

## DOES CHARGE CONFINEMENT AFFECT THE VIBRATION LEVEL IN BLASTING?

Phase I – Feasibility study

Bengt Niklasson

Mats Olsson

Ali Beyglou



# **DOES CHARGE CONFINEMENT AFFECT THE VIBRATION LEVEL IN BLASTING?**

Phase I - Feasibility study

## **Påverkas vibrationsnivån av inspända laddningar?**

Etapp I - Förstudie

Bengt Niklasson, Geosigma

Mats Olsson, EDZ-Consulting

Ali Beyglou, Swebrec at Luleå university of technology

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## Preface

Construction works in rock in Sweden is mainly done by the drill and blast method – a well-known method that has been developed and fine-tuned during centuries. In connection to blasting works it is important to restrict vibration levels to an acceptable level, and this is a demand in urban areas.

When vibration levels exceed allowed limits, the reason for this should be investigated to avoid repetition. Confined boreholes/charges are often mentioned as reason for increased vibrations. However, is there a physical explanation to this or is this an opinion without just cause? Indications from a number of detonated misfires without pull or rock breakage does not show increased vibration levels and if so, it speaks against the general perception. In order to make relevant adjustments and design of blasts to avoid high vibration levels it is important to know the cause and effect.

The present work is an initial study to investigate if confined charges affect the blast vibration levels. The result will primarily be of interest for contractors and clients to better knowledge how to mitigate exceeded vibration levels.

The work comprise of literature studies, personal communication with vibration specialists, construction contractors, rock blast contractors, and vibration consultants. Also, evaluation of existing vibration data from blast misfires is included in the study. A second phase of this project may be executed depending on the outcome of this initial work.

A project group consisting of Mats Olsson (EDZ-consulting), Bengt Niklasson (Geosigma) and Ali Beyglou (Swebrec at LTU) carried out the work. A reference group assisted the project group with valuable support and consisted of Daniel Johansson (Swebrec), Mathias Jern (Nitro Consult), Anders Östberg (Scandinavian Tunnelling), Pier Goliats (Årsta Berg och Bygg) and Per Tengborg (BeFo). The project financing came from Rock Engineering Research Foundation (BeFo).

Stockholm in July 2014

*Per Tengborg*

## Förord

Bergbyggnad bedrivs i Sverige till helt övervägande del med hjälp av sprängning - en väl beprövad metod som utvecklats och förfinats under århundraden. I samband med sprängarbeten är det bland annat viktigt att begränsa vibrationer inom tillåtna nivåer, vilket är ett krav vid sprängning i tätbebyggda områden.

I samband med överskridande av vibrationer bör orsaken till överskridande redas ut för att undvika att det upprepas. Inspända hål/laddning nämns ofta som en möjlig anledning till ökade vibrationer då förhöjda vibrationsnivåer ska förklaras. Men finns det en fysikalisk förklaring till det eller är det en uppfattning utan saklig grund? Indikationer från ett flertal detonerade bomsalvor där berget inte fallit ut tyder på att vibrationsnivåerna inte är förhöjda och skulle i så fall tala emot den allmänna uppfattningen. För att kunna göra relevant korrigering och design av sprängsalvor och därigenom undvika höga vibrationsnivåer vid sprängning är det viktigt att känna till orsak och verkan.

Föreliggande arbete är en inledande studie för att undersöka om en inspänd laddning påverkar vibrationsnivåerna vid sprängning. Resultatet förväntas främst vara till nytta för entreprenörer och beställare genom att bättre kunna åtgärda överskridna vibrationsnivåer.

Arbetet omfattar litteraturstudier, personliga kontakter med vibrationsspecialister, entreprenörer, bergsprängare och vibrationskonsulter. Vidare ingår utvärdering av befintlig vibrationsdata från bomsalvor. En andra etapp med fältförsök kan bli aktuell beroende på resultatet från denna inledande studie.

En projektgrupp bestående av Mats Olsson (EDZ-consulting), Bengt Niklasson (Geosigma) och Ali Beyglou (Swebrec vid LTU) genomförde arbetet. Den referensgrupp som bistått projektgruppen och bidragit med värdefullt stöd har bestått av Daniel Johansson (Swebrec), Mathias Jern (Nitro Consult), Anders Östberg (Scandinavian Tunnelling), Pier Goliats (Årsta Berg och Bygg) och Per Tengborg (BeFo). Projektet finansierades av Stiftelsen Bergteknisk Forskning (BeFo).

