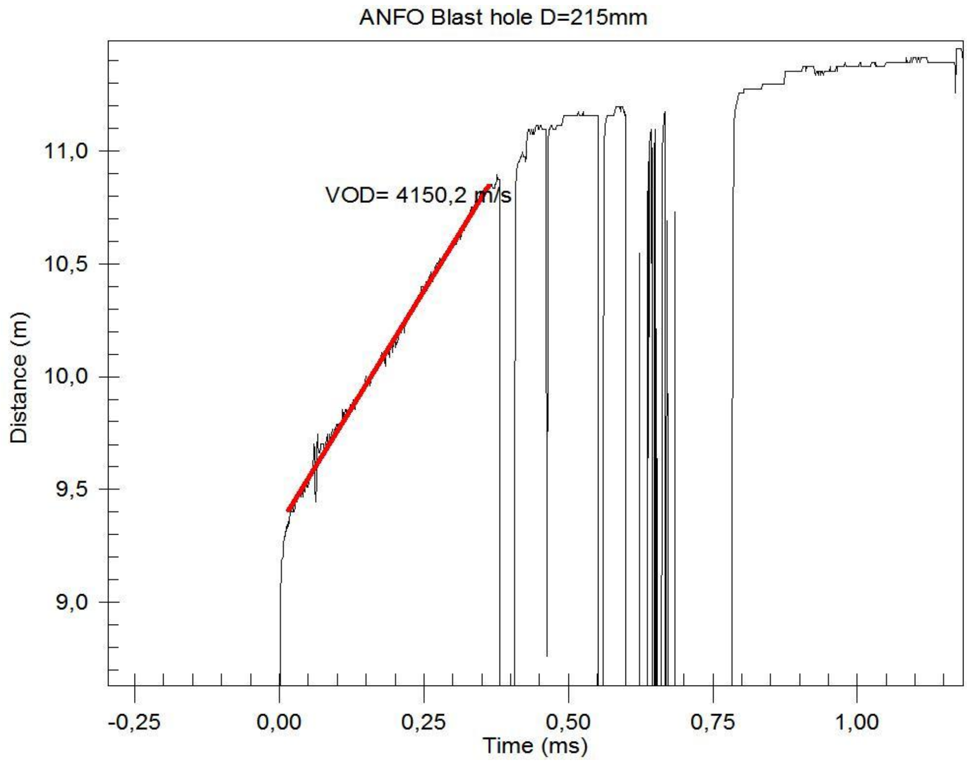

Figure A.14 VOD result for blast pattern 3842-145a

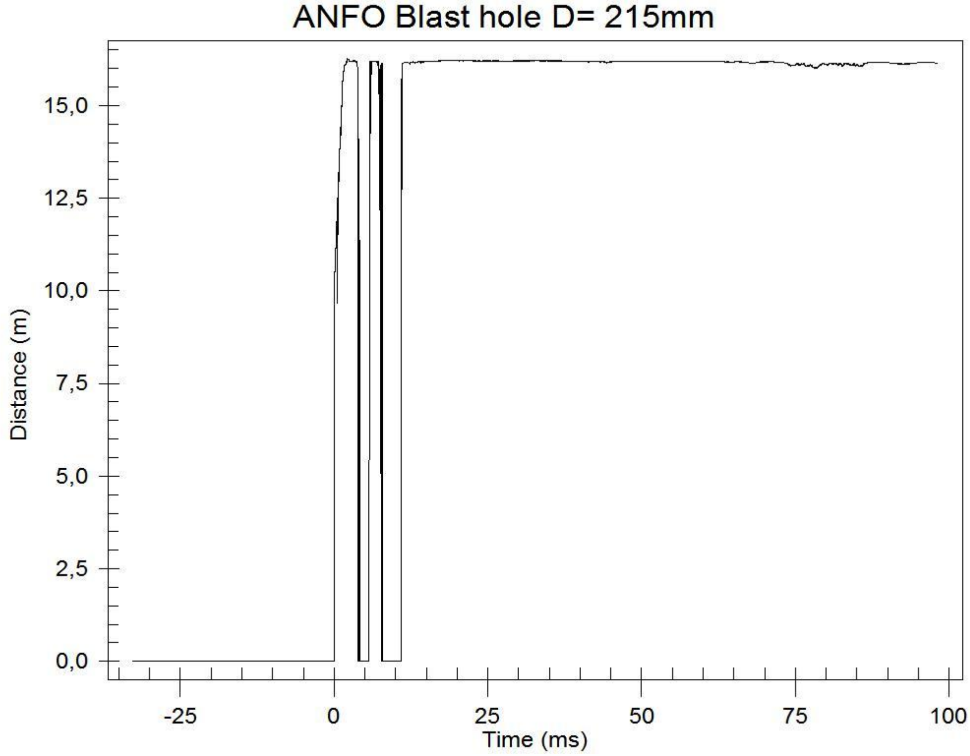

Figure A.15 The original VOD graph for blast pattern 3834-110

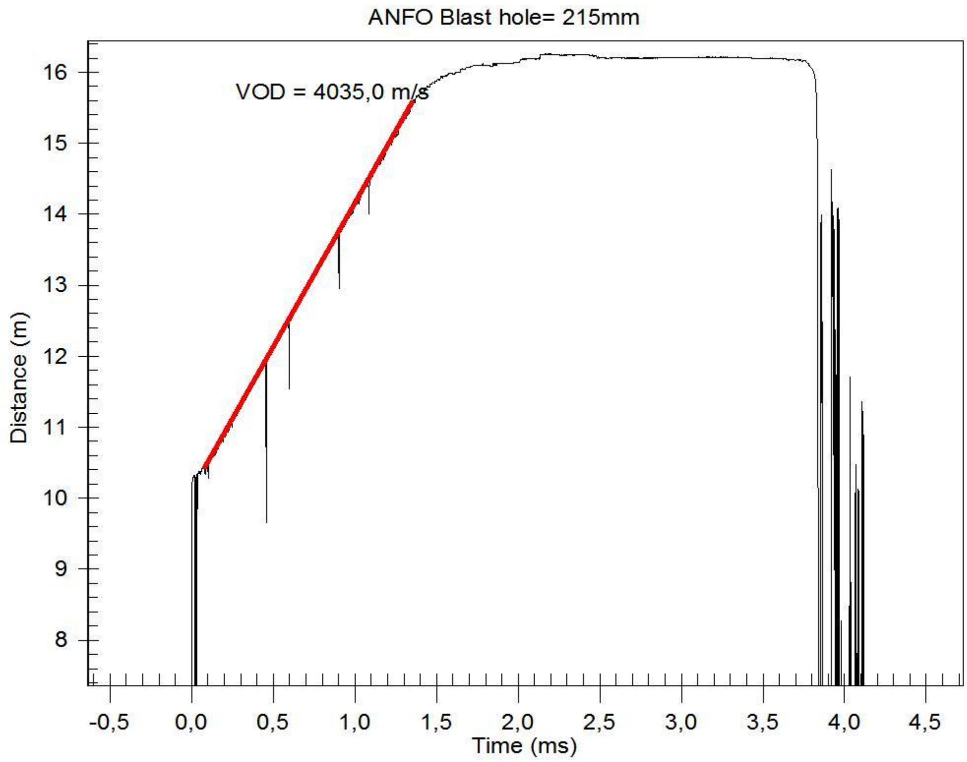

Figure A.16 VOD result for blast pattern 3834-110

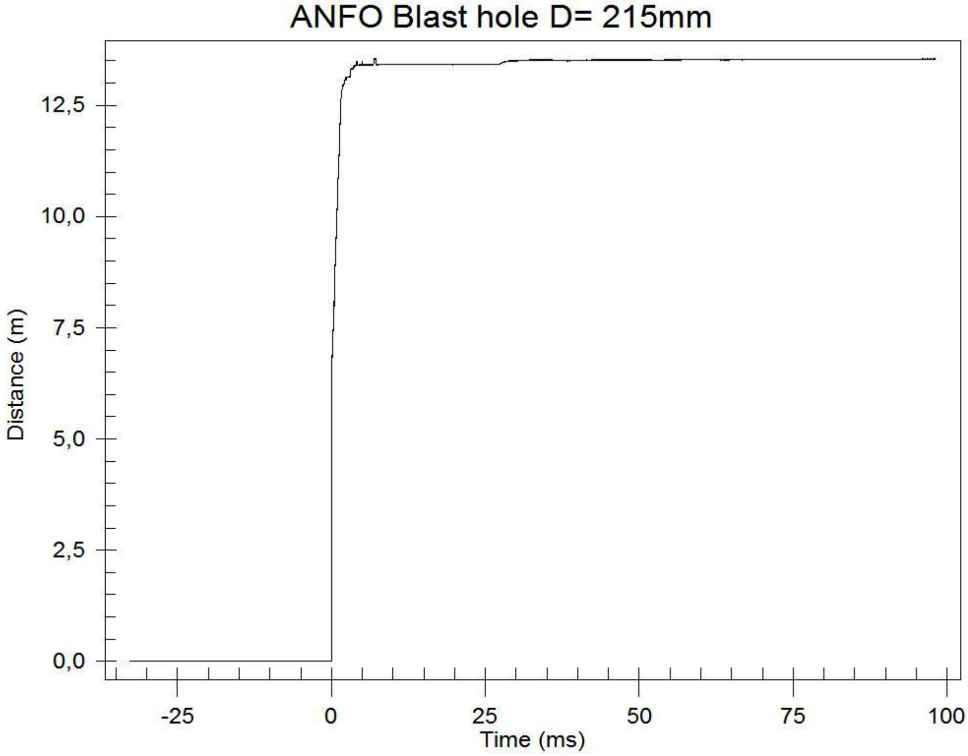

Figure A.17 The original VOD graph for blast pattern 4002-394

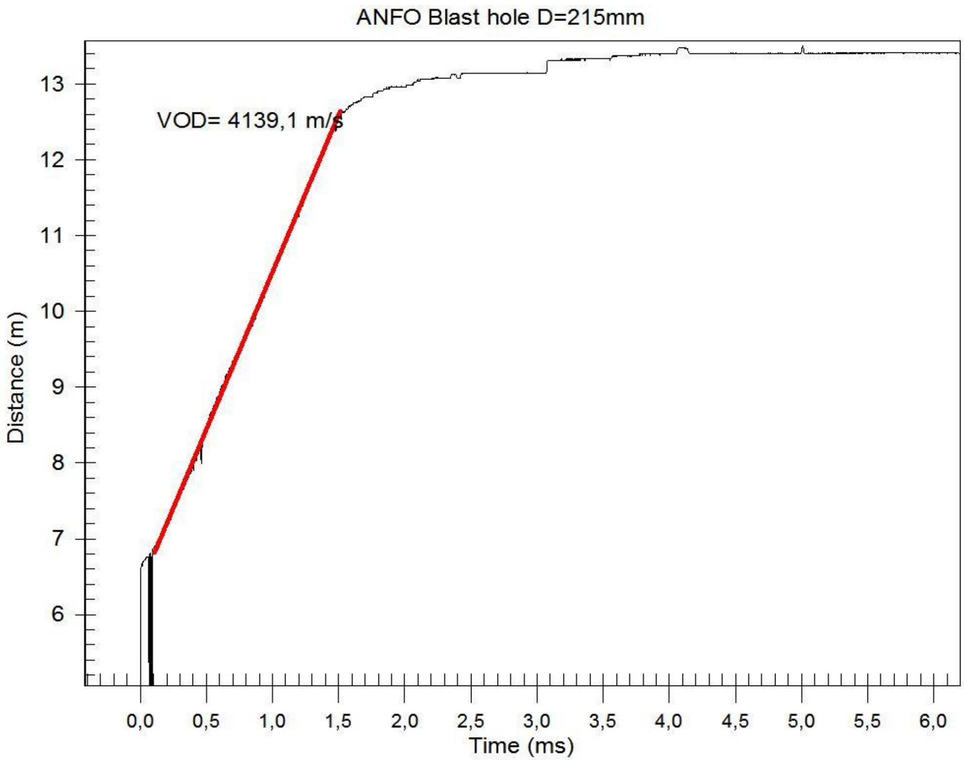

Figure A.18 VOD result for blast pattern 4002-394

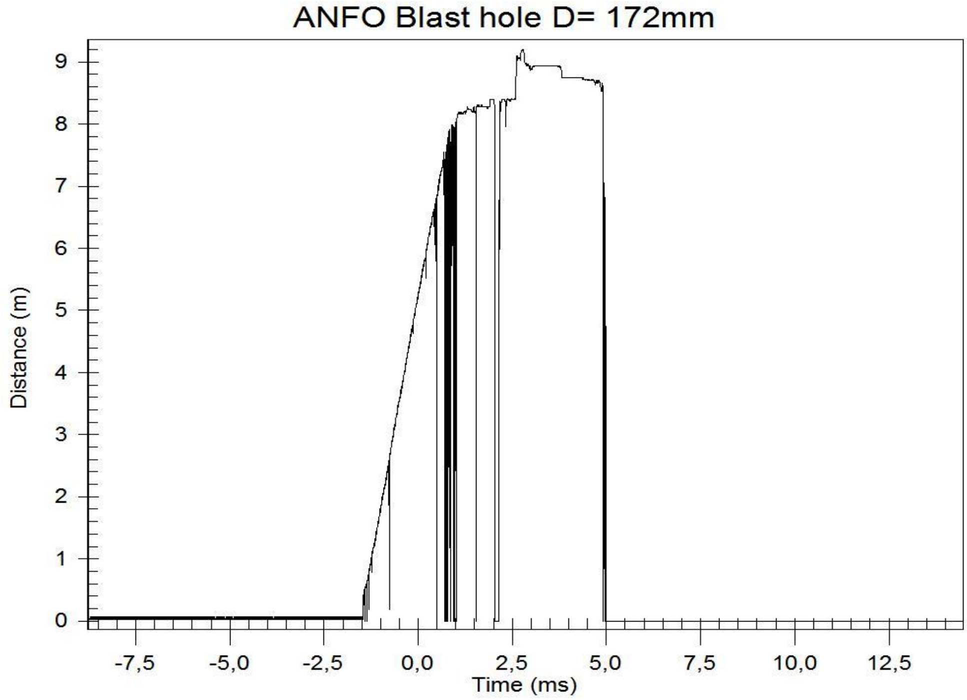

Figure A.19 The original VOD graph for blast pattern 3750-112

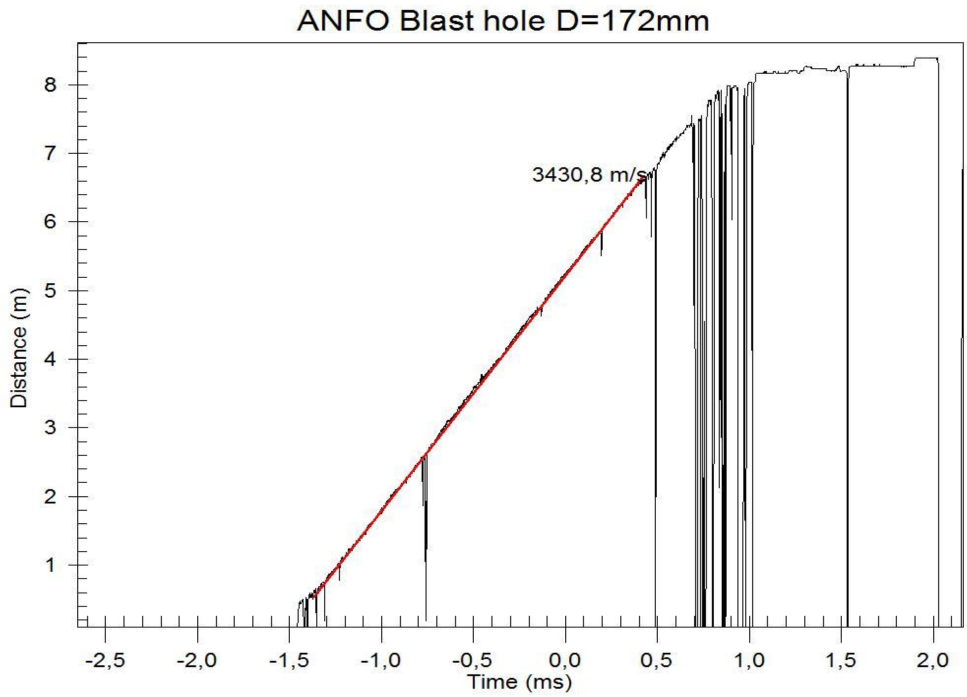

Figure A.20 VOD result for blast pattern 3750-112

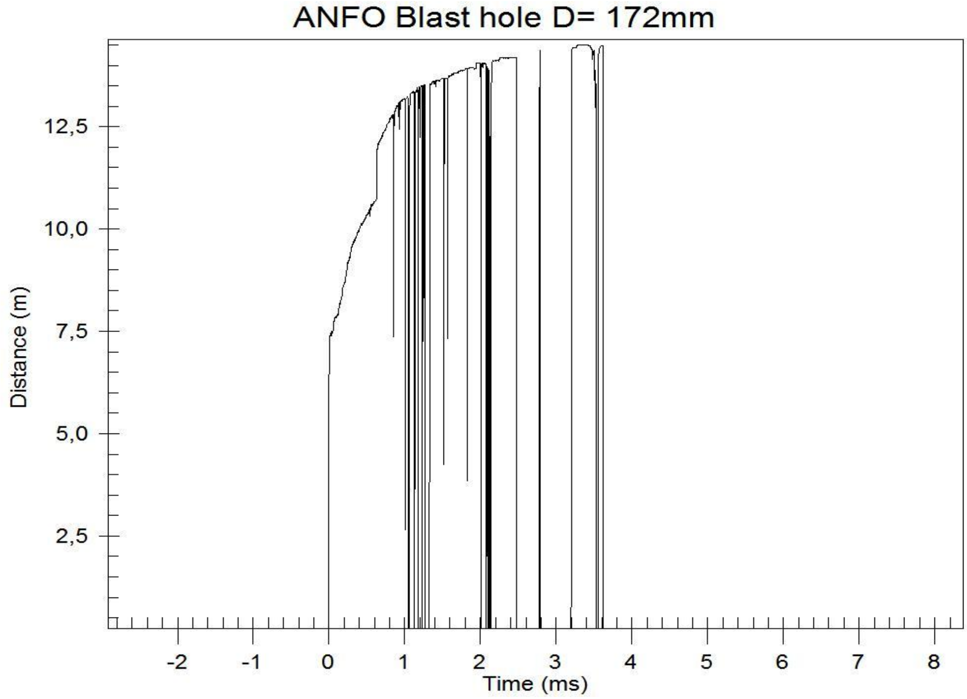

Figure A.21 The original VOD graph for blast pattern 3746-116

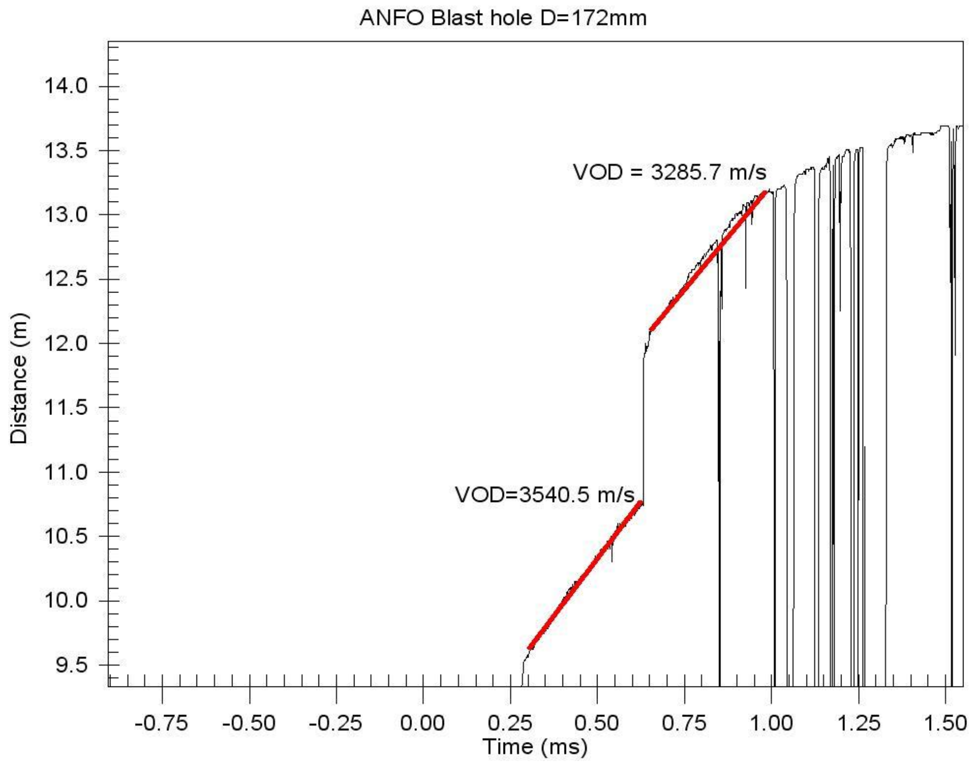

Figure A.22 VOD result for blast pattern 3746-116

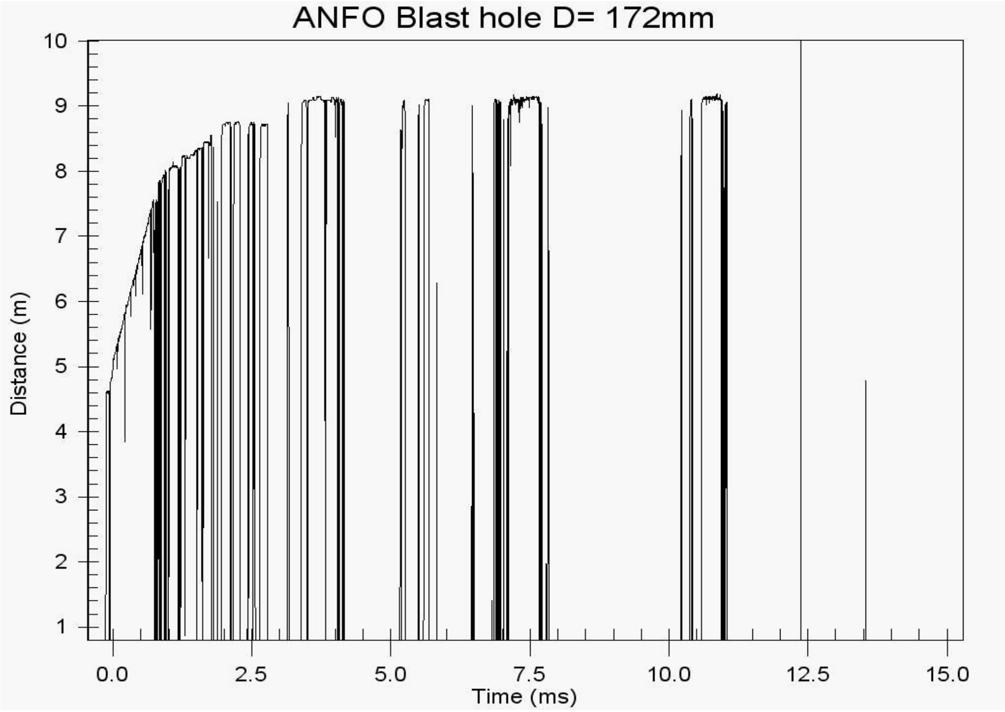

Figure A.23 The original VOD graph for blast pattern 3794-55a

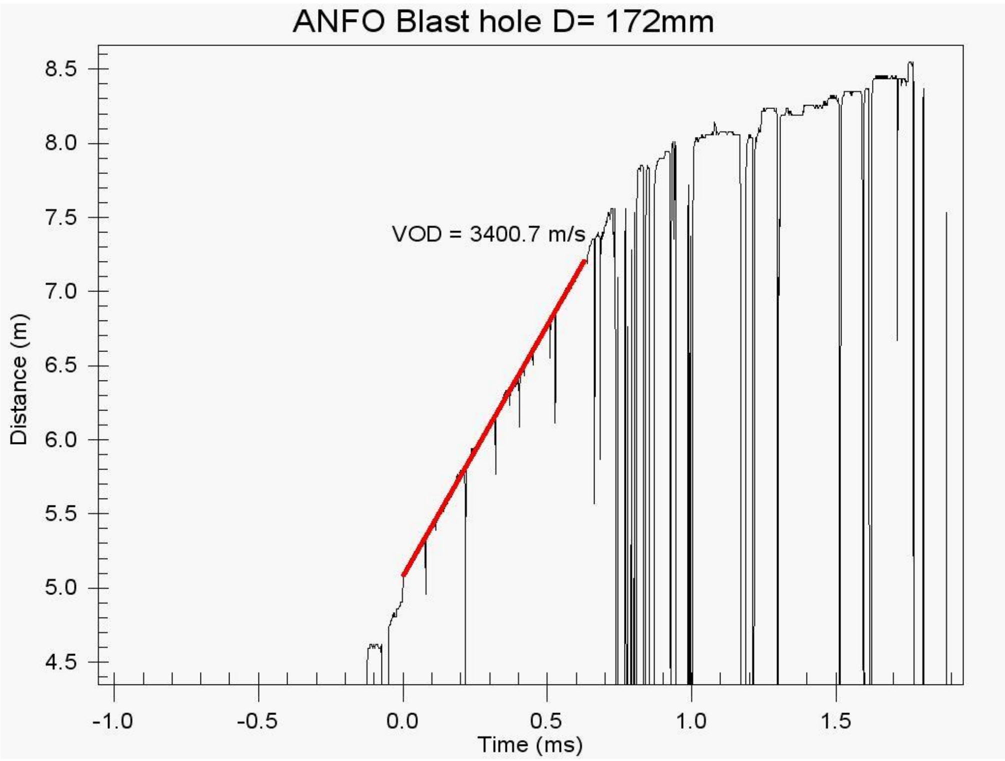

Figure A.24 VOD result for blast pattern 3794-55a

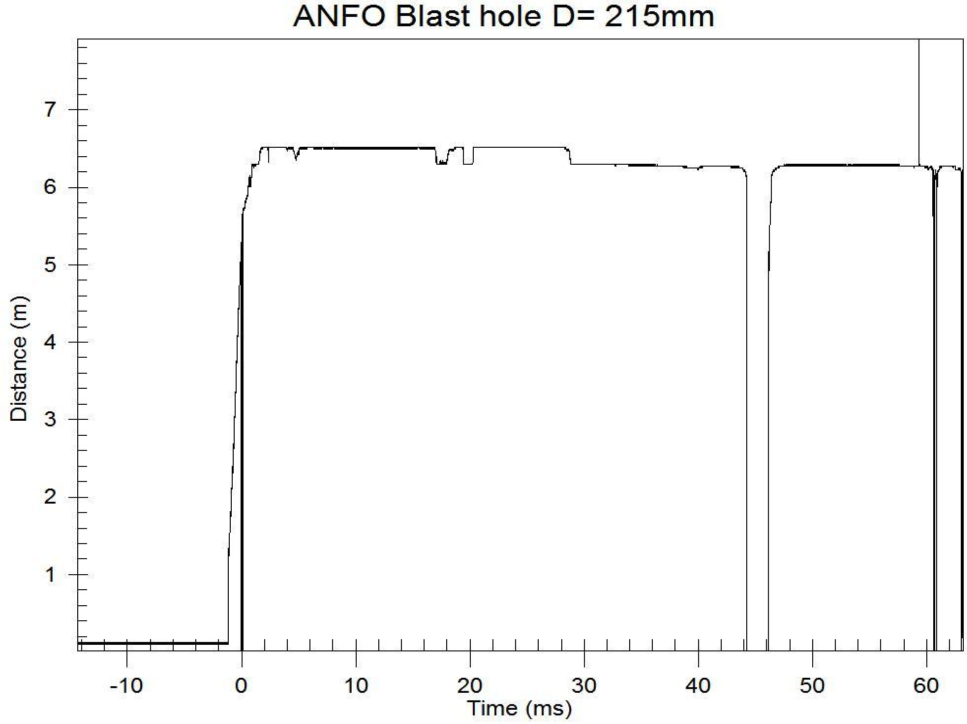

Figure A.25 The original VOD graph for blast pattern 3882-264a

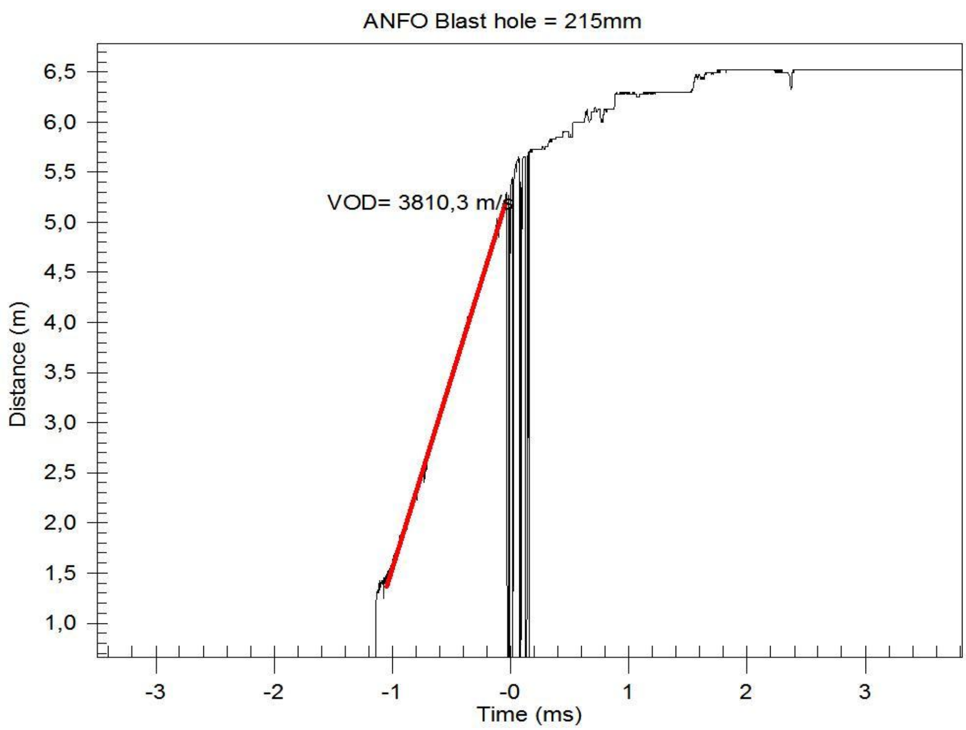

Figure A.26 VOD result for blast pattern 3882-264a

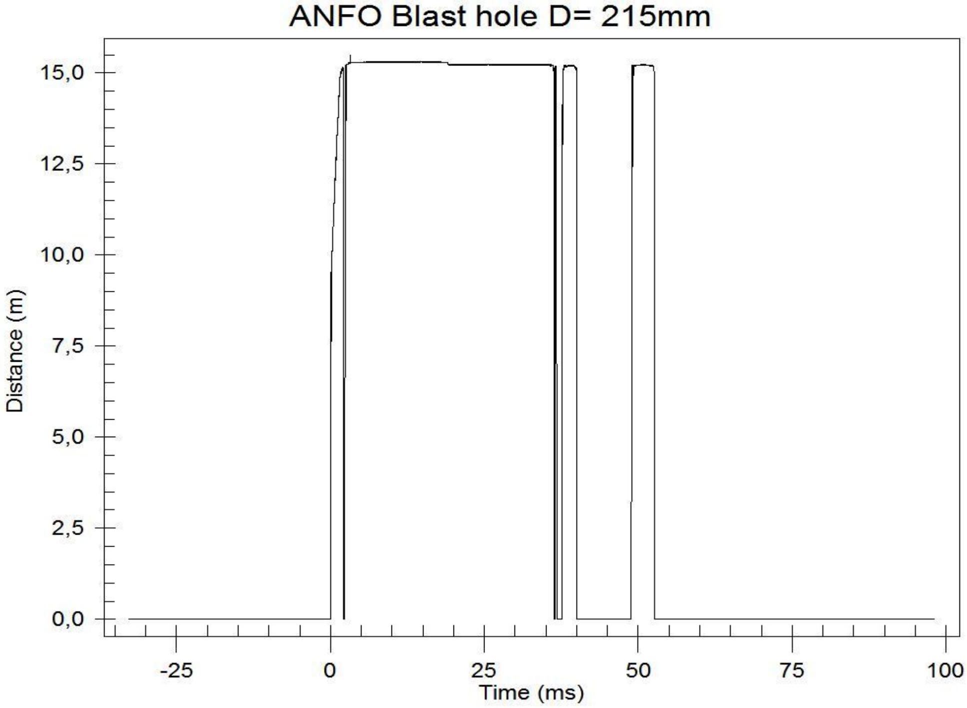

Figure A.27 The original VOD graph for blast pattern 3746-35

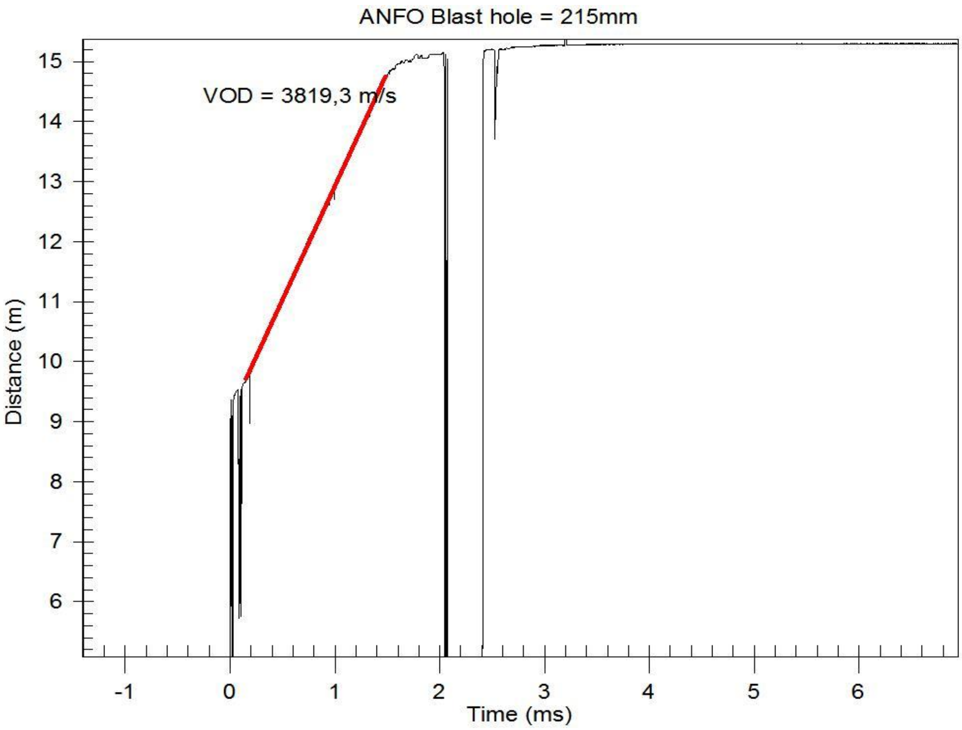

Figure A.28 VOD result for blast pattern 3746-35

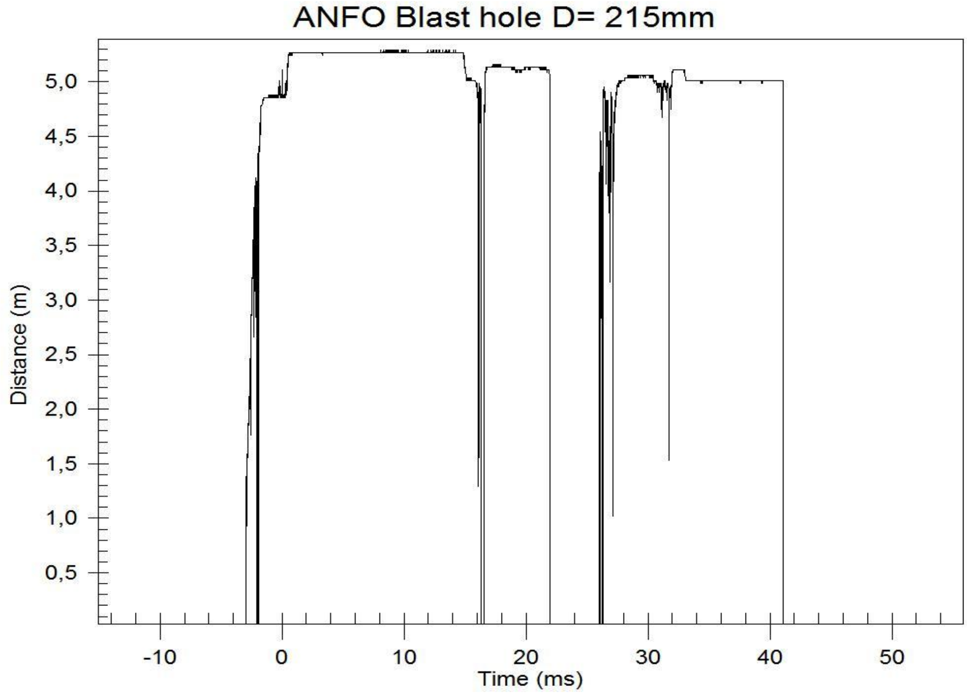

Figure A.29 The original VOD graph for blast pattern 3794-63

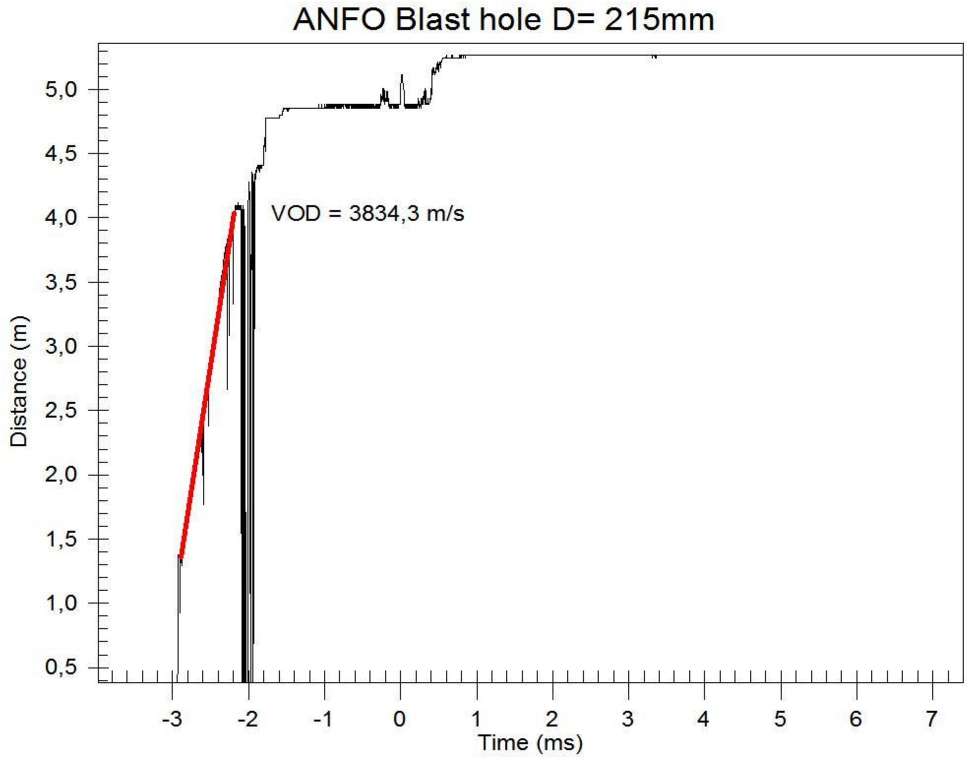

Figure A.30 VOD result for blast pattern 3794-63

APPENDIX B

VOD GRAPHS OF BULK EMULSION

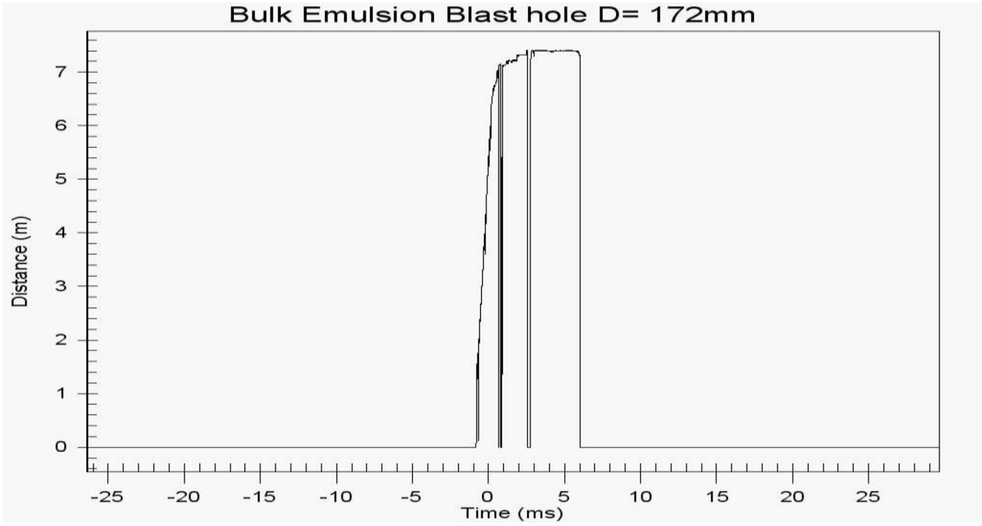

Figure B.1 The original VOD graph for blast pattern 3834-45

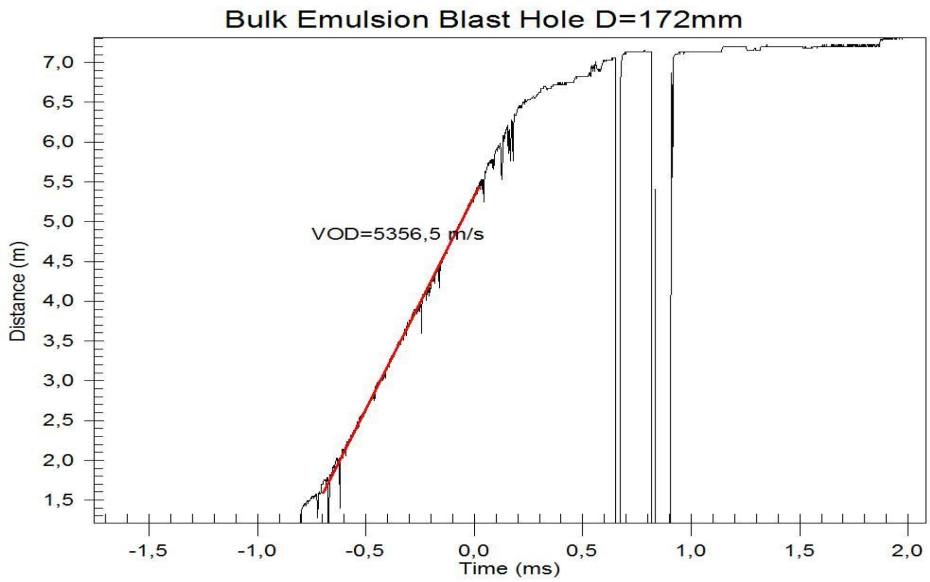

Figure B.2 VOD result for blast pattern 3834-45

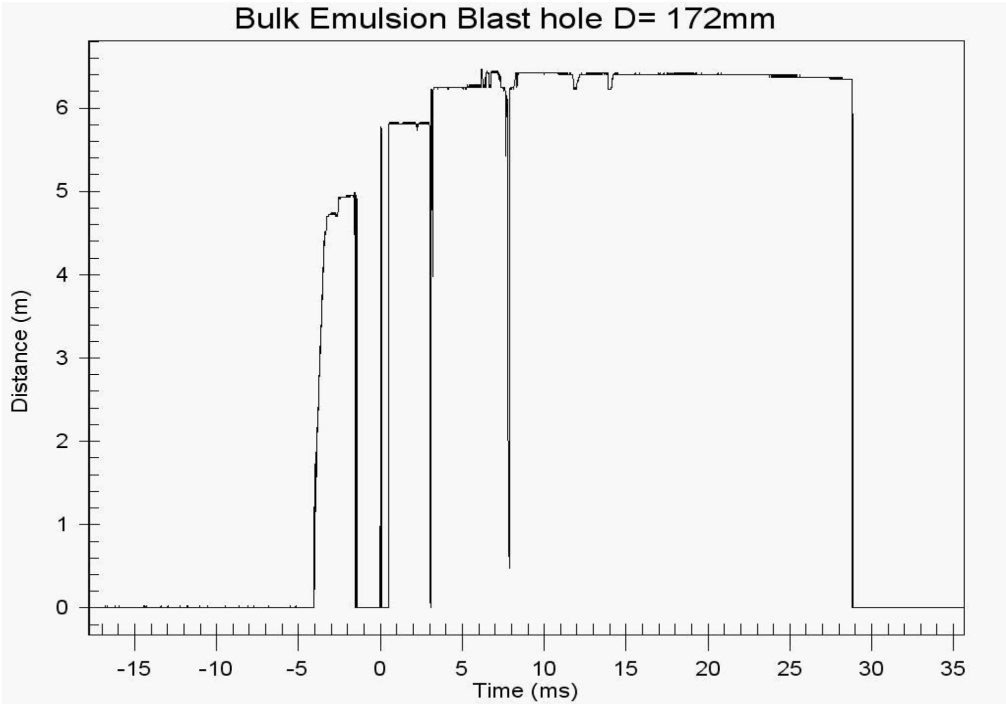

Figure B.3 The original VOD graph for blast pattern 4098-200b

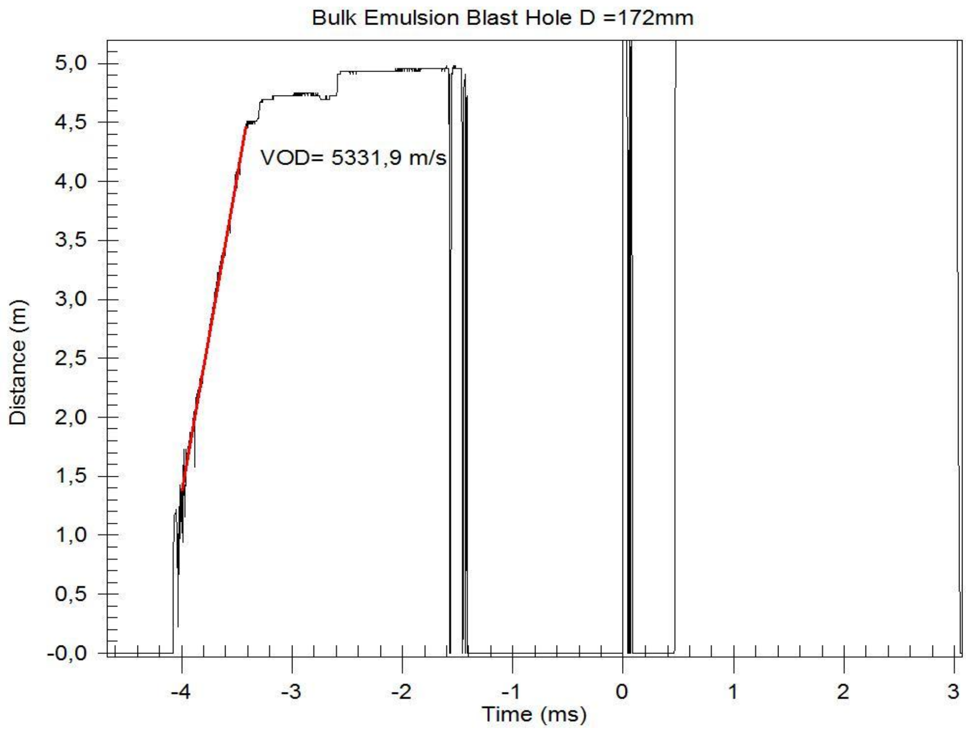

Figure B.4 VOD result for blast pattern 4098-200b

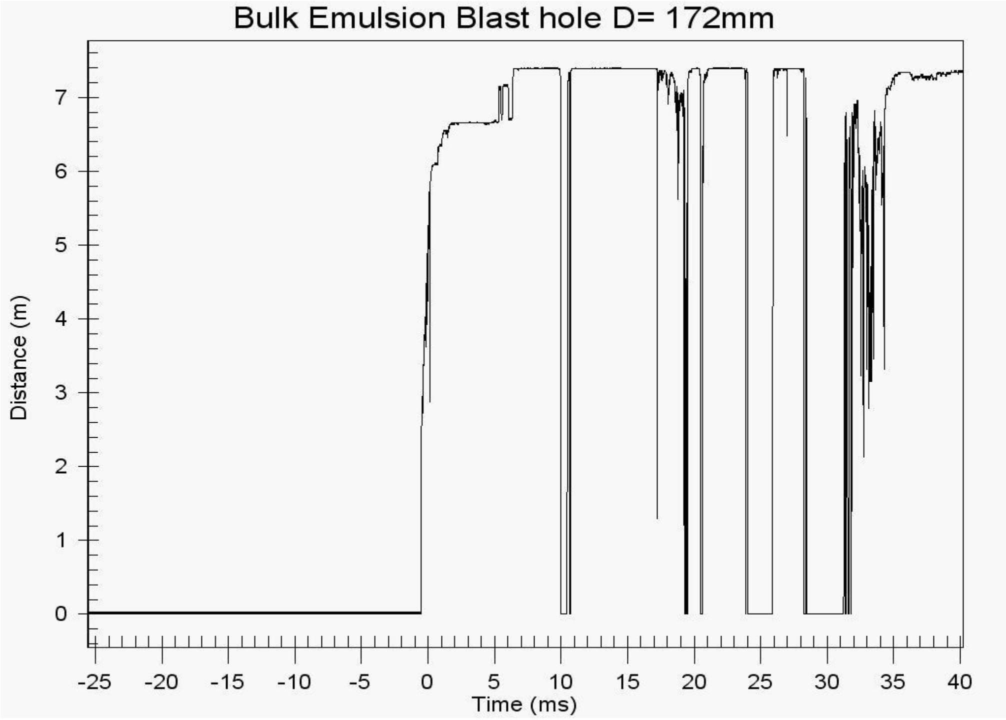

Figure B.5 The original VOD graph for blast pattern 3850-99a