Stockholm i juli 2014

*Per Tengborg*

## SUMMARY

Blasting in urban areas must involve techniques to control the vibration level. Charge confinement is one of the parameters that are believed to influence the vibration level. Some of the reasons for this are:

- Incorrect charge calculation (charge weight is too small for the drilled burden)
- Incorrect interval-time (holes behind are initiated before holes ahead)
- Incorrect selection of explosive for the burden or an influence of dead pressing
- Unfavourable selection of geometry

A common opinion among blasters is that an increased confinement results in a higher vibration level. Is there a physical explanation for this or is it just a common misunderstanding established a long time ago?

The purpose of this study is to find evidence for or against the understanding that confined charges affect the vibration level in blasting. This might have a significant benefit for contractors and clients by helping them to make better decisions of how to handle infringing vibration levels.

The report comprises a literature study and an assessment of a number of observed misfires in tunnels, still with correctly detonating charges but with a reduction of more than 50% in pull or rock breakage. It also comprises a statistical analysis of some of the rounds presented in the study.

The result of this study is that there is no evidence for a relationship between degree of charge confinement and vibration level. Both, the main part of the single observations and the statistical analysis confirm the independency. A 2<sup>nd</sup> step of work, a field study based on single hole shots, is proposed in the report.

## SAMMANFATTNING

Vid sprängning inom tätbebyggt samhälle så måste man alltid ta hänsyn till nivån på vibrationerna. Detta medför ofta komplicerade och dyrbara åtgärder. I den sprängtekniska litteraturen så brukar laddningens inspänning nämnas som en av de viktigaste orsaker till förhöjda vibrationsnivåer. Inspända förhållanden kan t.ex. uppkomma vid:

- Felaktig laddningsberäkning
- Fel intervalltid
- Fel val av sprängämne
- Ogynnsam geometri

Oftast brukar man med inspändhet mena att laddningen har fått för stor försättning för att åstadkomma planerat utslag. Det är en vanlig uppfattning bland sprängare att dessa inspända hål då ger förhöjda vibrationsnivåer. Finns det någon fysikalisk förklaring till detta eller är påståendena om förhöjda vibrationer en missuppfattning?

Målsättningen till detta projekt var att undersöka om det finns fog för att inspända laddningar verkligen orsakar förhöjda vibrationsnivåer. Vetskapen om detta skulle kunna hjälpa beställare och entreprenörer att fatta bättre beslut att hantera ev. överskridande av fastställda vibrationskrav.

Denna rapport omfattar en litteraturstudie, en teoretisk betraktelse av vibrationer samt en genomgång av ett antal observerade bomsalvor från tunneldrivning. Bomsalvorna har här definierats som salvor där hålen detonerat enligt tändplanen men där indriften reducerats mer än 50 %. Rapporten omfattar också en statistisk analys av några av dessa bomsalvor.

Resultatet av denna undersökning visar att det finns två skilda uppfattningar i världen vad gäller inspändhet och då uppkomna vibrationer. Den ena uppfattningen är att inspändheten har betydelse på vibrationerna och den andra uppfattningen är att inspändheten saknar betydelse. Den genomförda studien av vibrationer från ett antal bomsalvor och den statistiska analysen visar inga bevis på att inspändheten hos laddningar skulle ha någon betydelse för vibrationsnivån.

Rapporten föreslår slutligen att en noggrant kontrollerad undersökning bör göras genom sprängning av ett antal hål med olika försättningar och med registrering av vibrationerna.



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## **1 BACKGROUND**

Blasting in urban areas must involve techniques to control the vibration level. Charge weight and distance between the charge and the location of the vibration monitor are two of the more clarified parameters involved. Another parameter that could influence the level of vibrations is often mentioned to be the charge confinement. The level of vibration will increase when the degree of confinement increases. On the basis of a number of blast rounds with documented high degree of confinement, this study will hopefully bring some more light to the issue of relationship between charge confinement and vibration level.

### **1.1 Charge confinement**

The definition of charge confinement is often described as the size of the burden. As the burden increases confinement also increases. A loaded hole with a larger burden compared to calculated, taken into account charge weight, geology and small breakage angles, could be considered as too confined. One example of maximal confinement of a charge is if no free surface exists in any direction. An example of a minimum confinement of a charge is a concussion charge which is placed directly on the rock surface. Unwanted high confinement could also occur where one hole in a round is sub drilled deeper compared to the others holes or in tunnelling where one hole is drilled longer than the other holes

Consequently some of the reasons for confinement are:

- Incorrect charge calculation (charge weight is too small for the drilled burden)
- Incorrect interval-time (holes behind are initiated before holes ahead)
- Incorrect selection of explosive for the burden or an influence of dead pressing
- Unfavourable selection of geometry

A common opinion among blasters is that an increased confinement results in a higher vibration level. Is there a physical explanation for this or is it just a common misunderstanding established a long time ago?