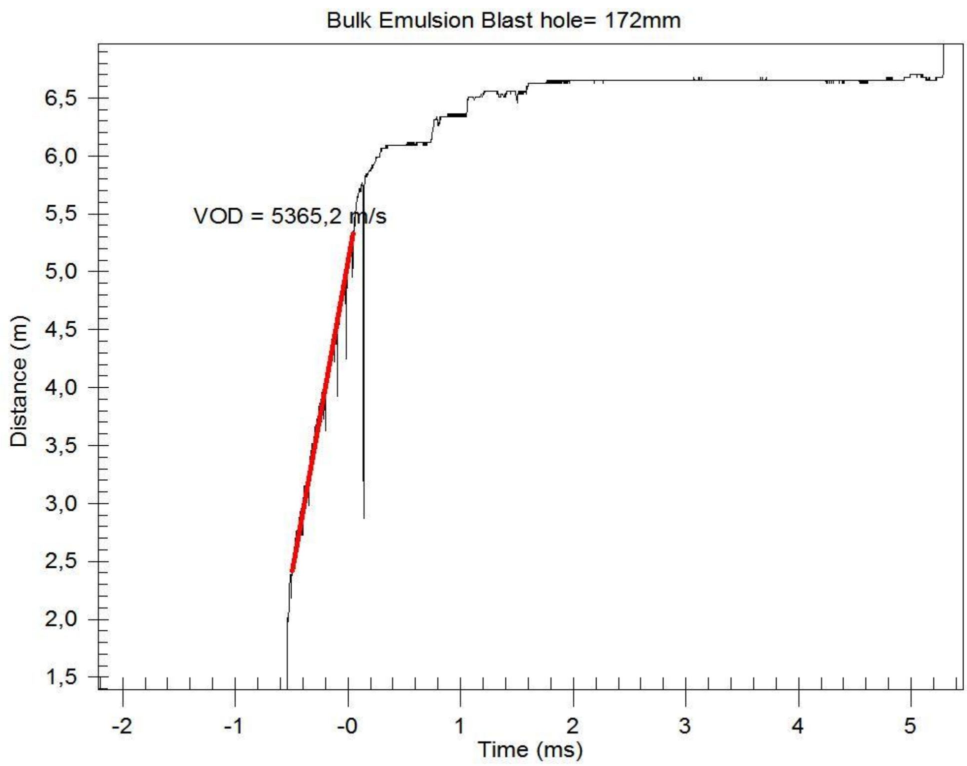

Figure B.6 VOD result for blast pattern 3850-99a

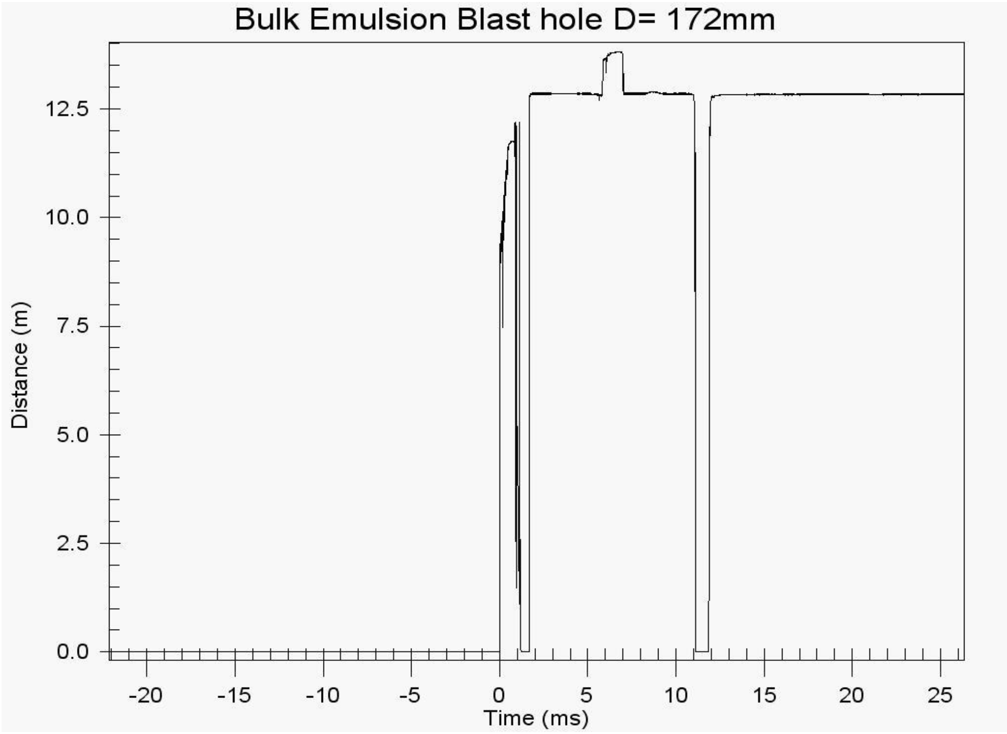

Figure B.7 The original VOD graph for blast pattern 3842-145

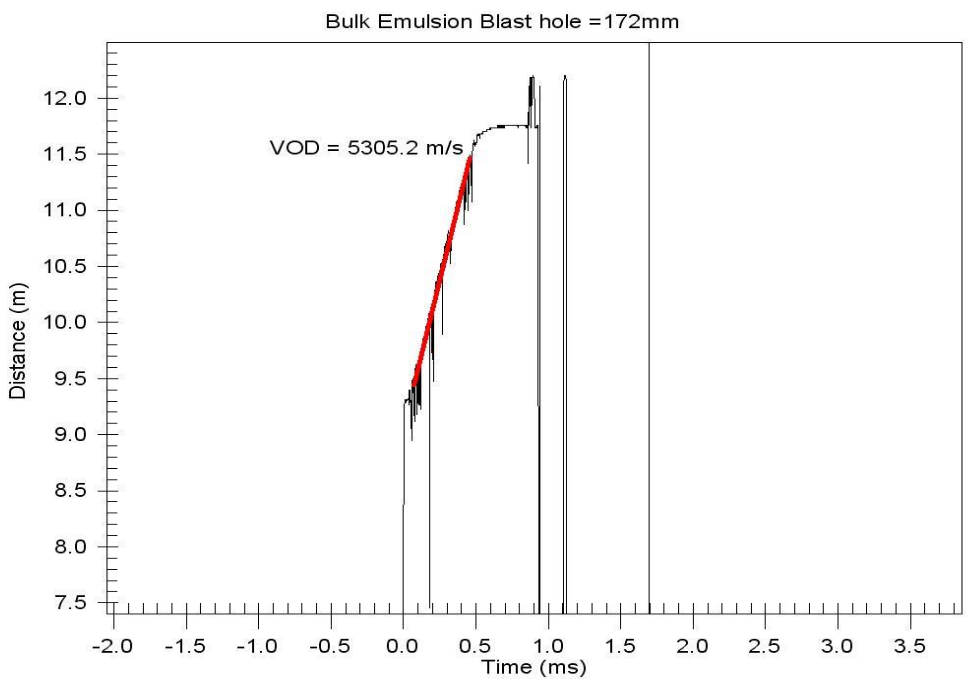

Figure B.8 VOD result for blast pattern 3842-145

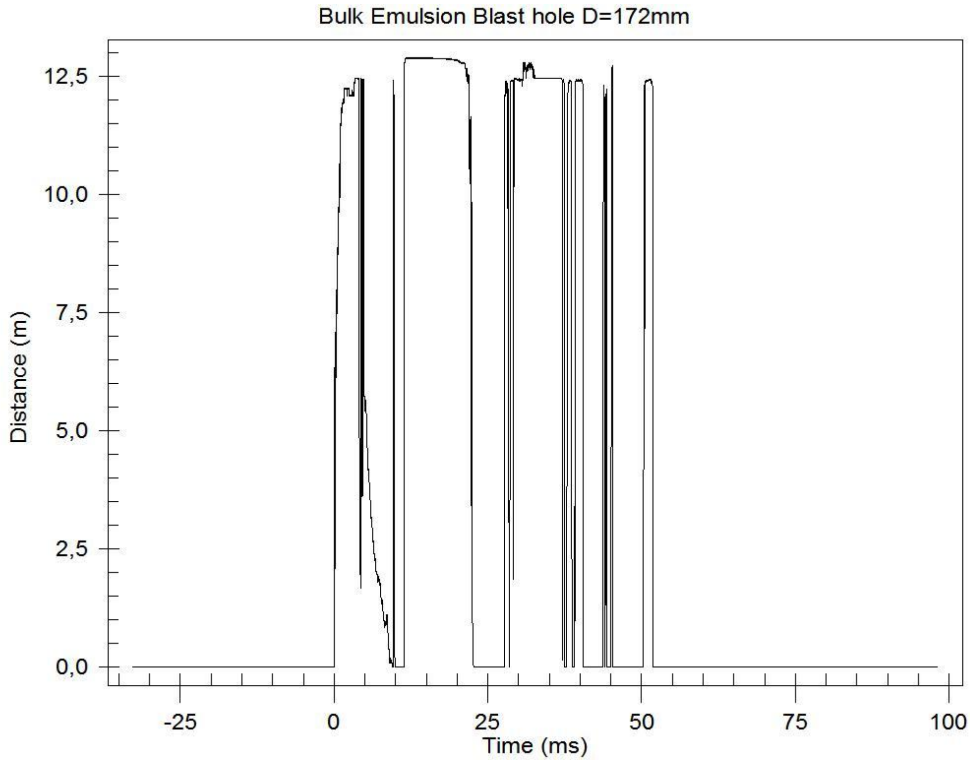

Figure B.9 The original VOD graph for blast pattern 4040-6b-7b

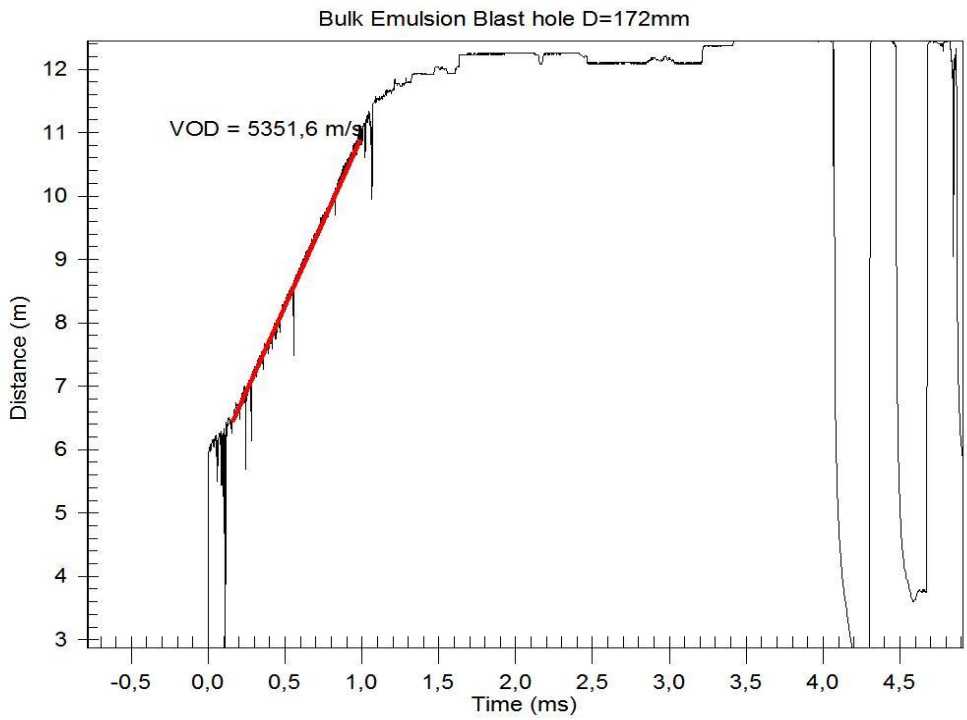

Figure B.10 VOD result for blast pattern 4040-6b-7b

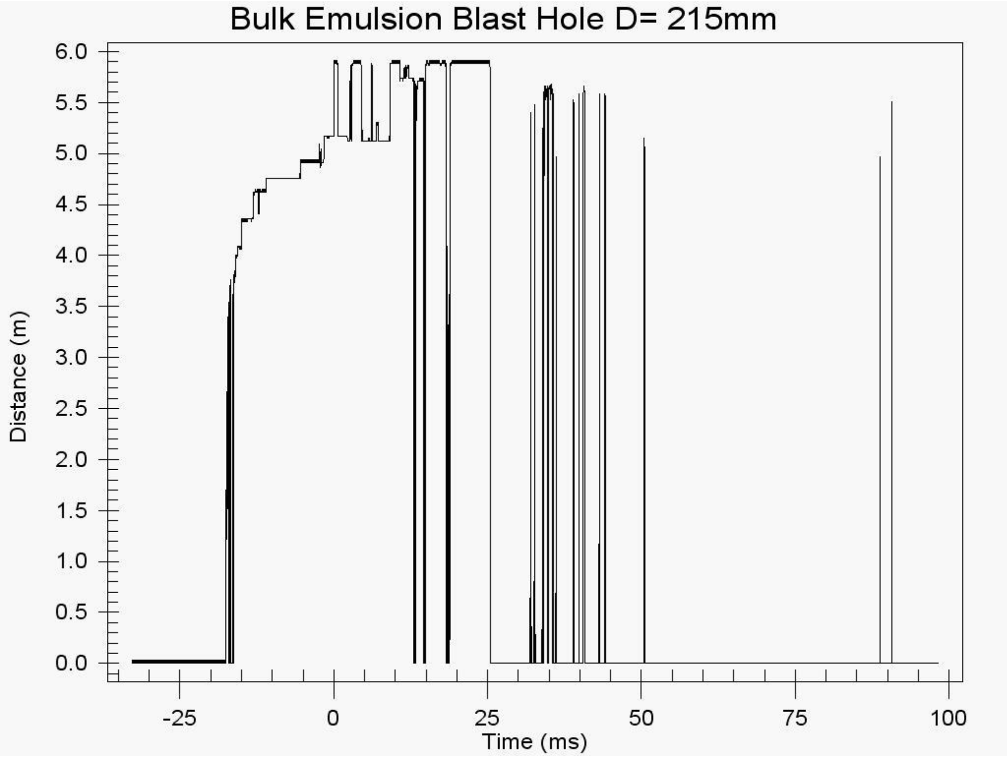

Figure B.11 The original VOD graph for blast pattern 3810-59

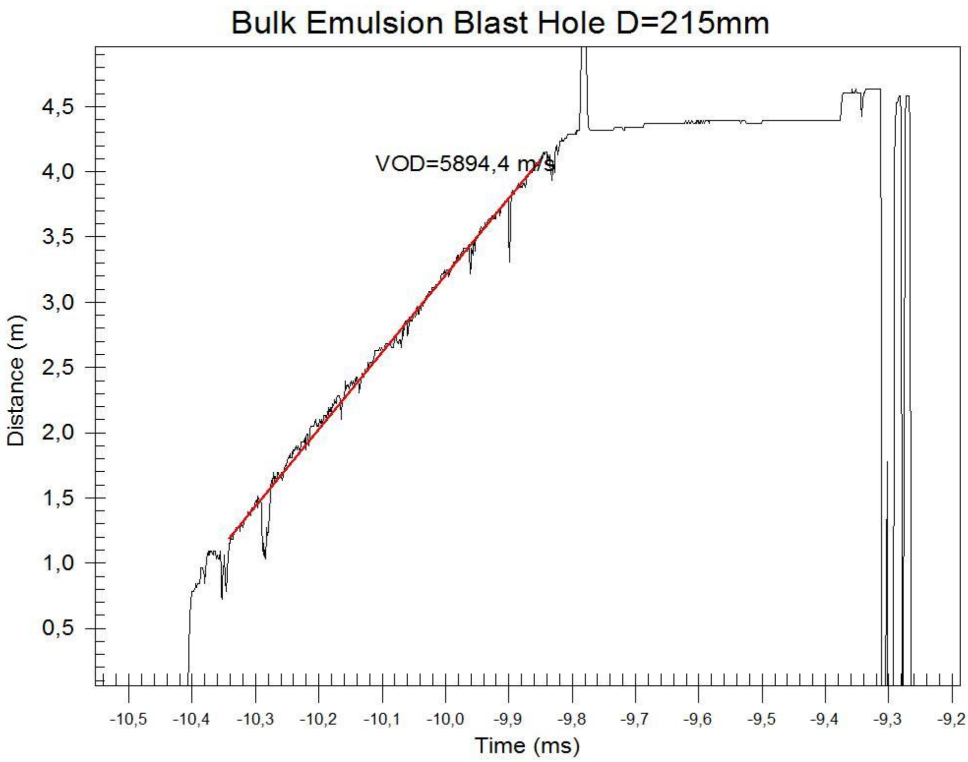

Figure B.12 VOD result for blast pattern 3810-59

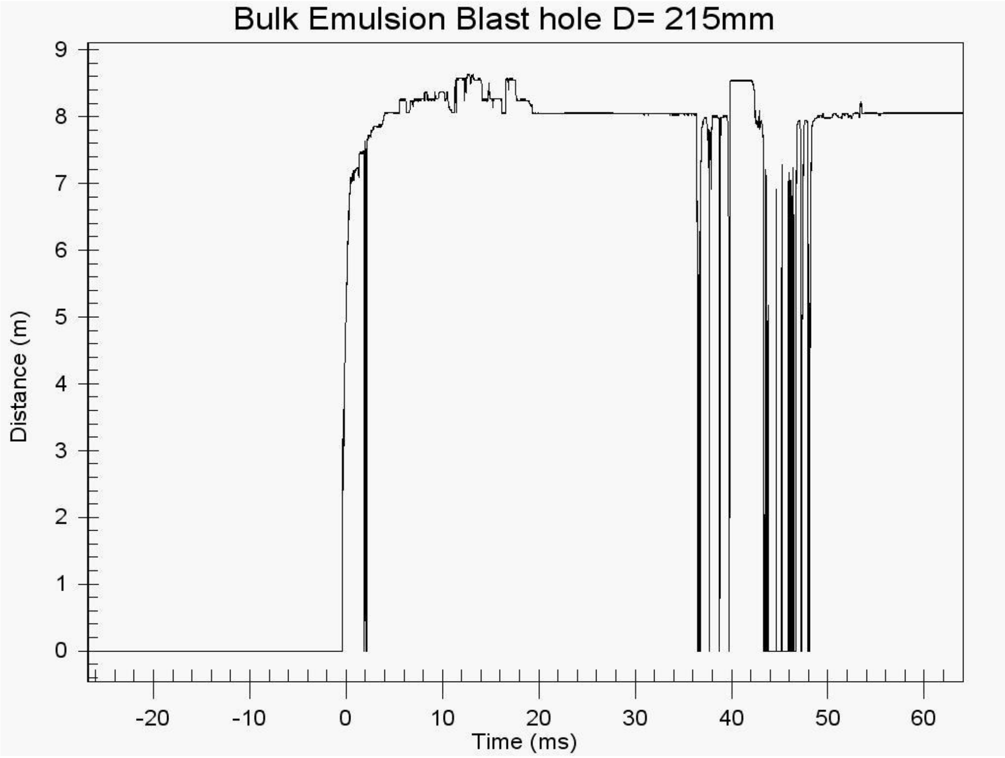

Figure B.13 The original VOD graph for blast pattern 3834-300a

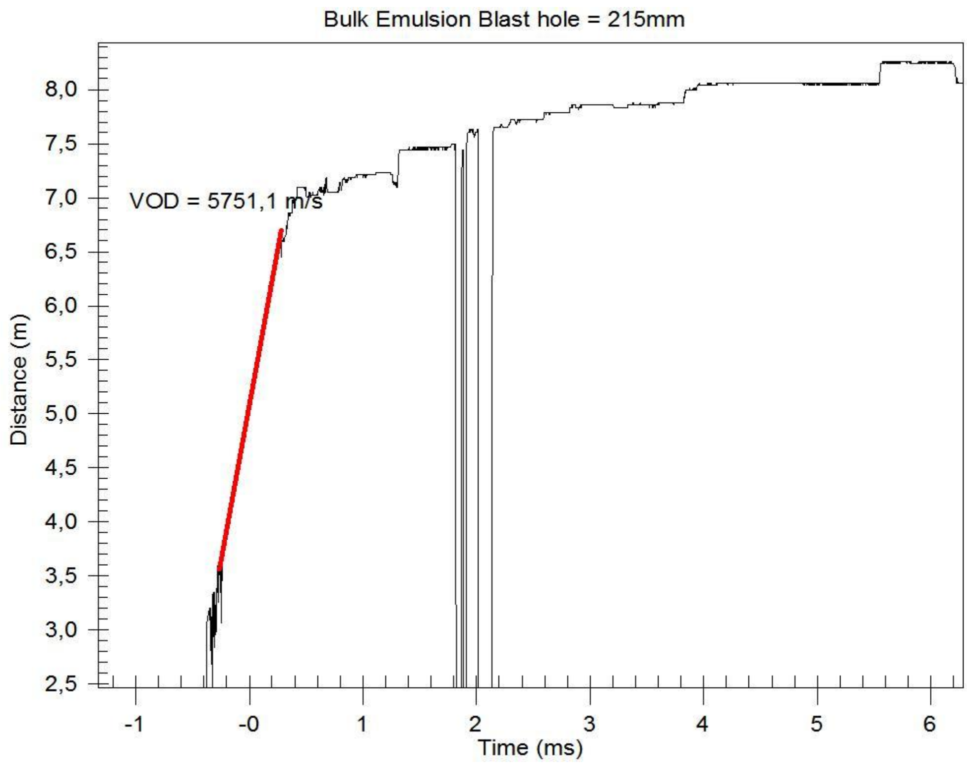

Figure B.14 VOD result for blast pattern 3834-300a

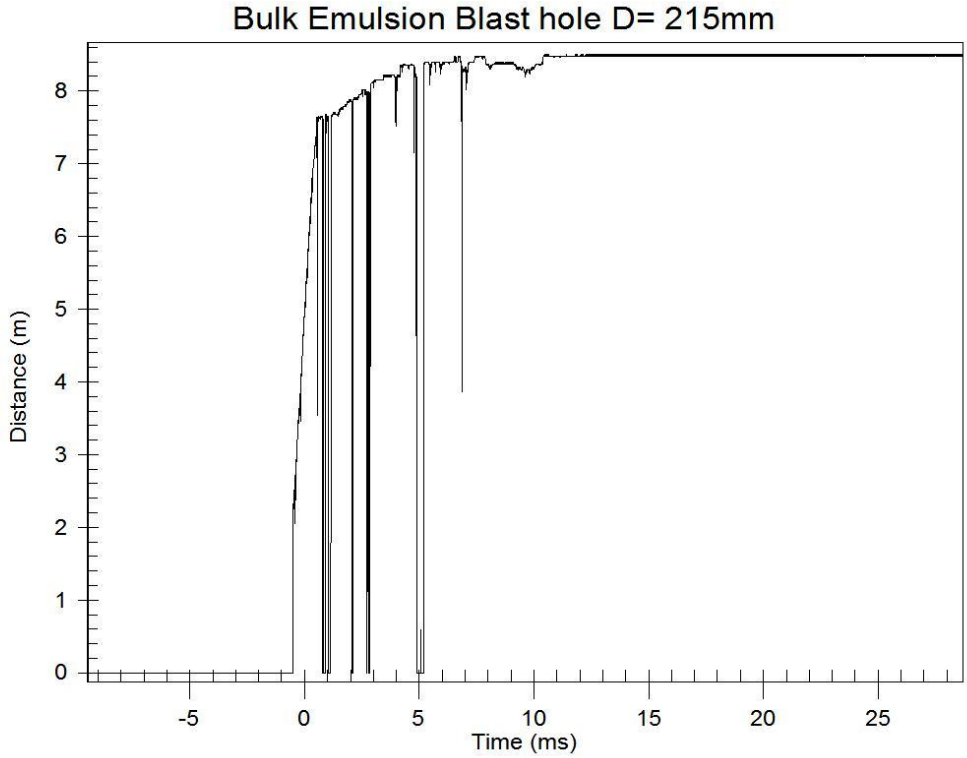

Figure B.15 The original VOD graph for blast pattern 3786-52

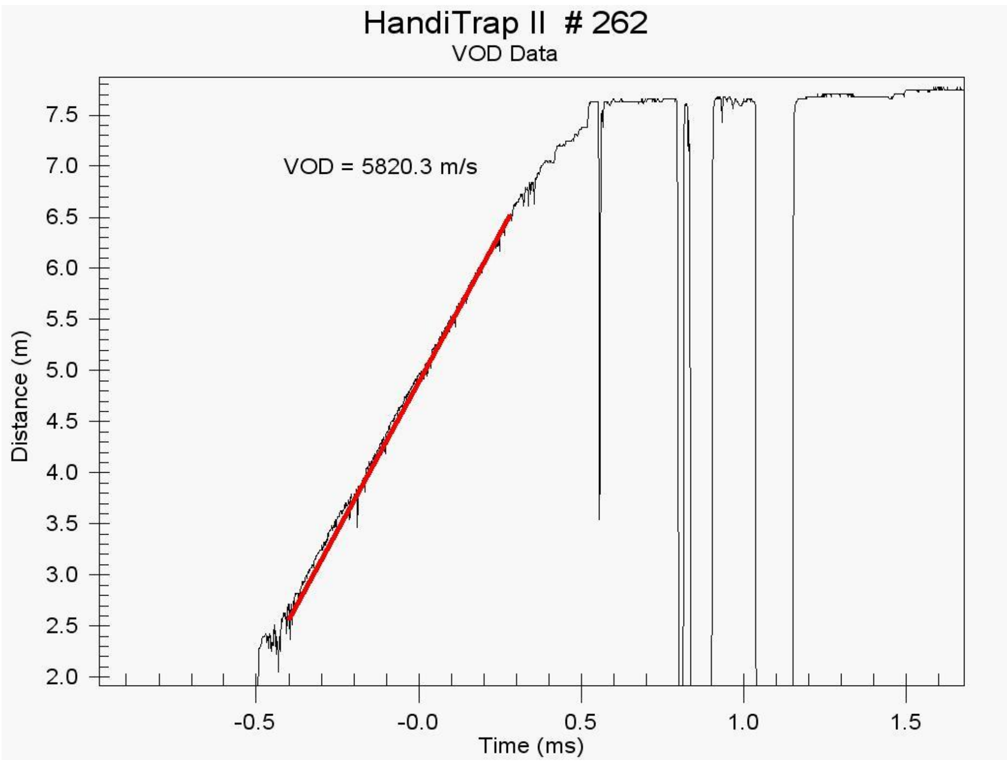

Figure B.16 VOD result for blast pattern 3786-52

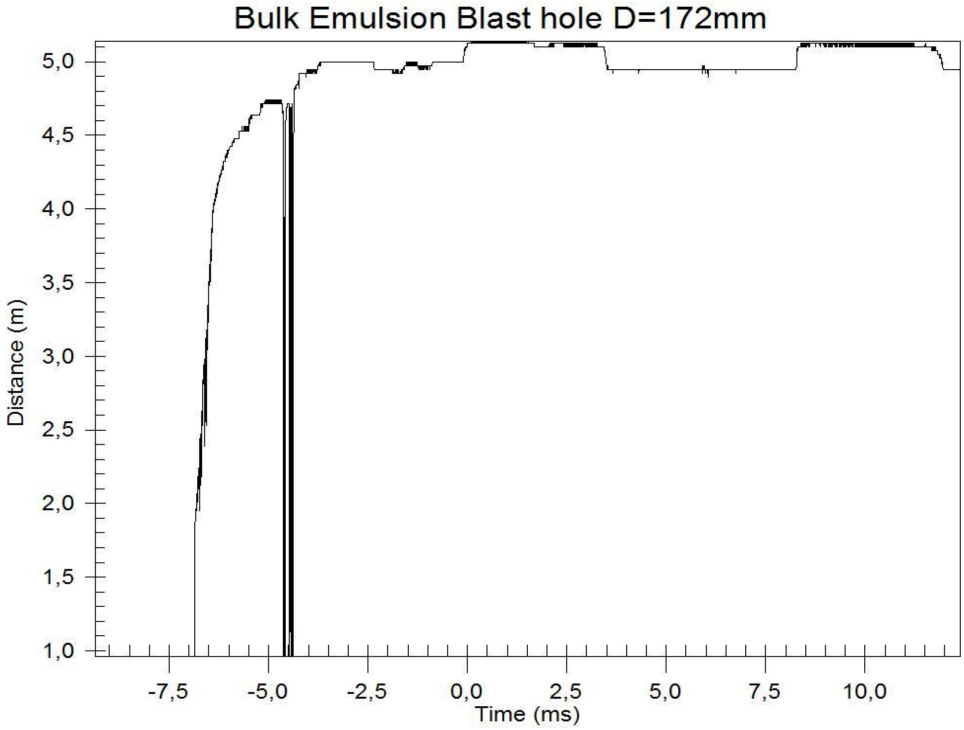

Figure B.17 The original VOD graph for blast pattern 3754-11

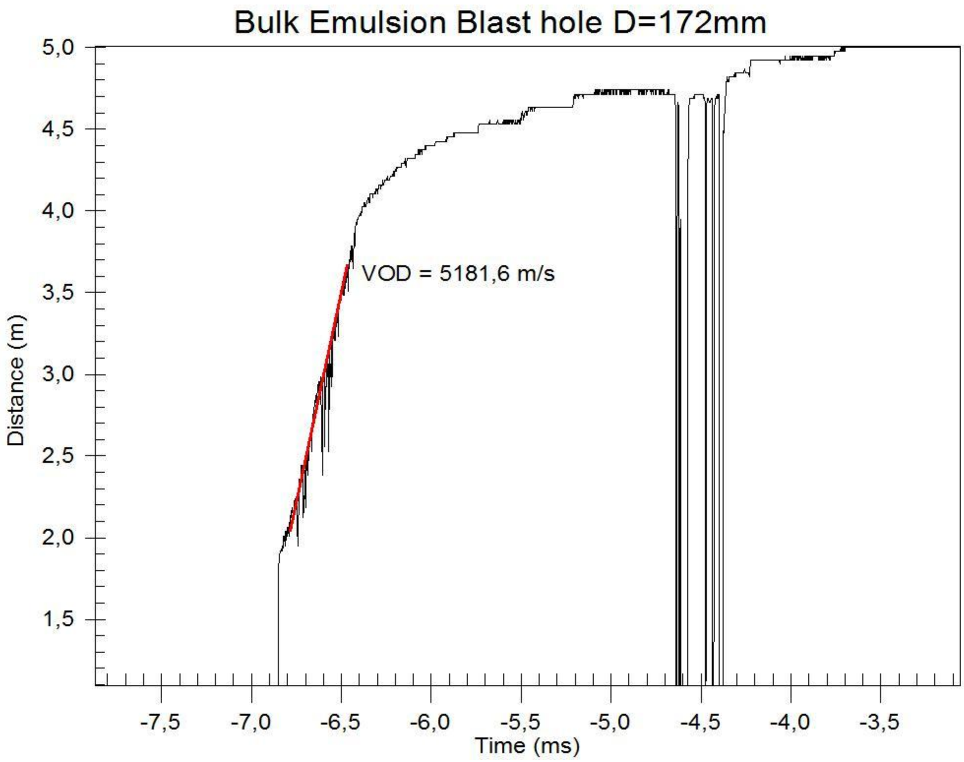

Figure B.18 VOD result for blast pattern 3754-11

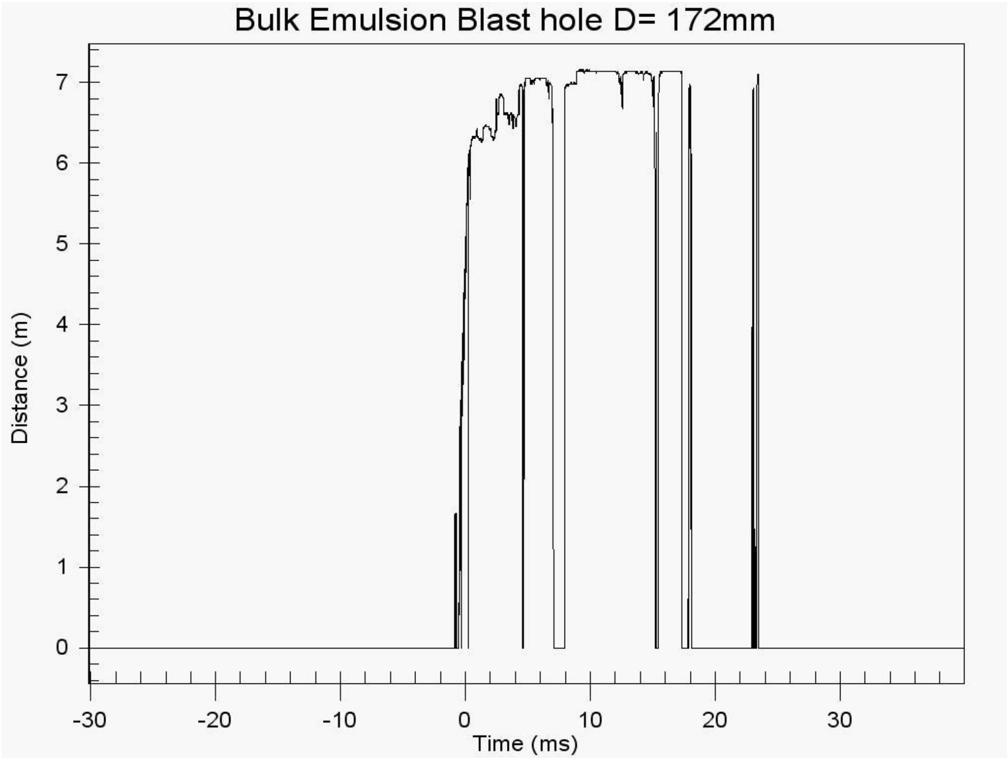

Figure B.19 The original VOD graph for blast pattern 3746-13

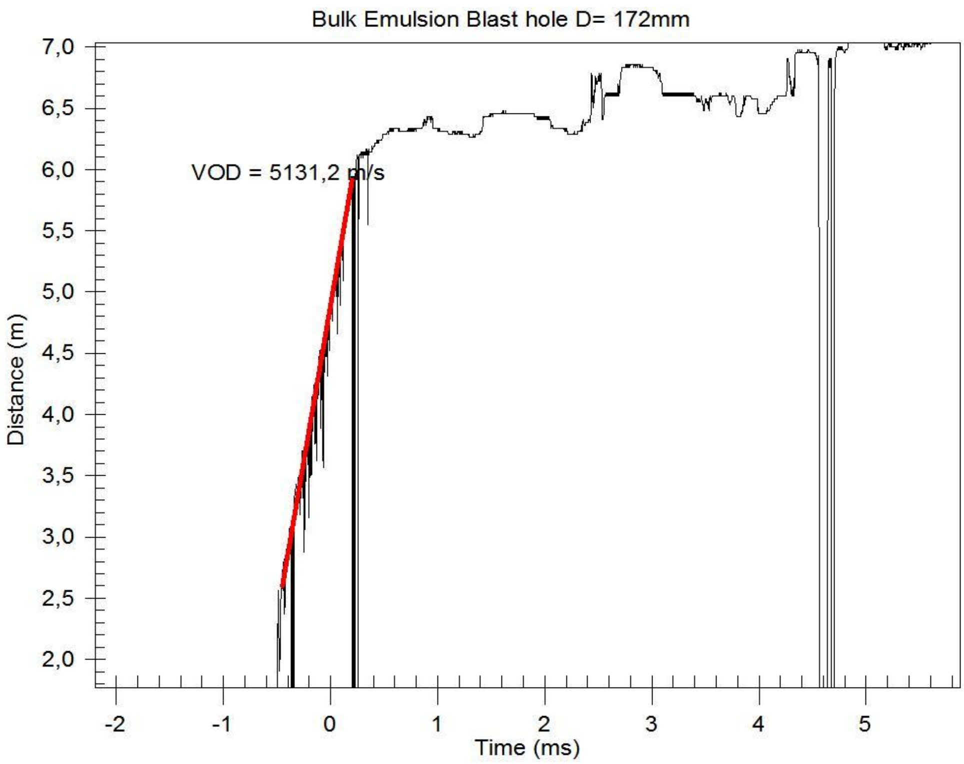

Figure B.20 VOD result for blast pattern 3746-13

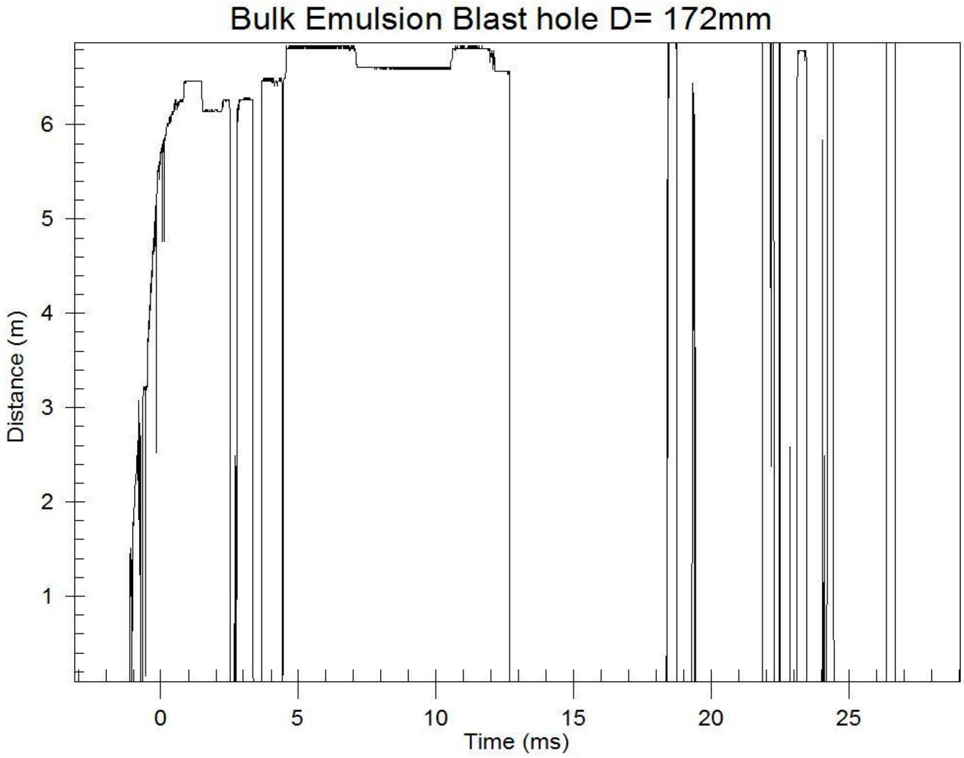

Figure B.21 The original VOD graph for blast pattern 3706-1

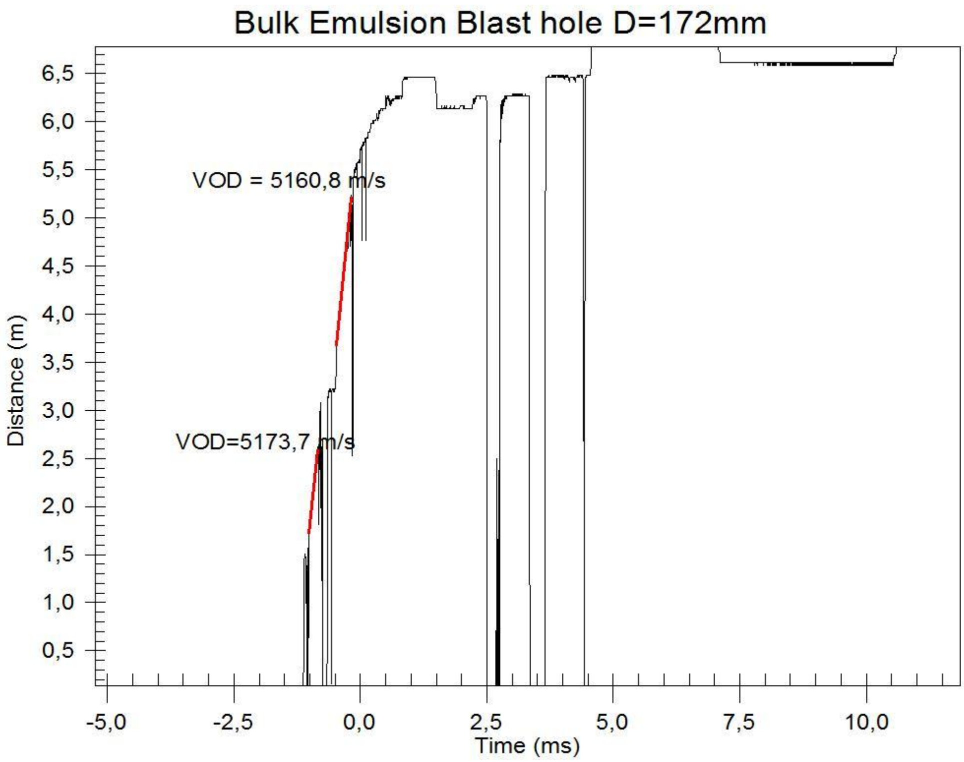

Figure B.22 VOD result for blast pattern 3706-1

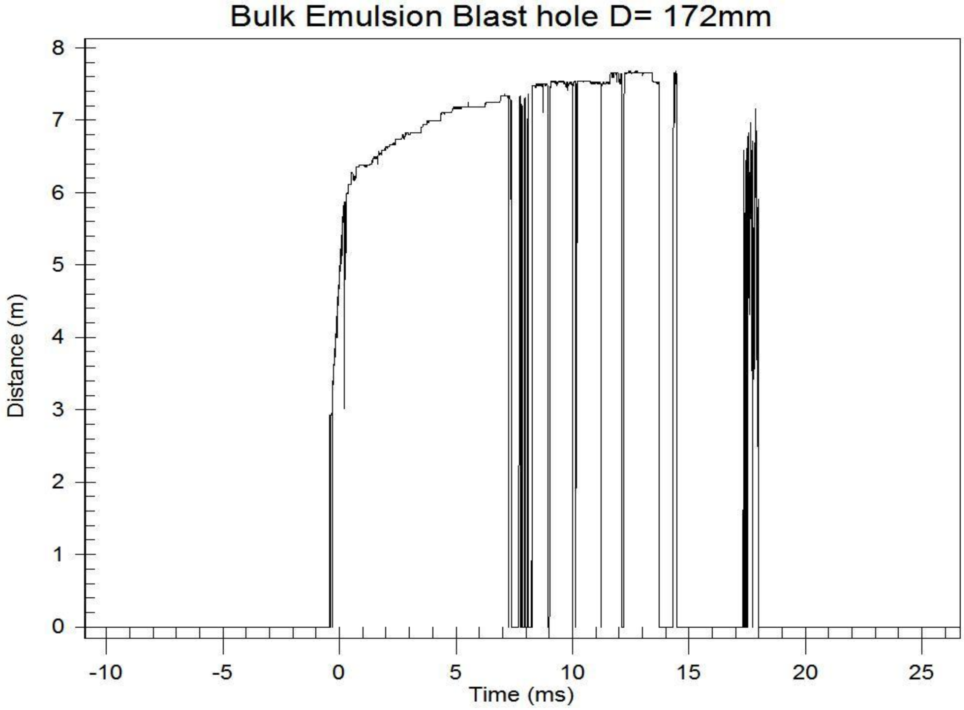

Figure B.23 The original VOD graph for blast pattern 3754-57

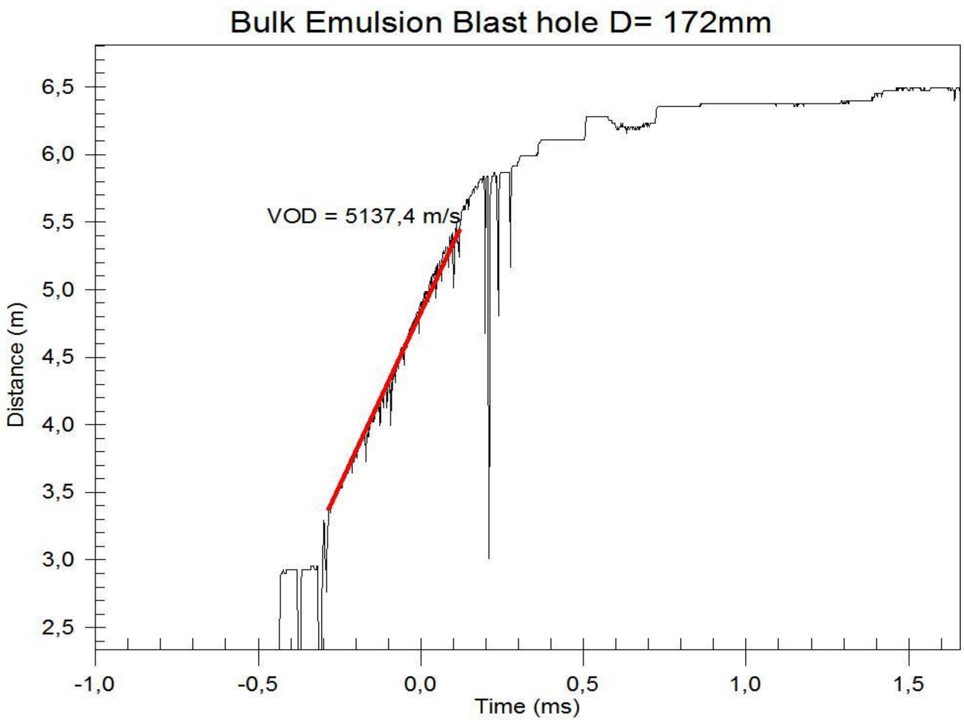

Figure B.24 VOD result for blast pattern 3754-57

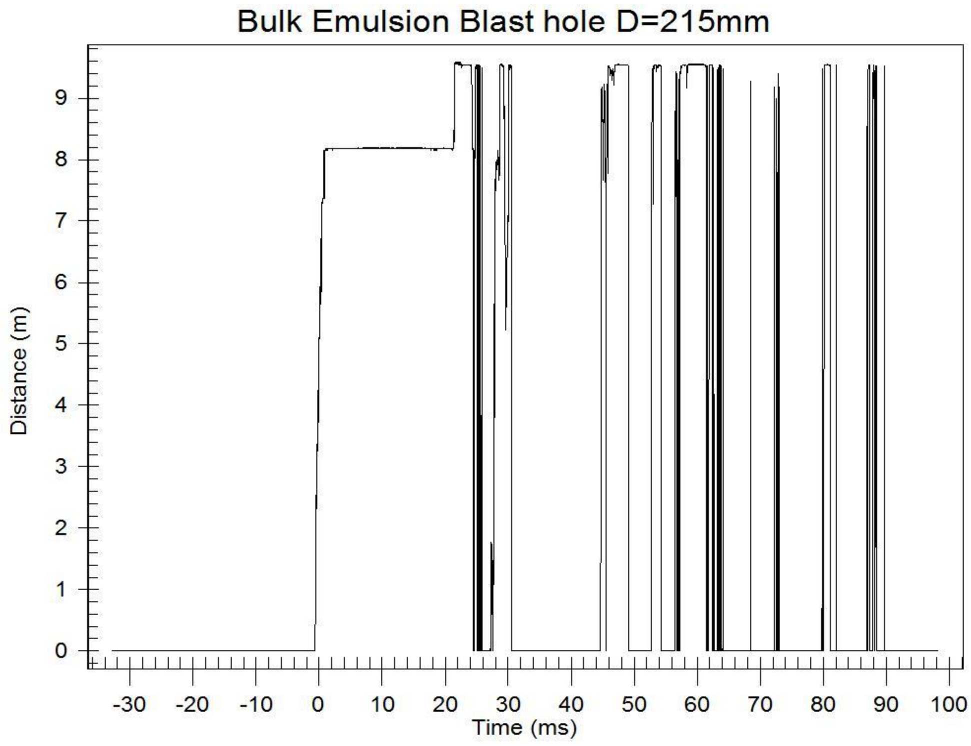

Figure B.25 The original VOD graph for blast pattern 3746-11

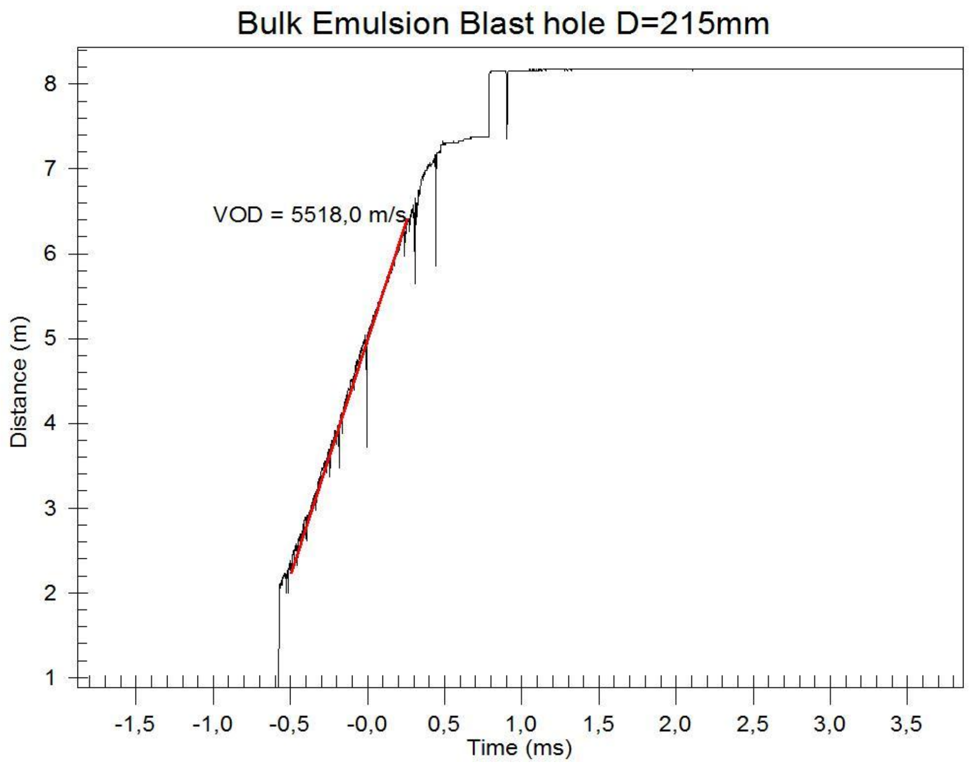

Figure B.26 VOD result for blast pattern 3746-11

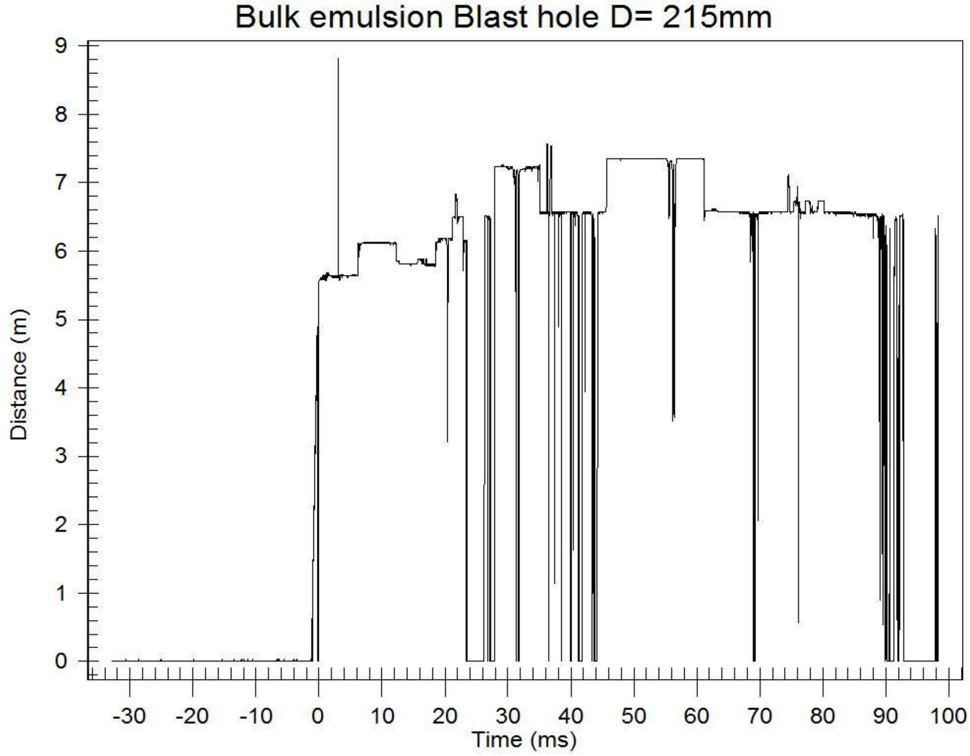

Figure B.27 The original VOD graph for blast pattern 3746-9

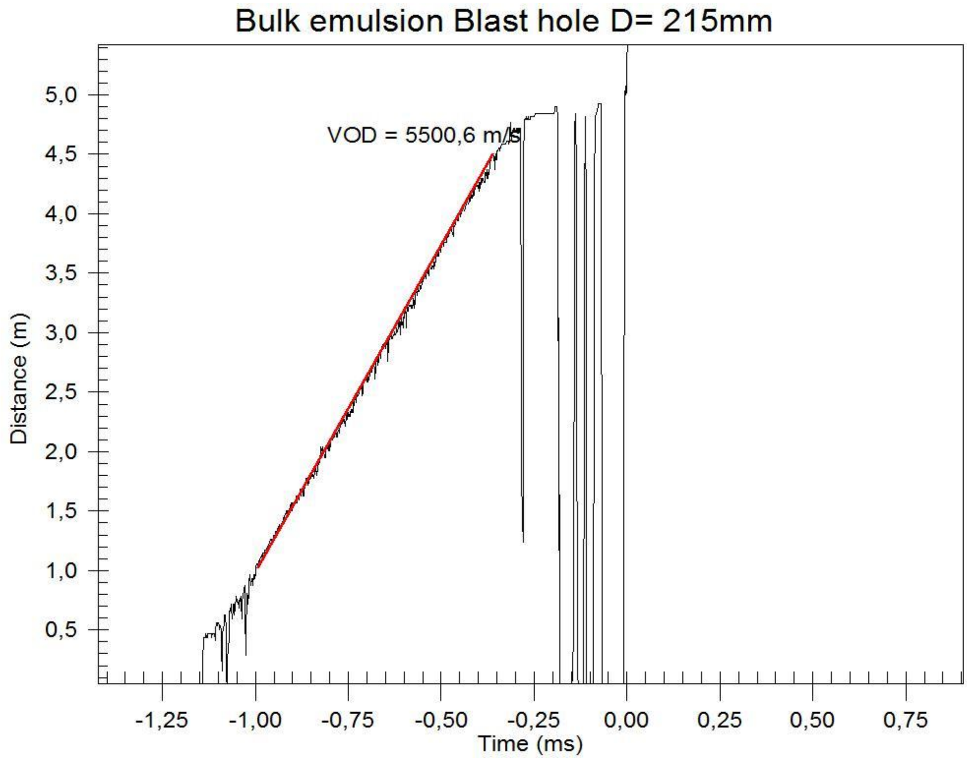