### **1.2 Correcting measures**

Today in Swedish tunnelling projects production may be stopped if the allowed vibration level is exceeded which of course causes increased costs and time delay for the project. The reason for stopping the production is in general the risk of damage to a building, construction or any other sensitive object. In order to get the starting permit after the production stop the contractor must present actions in the deviation report where it is shown that the next blasts will not exceed the vibration limits. In order to take some actions an analysis of the blasted round must be conducted. Compared to tunnelling 10-30 years back in time, the monitoring and documentation of the single

round is much more thorough and the results are more accessible. Blast reports are easy to find in databases and all rounds are being monitored with time/history presentation of amplitude where the signal resolution often allows for identification of single holes in the round. Logs from the drill rig and the mixing/charging unit will contribute with information on drilling geometry and drilling machine parameters as well as weight of each charge. The accessibility to modern monitoring technique has decreased the amount of speculation in analysing a blast round but there are still many uncertainties left to explore. For example, the introduction of electronic detonators with short time delays makes it easier to identify single charges in a blast round but it can still be difficult to separate charges especially at longer distances.

The analysis of the blast round is usually conducted by the contractors blasting engineer. The engineer is together with the certified rock blaster responsible for drill, charge and initiation plans. Sometimes also the clients engineer will take part in the analysis work and in very rare cases the client involves a blasting specialist. Possible backgrounds often pointed out for the high vibration level could include:

- human mistakes in planning the blast round
- human mistakes in drilling, charging and hooking up the blast round
- material error
- detonation failure, sympathetic detonation of two or more charges or dead pressing of a charge caused by a nearby detonation charge
- charges being more confined than normal, for example the lower corner holes in a tunnel round.

There is a broad spectrum of reasons that could be assigned for causing the high vibrations. Some of them are easier to confirm than others. For example, human errors can be easy to confirm provided the tunnel crew is aware of the error and want to share the information. Vibration monitoring can explain detonation failure especially in the first opening part of the tunnel round. The influence of confinement has been claimed to influence the level of vibrations and is often pointed out as the reason for exceeding vibration levels but is one of the more difficult parameters to confirm.

A quick look in some blasting handbooks will, in some cases confirm a relationship between confinement and vibration level.

- Langefors and Kihlström, The modern technique of rock blasting, third edition 1978. Langefors and Kihlström do not mention the effect of charge confinement on vibration level.
- Persson, Holmberg and Lee, Rock blasting and explosives engineering, 1993, section 13.10 Methods to reduce the vibration level. Persson et al. note that confinement condition is one of the parameters involved in vibration control and

also measures to take in order to reduce the charge confinement and thereby reduce the vibration level.

- Stig O Olofsson, Applied explosives technology for construction and mining, 2002, section 11.2.4 Planning of blasting operations. Olofsson points out that “Steeper hole inclination or other conditions increasing the constriction of the blast (misfires etc.) may cause considerable increase of vibration velocity.”

Usually, not too long after the blasting work in a project has been halted, a conclusion is established based on round documentation and experience. Quite often the correction of confined holes is one of the measures taken. The drill plan is changed in order to reduce the risk of over-confined holes. Before the fundamental knowledge of how the confinement of a charge influences the vibration level is known that measure should not be used as a correcting action. Especially when this action may have a direct influence on time and costs.

## **2 OBJECTIVE**

The purpose of this pre-study is to find evidence for or against the understanding that confined charges affect the vibration level in blasting.

The results of this project are expected to have significant benefit for contractors and clients by helping them to make better decisions of how to handle infringing vibration levels.

The pre-study comprises a literature study and an assessment of a number of observed misfires in tunnels, still with correctly detonating charges but with a reduction of more than 50% in pull or rock breakage. It also comprises a statistical analysis of two of the rounds presented in the study.



### 3 BLASTING THEORY

When a charge is detonated inside a bore hole, the rock is affected in three steps, see Figure 1.