Figure B.28 VOD result for blast pattern 3746-9

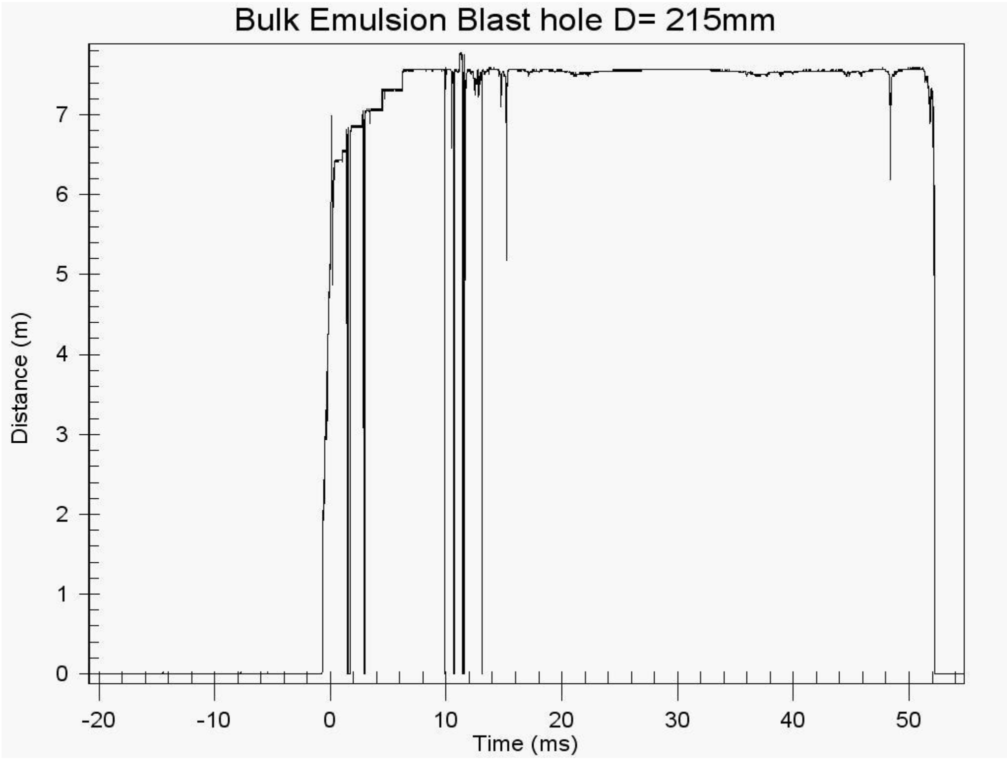

Figure B.29 The original VOD graph for blast pattern 3882-265

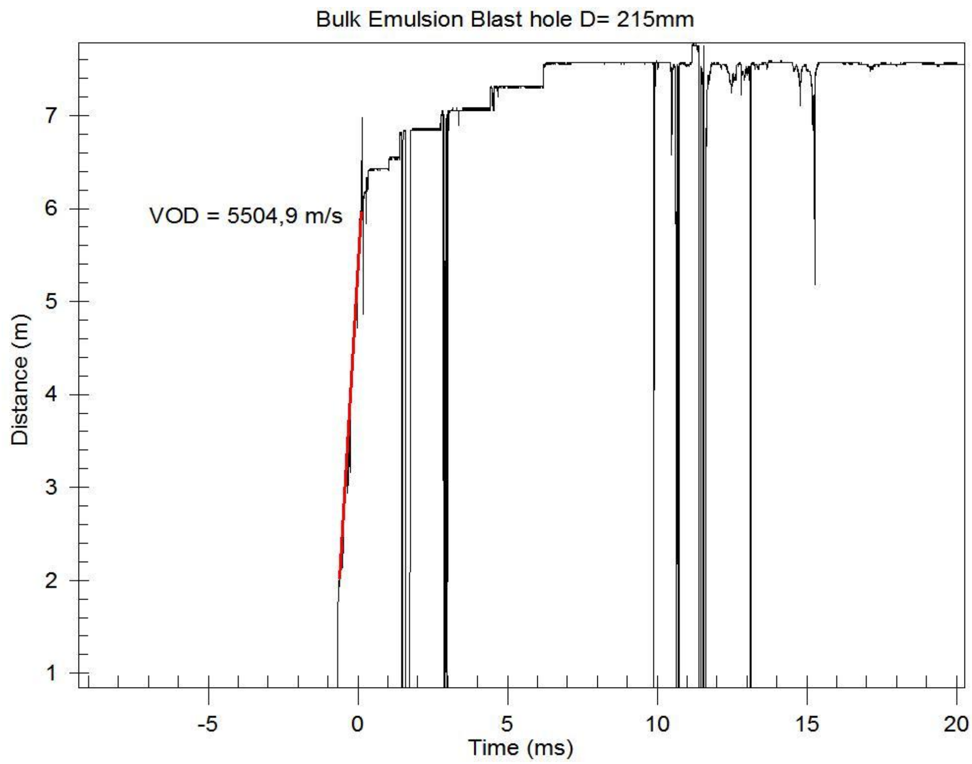

Figure B.30 VOD result for blast pattern 3882-265

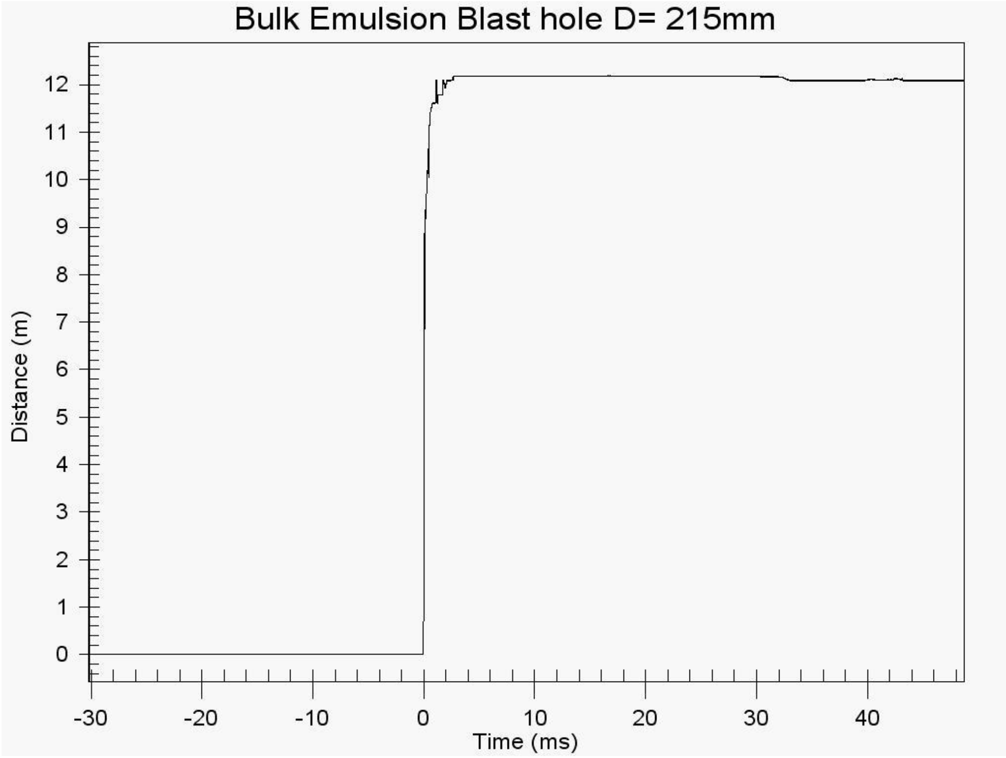

Figure B.31 The original VOD graph for blast pattern 3802-60

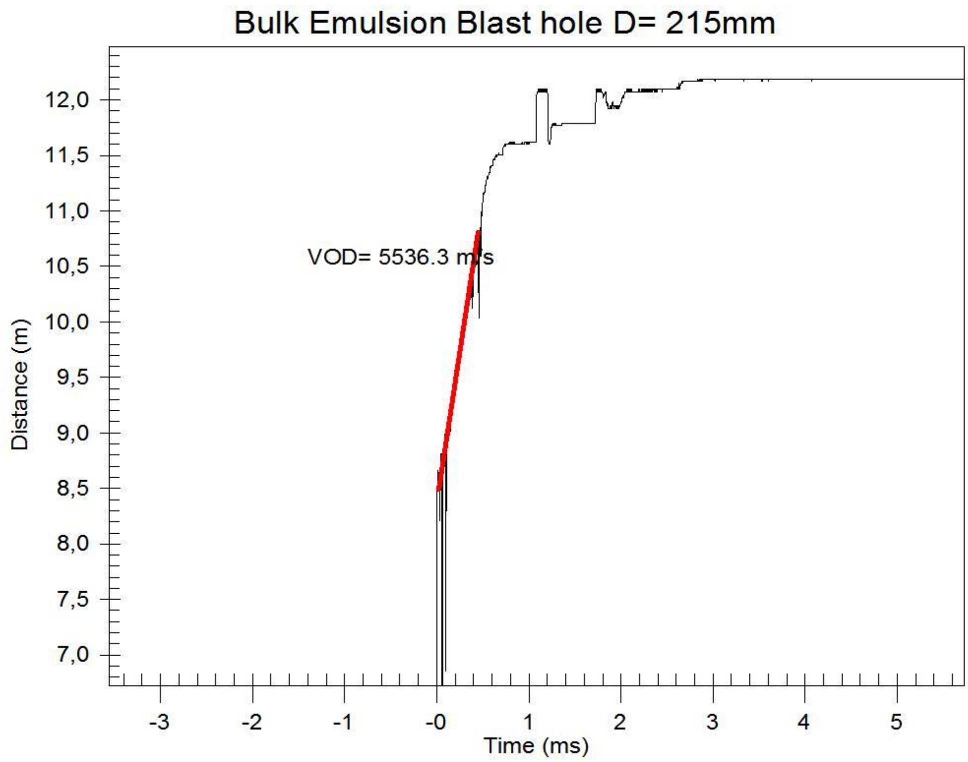

Figure B.32 VOD result for blast pattern 3802-60

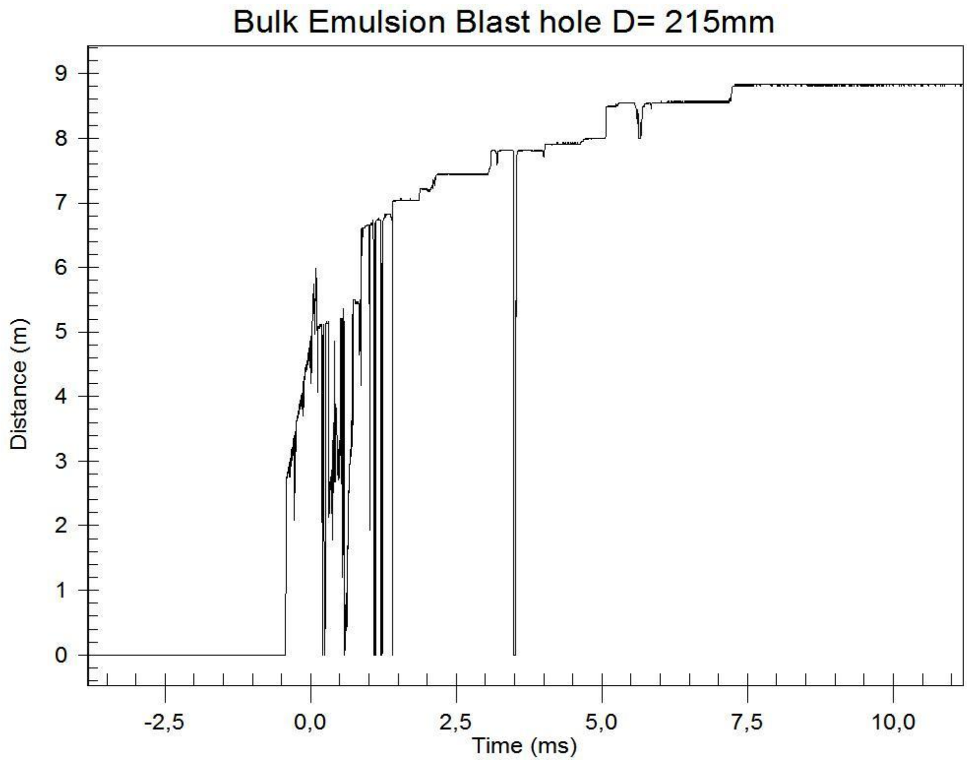

Figure B.33 The original VOD graph for blast pattern 3786-53

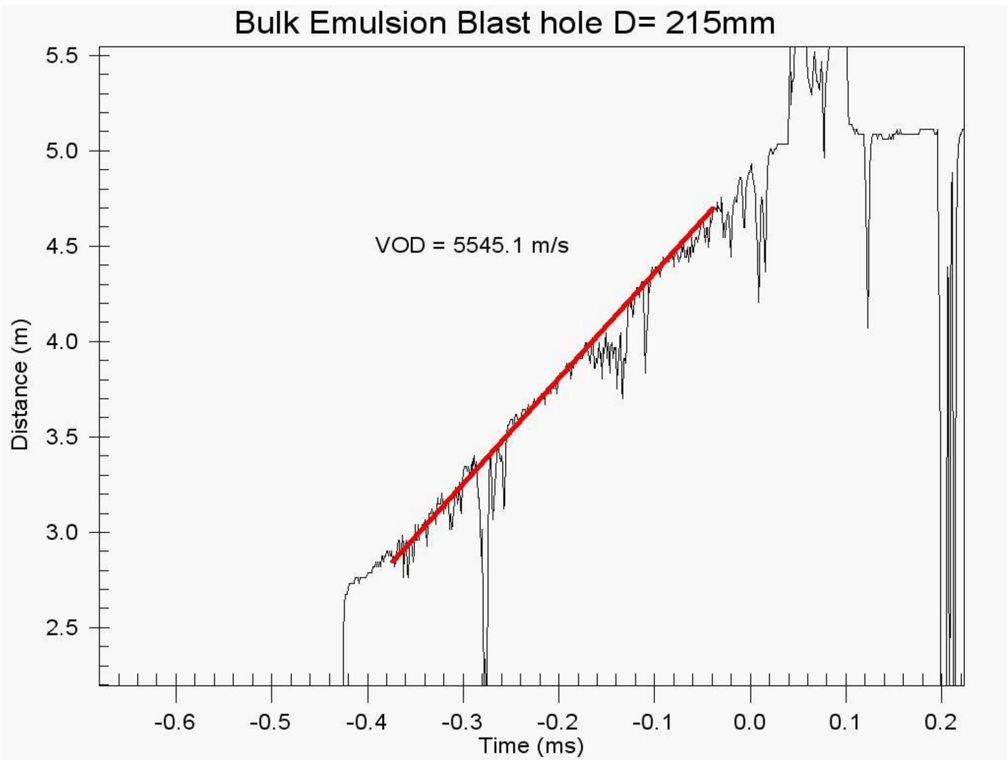

Figure B.34 VOD result for blast pattern 3786-53

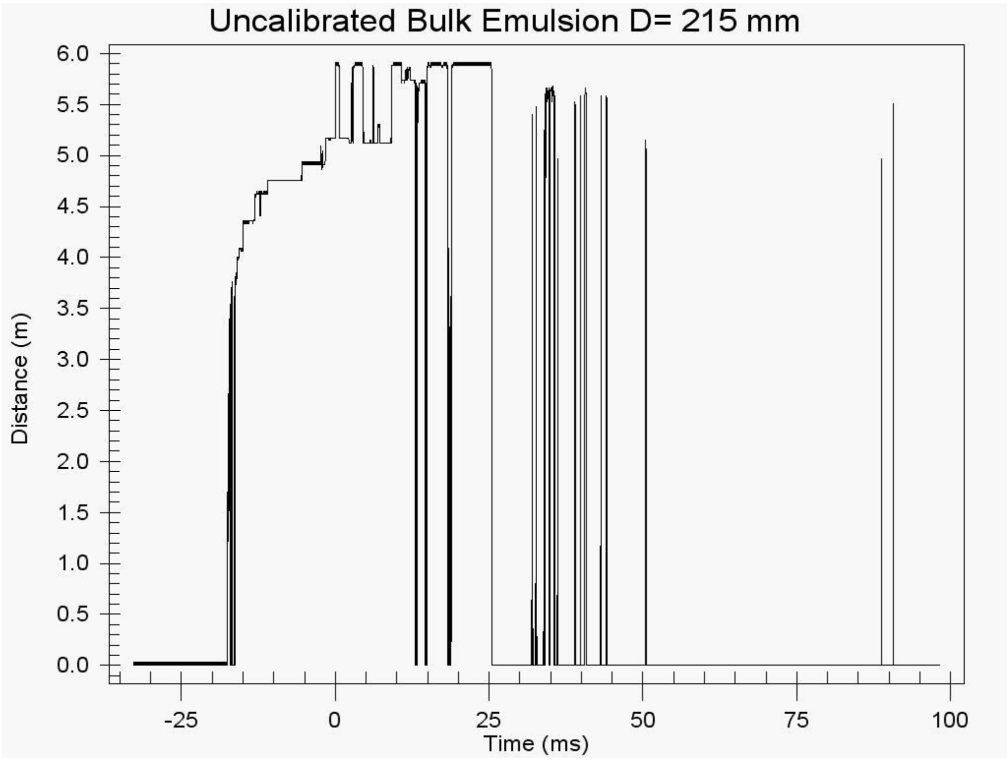

Figure B.35 The original VOD graph for blast pattern 3706-2

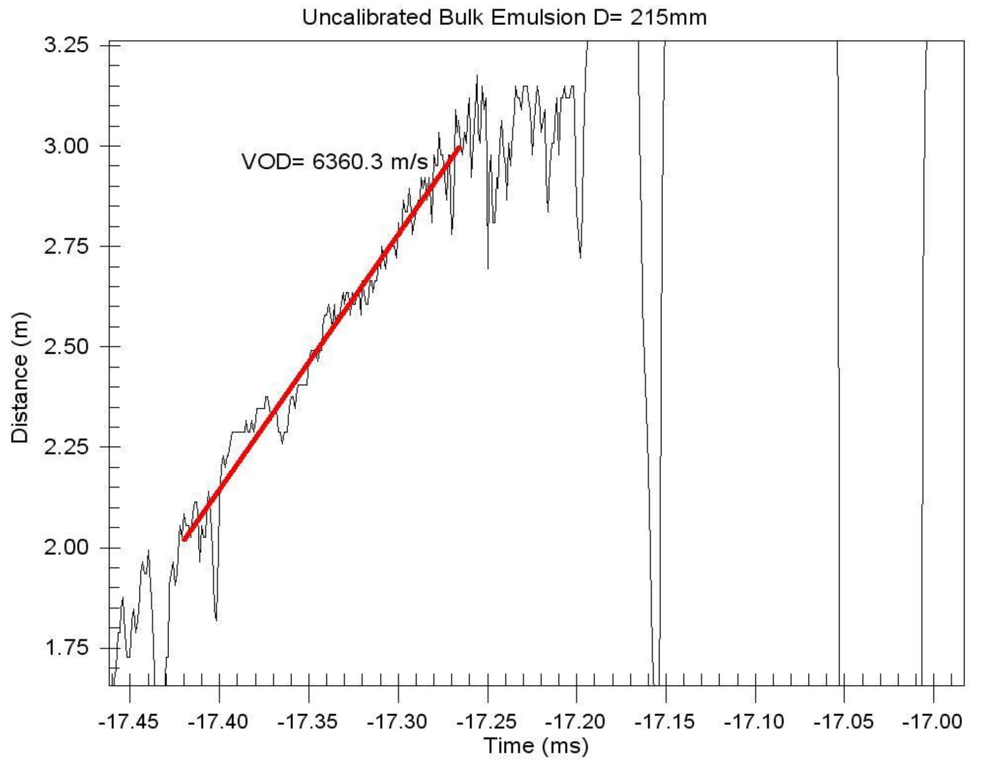

Figure B.36 VOD result for blast pattern 3706-2

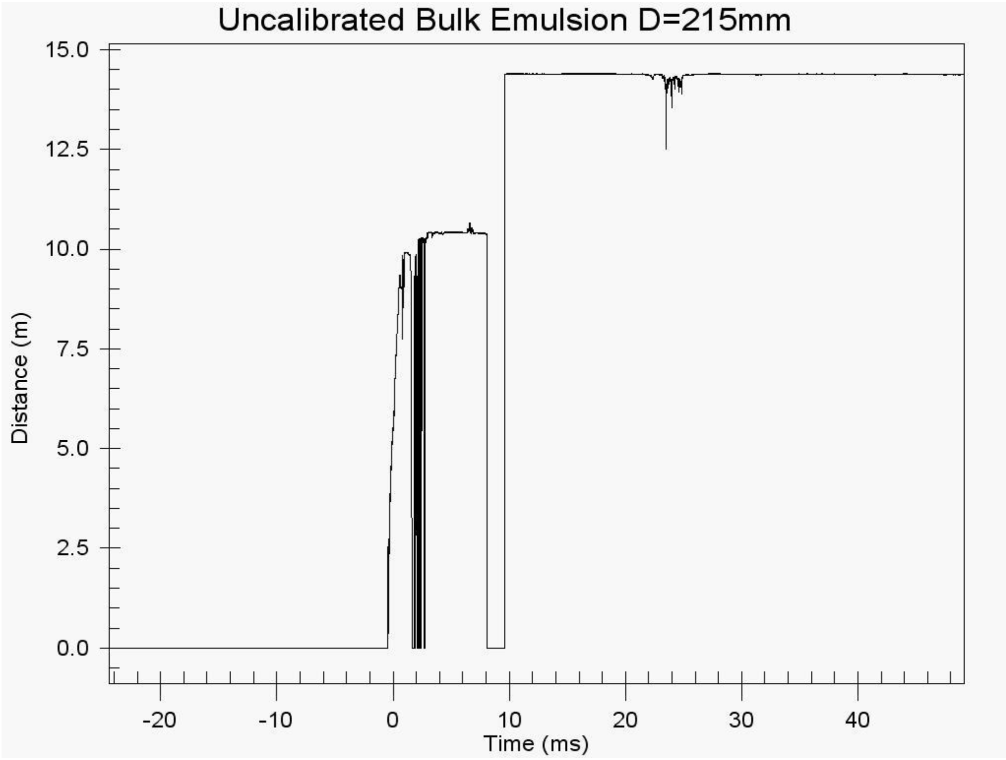

Figure B.37 The original VOD graph for blast pattern 4002-308

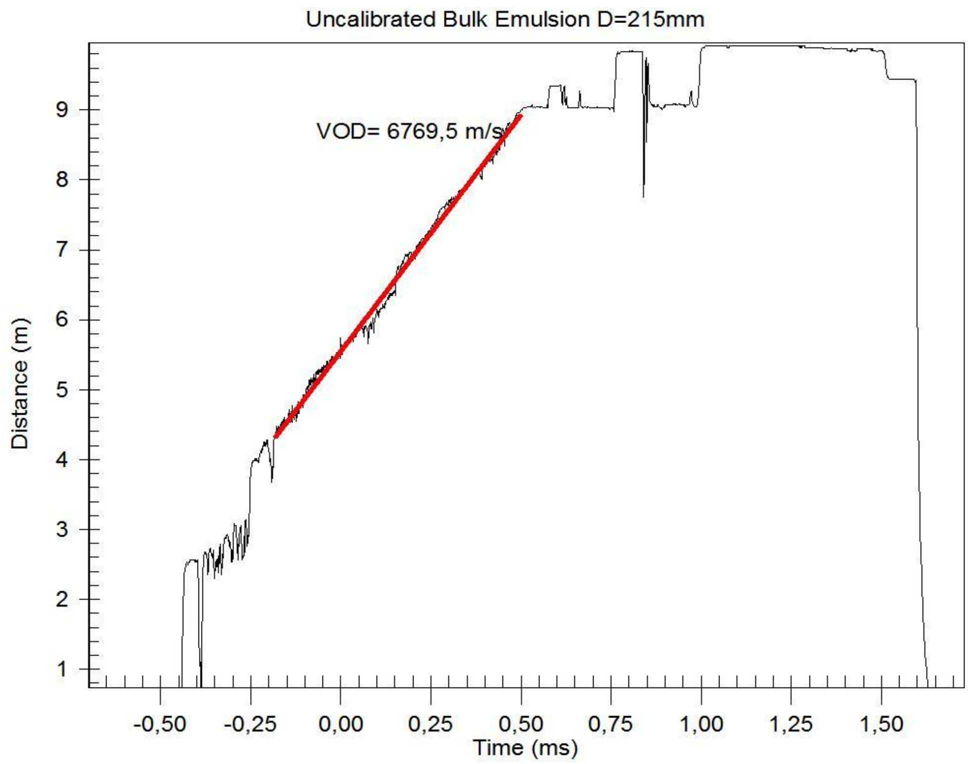

Figure B.38 VOD result for blast pattern 4002-308

APPENDIX C

VOD GRAPHS OF BULK ANFO IN GLACIER

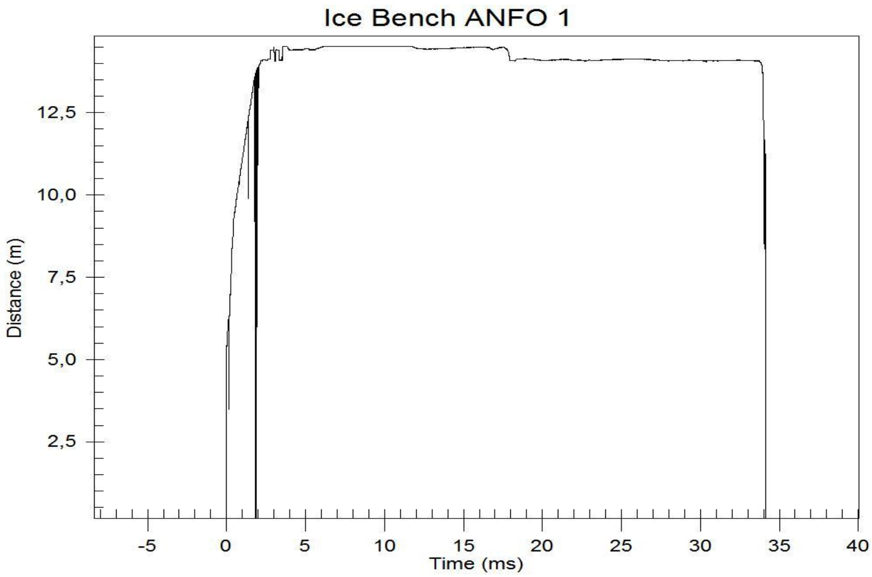

Figure C.1 The original VOD graph for blast pattern 3898-328a

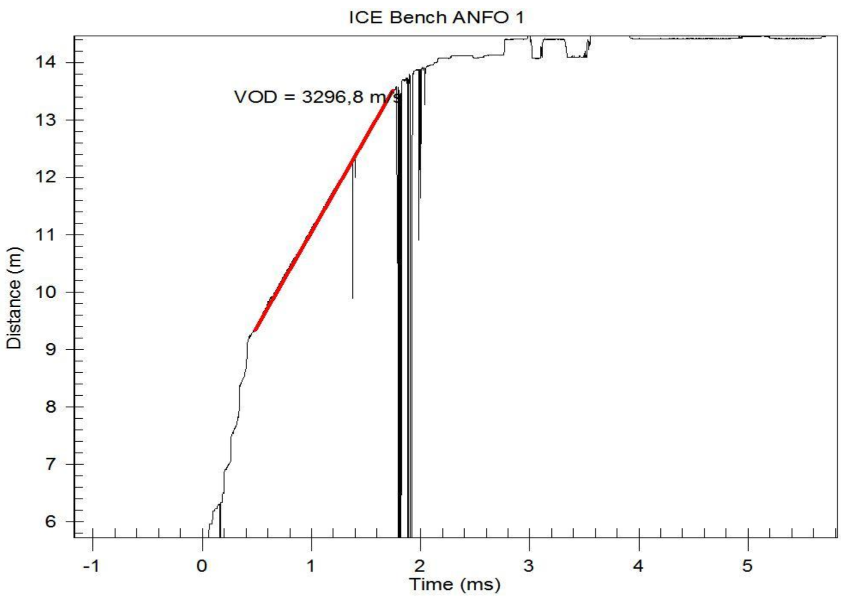

Figure C.2 VOD result for blast pattern 3898-328a

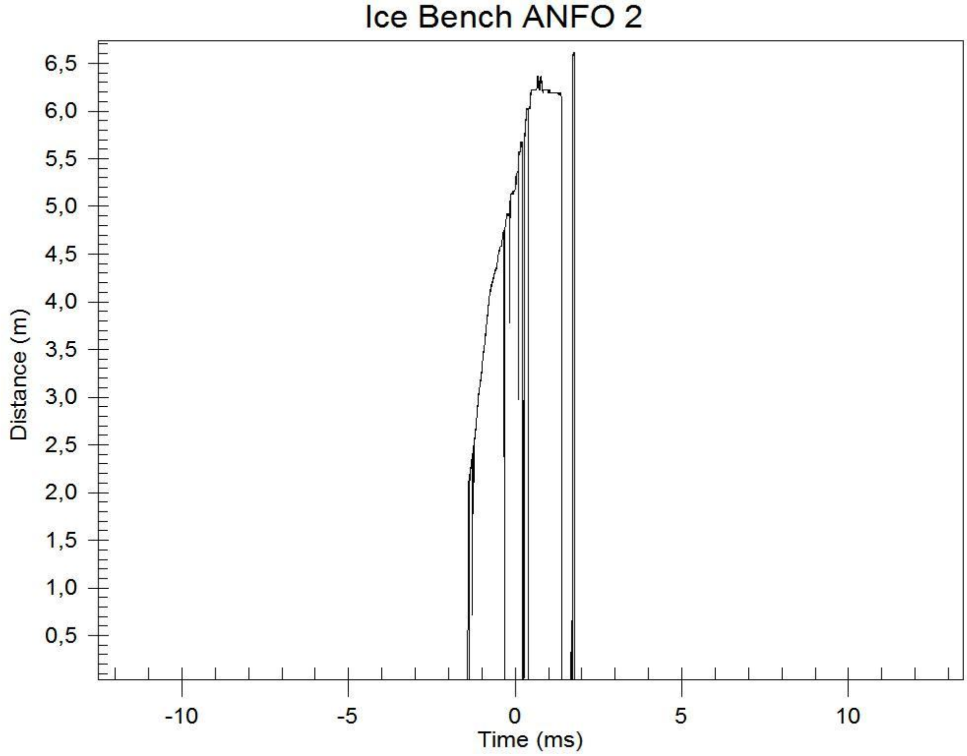

Figure C.3 The original VOD graph for blast pattern 3890-322

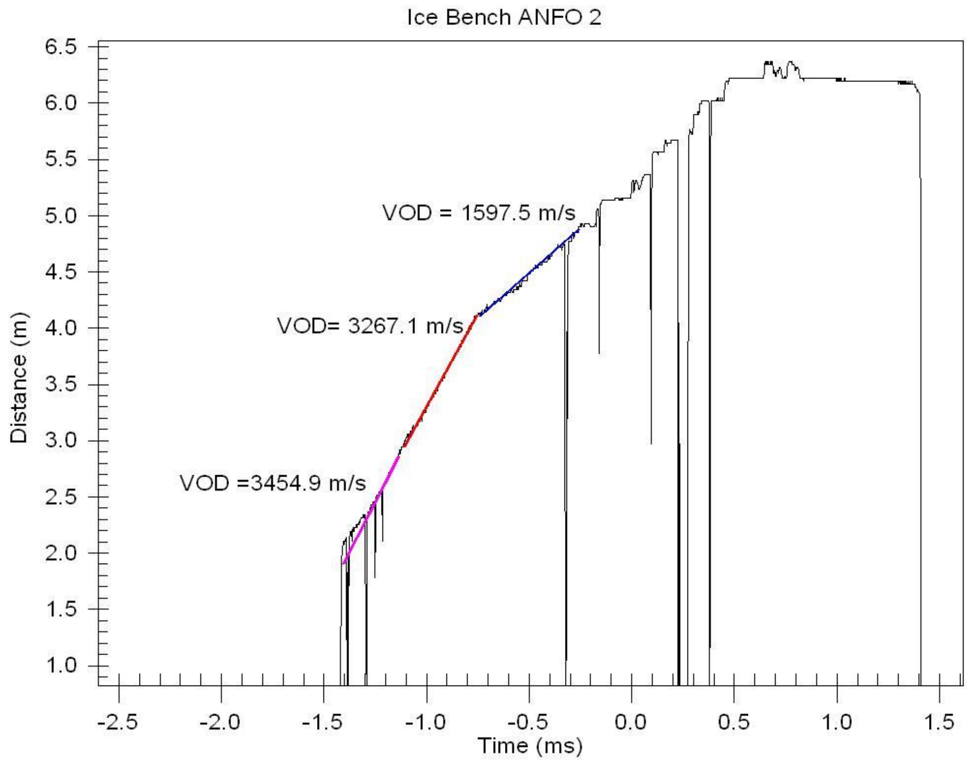

Figure C.4 VOD result for blast pattern 3890-322

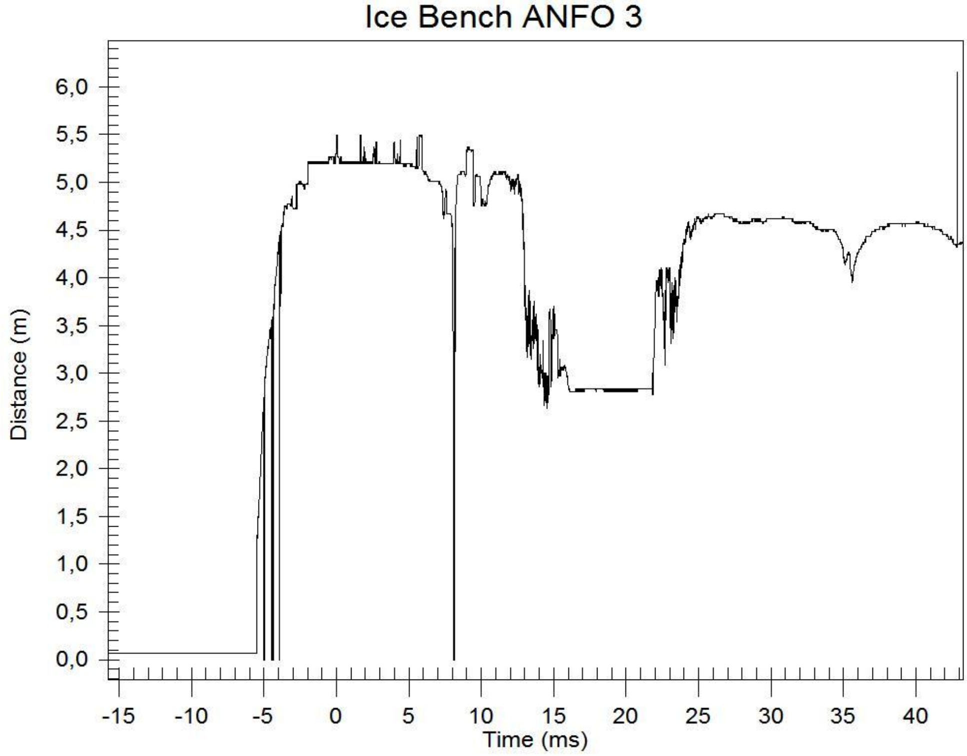

Figure C.5 The original VOD graph for blast pattern 3890-333

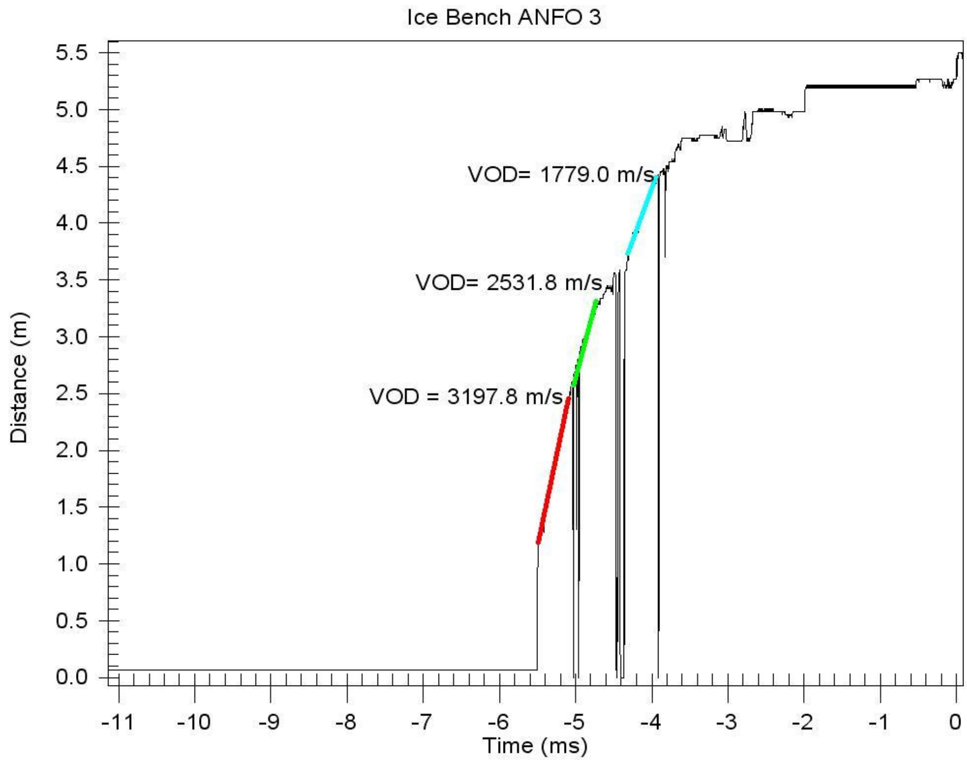

Figure C.6 VOD result for blast pattern 3890-333

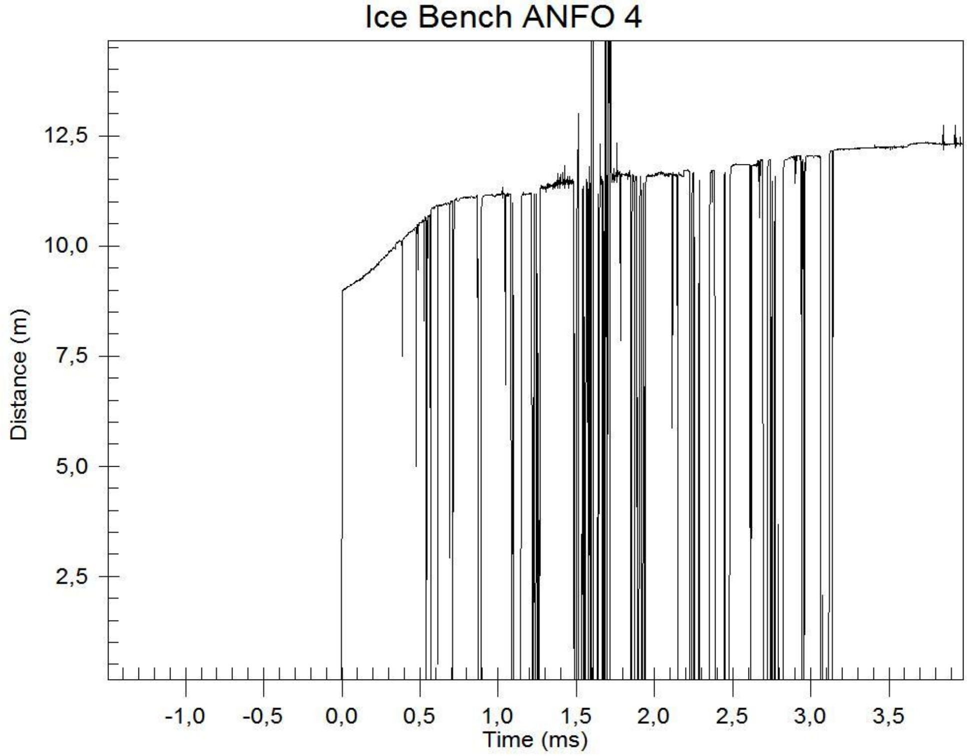

Figure C.7 The original VOD graph for blast pattern 3858-177

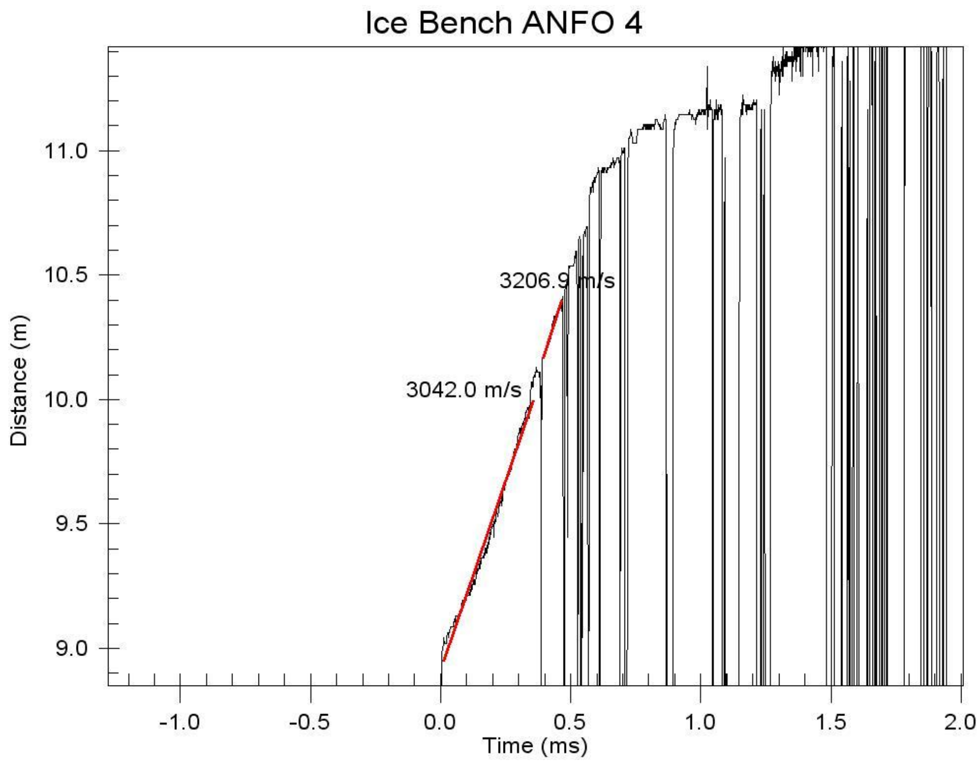

Figure C.8 VOD result for blast pattern 3858-177

APPENDIX D

BLAST HOLE DRILL DATA

Table D.1 Blast hole drilling speed in zone 3B

Drill Id	Zone	Hole Diameter (mm)	Hole Depth (m)	Drilling Time (min)	Drill Speed (m/min)	Average Drill Speed (m/min)
1108	Zone 3B	215	11.0	16.27	0.68	
1108	Zone 3B	215	11.0	23.08	0.48	
1108	Zone 3B	215	11.0	25.08	0.44	
1108	Zone 3B	215	11.0	21.33	0.52	