1. The bore hole expands due to the high pressure. The pressure inside the hole exceeds the compression strength of the rock. The walls in the hole are pulverized and short fractures are formed in the rock round the hole.
2. Compression waves, shock waves, propagate in all directions from the hole periphery with a velocity equal to the sonic velocity in the rock. As these shock waves reflect against a free rock face, they are transformed into tensile waves returning back into the rock. If the tensile strength of the rock is exceeded, longer fractures appear into the rock and the rock starts to break.
3. In the third step, the released gas volume penetrates the fractures under a high pressure and expands the fractures and finally throws the rock forward.

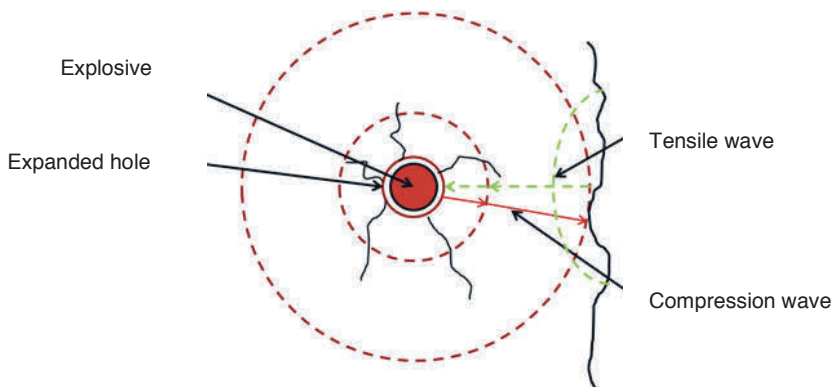


Figure 1. Blasting theory

In Table 1 some typical data from a detonation are presented. The produced gas volume is 150-1100 l/kg and the pressure inside the bore hole is 6-20 GPa which far exceeds the strength of the rock.

Table 1. Duration in a bench blast

Important blasting factors	Velocity(m/s)	Duration (ms)
Detonation	2000-8000	2-3
Shock waves	4000-6000	2-3
Fractures	Ca. 1000	5-10
Gas flow	100-500	20-80
Movements of the bench	10-20	Some seconds





## 4 VIBRATIONS FROM BLASTING

### 4.1 Seismic waves

Some of the energy released from a blast propagates in all directions from the hole as seismic waves with different frequencies and are thereby damped by the distance. Waves with high frequencies are quickest damped. Higher frequencies dominate at short distances while waves with lower frequencies dominate at longer distance between the blast and the measure points. The amplitude of the seismic wave mainly depends on the amount of co-operating charges, rock conditions, distance from the blasting site and the geology of covering earth deposits. Furthermore, the confinement is a factor which is often referred to.

Propagation of seismic waves in the ground is a complicated process combining three types of different waves, the P-wave, the S-wave and the R-wave. The P-wave (primary wave) is the fastest of the waves. In this wave the particles moves in a reciprocating way like acoustic waves in the air. The particles in the S-wave (secondary wave) moves perpendicular to the P-wave and at a slower speed. The R-wave (Rayleigh) is a surface wave and the particles moves in an elliptical way. The R-wave moves more slowly than the P- and S-wave. It's most important when the vibration source is located close to the surface.

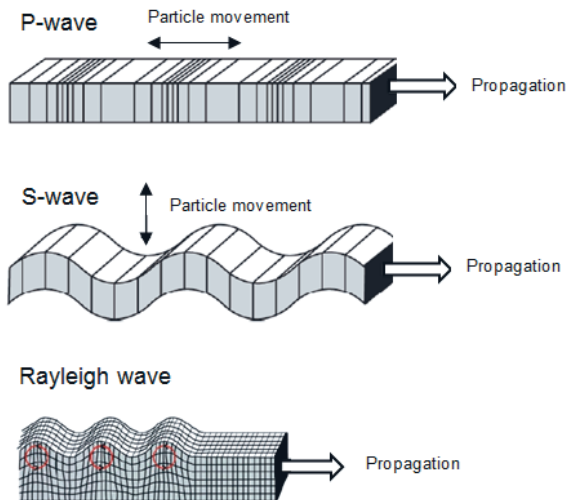


Figure 2. P, S and R waves (Fomenko & Alsterdal, 2008)

The oscillation of the waves could be compared to a sinus wave and the movement can be described knowing the time dependence for the displacement, vibration velocity or acceleration.