1108	Zone 3B	215	11.0	18.18	0.61	
1108	Zone 3B	215	11.0	19.47	0.56	
1108	Zone 3B	215	11.0	22.34	0.49	
1108	Zone 3B	215	11.0	17.36	0.63	
1108	Zone 3B	215	11.0	17.38	0.63	
1108	Zone 3B	215	11.0	24.22	0.45	
1108	Zone 3B	215	11.0	19.25	0.57	0.6
1108	Zone 3B	215	11.0	18.46	0.60	
1108	Zone 3B	215	11.0	14.52	0.76	
1108	Zone 3B	215	11.0	14.44	0.76	
1108	Zone 3B	215	11.0	16.31	0.67	
1108	Zone 3B	215	11.0	23.56	0.47	
1108	Zone 3B	215	11.0	24.47	0.45	
1108	Zone 3B	215	11.0	17.46	0.63	
1108	Zone 3B	215	11.0	15.29	0.72	
1108	Zone 3B	215	11.0	13.23	0.83	
1108	Zone 3B	215	11.0	19.43	0.57	

Table D.2 Blast hole drilling speed in zone 2

Drill Id	Zone	Hole Diameter (mm)	Hole Depth (m)	Drilling Time (min)	Drill Speed (m/min)	Average Drill Speed (m/min)
1108	Zone 2	215	10.0	11.39	0.88	1.13
1108	Zone 2	215	10.0	16.15	0.62	
1108	Zone 2	215	10.0	13.07	0.77	
1108	Zone 2	215	10.0	8.24	1.21	
1108	Zone 2	215	10.2	9.45	1.08	
1108	Zone 2	215	10.2	10.38	0.98	
1108	Zone 2	215	10.2	12.11	0.84	
1108	Zone 2	215	10.2	12.25	0.83	
1108	Zone 2	215	10.7	16.56	0.65	
1108	Zone 2	215	10.7	6.43	1.66	
1108	Zone 2	215	10.7	5.17	2.07	
1108	Zone 2	215	10.7	6.45	1.66	
1108	Zone 2	215	10.7	8.41	1.27	
1108	Zone 2	215	10.7	15.52	0.69	
1108	Zone 2	215	10.7	13.03	0.82	
1108	Zone 2	215	10.7	9.02	1.19	
1108	Zone 2	215	10.7	8.02	1.33	
1108	Zone 2	215	10.7	6.23	1.72	

Table D.3 Blast hole drilling speed in glacier

Drill Id	Zone	Hole Diameter (mm)	Hole Depth (m)	Drilling Time (min)	Drill Speed (m/min)	Average Drill Speed (m/min)
1108	Glacier	215	11.2	8.00	1.40	
1108	Glacier	215	11.2	6.48	1.73	
1108	Glacier	215	11.2	7.19	1.56	
1108	Glacier	215	11.2	6.30	1.78	
1108	Glacier	215	11.2	5.37	2.09	
1108	Glacier	215	11.2	6.08	1.84	
1108	Glacier	215	11.2	5.57	2.01	
1108	Glacier	215	11.2	5.04	2.22	
1108	Glacier	215	11.2	5.48	2.04	
1108	Glacier	215	11.2	5.13	2.18	
1108	Glacier	215	11.2	4.33	2.59	2.08
1108	Glacier	215	11.2	5.22	2.15	
1108	Glacier	215	11.2	6.08	1.84	
1108	Glacier	215	11.2	6.12	1.83	
1108	Glacier	215	11.2	4.44	2.52	
1108	Glacier	215	11.2	4.35	2.57	
1108	Glacier	215	11.2	4.43	2.53	
1108	Glacier	215	11.2	5.19	2.16	
1108	Glacier	215	11.2	4.30	2.60	
1108	Glacier	215	11.2	5.03	2.23	
1108	Glacier	215	11.2	6.16	1.82	