In vibration measurements the particle velocity is usually stated but it is also easy to calculate the acceleration and displacement according to the following formula:

$$v = 2 \cdot \pi \cdot f \cdot A$$

where  $v$  = particle velocity (mm/s),  $f$  = frequency (Hz) and  $A$  = displacement (mm)

The acceleration can be calculated from:

$$a = 4 \pi^2 \cdot f^2 \cdot A$$

where  $a$  = acceleration in  $g$  ( $9,81\text{m/s}^2$ )

As a wave strikes a material with a different density and stiffness the wave either continues through the material or is reflected back. This wave phenomenon is called refraction or reflection. Both P- and S-waves are formed and refracts or reflects differently due to the material.

When two or more waves strikes the same point this results in either intensification or weakening, due to if the waves are in phase or displaced to each other, see Figure 3.

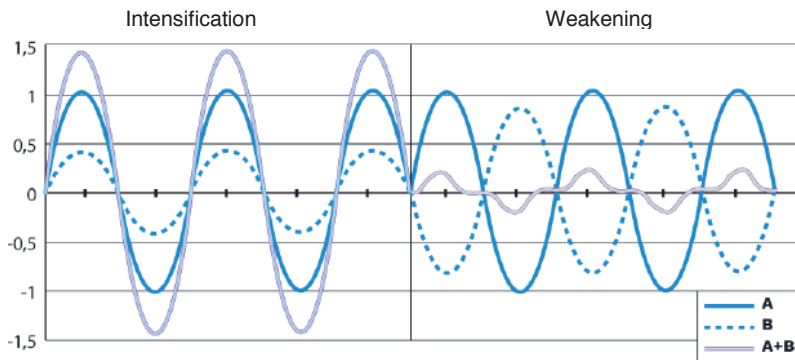


Figure 3. Intensification or a weakening of a signal (Fomenko & Alsterdal, 2008)

The waves are damped during their propagation and the damping depends on the material and the distance to the vibration source.

The waves and their propagation are very complicated and are thereby difficult to measure and evaluate. Measurements have to be done in three directions, longitudinal, vertical and transversal. Three axial geophones or accelerometers are used but according to Swedish Standard SS460 48 66 it is normally only necessary to measure in the

vertical direction. The standard can call for extended measurement where monitoring in three directions is applied.

One example of a vibration curve from one of the evaluated tunnel rounds is shown in Figure 4. The figure shows the time history of a blast round with duration of a bit over 5.5 seconds. The first 8 holes in the cut are delayed longer than the rest of the round. The detonators are electronic detonators which make it possible to use shorter time delays between holes compared to conventional detonators. The delay times are except for the cut holes 30 – 50 ms. A typical peak amplitude could be seen after approx. 4 seconds. The possibility of evaluating abnormal behaviour in the initiation process is quite good from this type of registration.

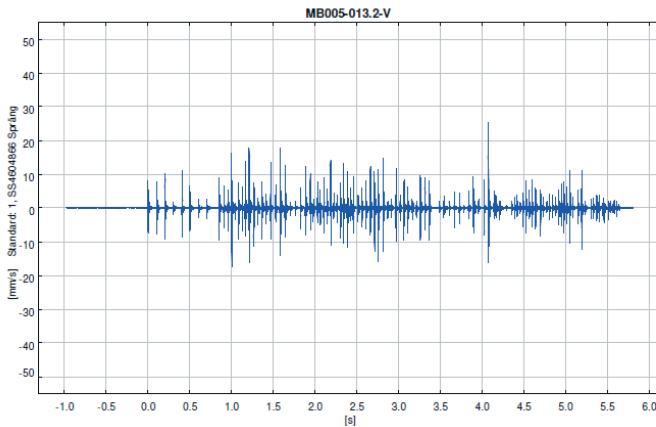


Figure 4. Example of a vibration curve from blasting

Modern rock blasting technique permits advanced blasting in urban areas. One recent example is the construction of a new commuter railway, ”the Citybanan”, which goes under the city of Stockholm with many sensitive objects and installations. Blasting in urban environments require very careful planning and preparedness for unexpected situations. Ground vibrations, air blasts and throw are some of the important factors that have to be taken into account. The excavation work is most often controlled by the allowable vibration levels.

## 4.2 The importance of charge confinement

As described earlier, when the charge in a hole detonates a shock wave is formed round the hole. The shock wave propagates spherically around the charge and into the rock mass, see Figure 5. The propagating shock wave is not carrying any information about the size of confinement of the charge. The shock wave propagating behind the charge into the rock mass doesn't know the distance to the free face in the opposite direction.

The first wave to reach the measure point is the compression wave. Later, the returning wave from the free surface, i.e. the tensile wave, reaches the measure point. This tensile wave has a much longer distance to travel, it passes crushed rock and should therefore be weakened compared to the first compression wave.

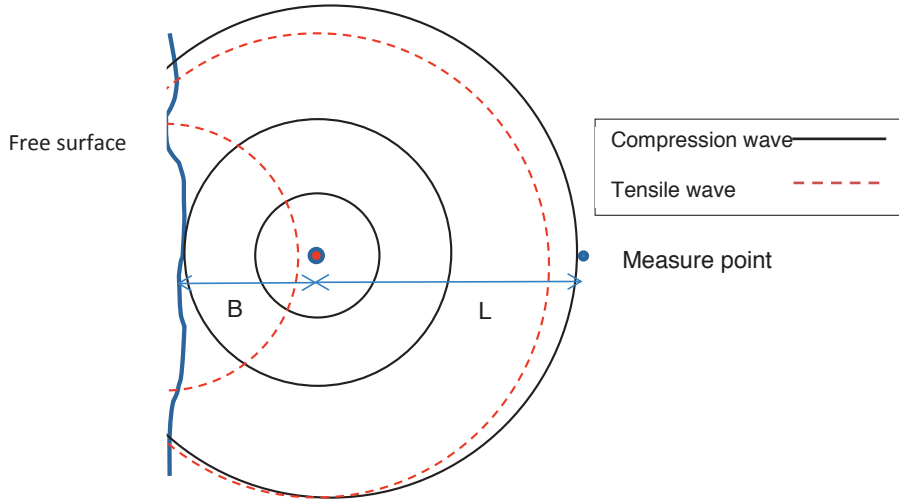


Figure 5. Travel distances for the different waves

The compression wave travels the distance  $L$  while the tensile wave must travel the distance  $L+2B$  before it will reach the measure point. Furthermore the tensile wave will lose some of its energy due to the irregularity of the free face.

The first arrival of the compression wave has no information of the size or characteristics of the burden. Therefore, it doesn't seem to be very likely that an increase of the burden should result in a higher vibration level for the first arrival of the compression wave.

A more complicated seismic situation will take place directly after the first arrival when reflections from the original wave package follows. The amplitude of the following reflecting waves may very well be higher than the first arrival.

The physical explanation for a relationship between confinement and vibration level is not evident.

## 5 LITERATURE STUDY

A literature study of the subject has been performed by Swebrec and is fully viewed in the Appendix 1. The study covered some 24 references. The result of the literature study could be summarized in the following points:

1. There are mainly two opinions. According to the first opinion the vibration levels are increased with an increased burden. This opinion is pleaded by Ramulu. The other opinion argues that the vibration levels do not increase with the burden. This opinion is pleaded by Blair.
2. It's difficult to find details of the geology, water in the rock, explosives, equipment for the measurement etc. used in the tests.
3. Most of the reports are from quarry blasting. There are very few reports from underground blasts.
4. Most of the papers give no physical explanations of the results.

The final words of the literature study are:

“According to the mentioned studies, many trials have been conducted in order to investigate the effect of burden on vibrations. However, various experimental and statistical methods utilized by researchers have led to entirely contradictory results. Altogether, a confident conclusion cannot be drawn about the effect of confinement on blast vibrations. Such controversy is partly due to different theories behind vibration production and partly owes to different experimentation approaches and divergent presumptions about the effect of confinement”.

## 6 OTHER CONTACTS

In order to further extend the information of whether confinement does affect the vibration level a number of international blasting expertise have been contacted.

The following persons have been contacted to leave their points of view:

- Claude Cunningham, Blasting Investigations and Consultancy, South Africa
- Finn Ouchterlony, Momentanuniversität, Leoben, Austria
- Alex Sphatis, Orica, Australia
- Dane Blair, Orica, Australia
- Gary Sharpe, Blue Dog Scientific, England

Their point of view of this matter did not in any way change the information given in the literature study.



## **7 OBSERVATION OF MISFIRED TUNNEL ROUNDS AND TEST BLASTS WITH FULLY CONFINED CHARGES**

### **7.1 Background**

In order to find proof for or against a relation between charge confinement and vibration level a search for misfired rounds started. The definition of a misfired round is according to TNC (The Swedish Centre for Terminology) a blast fully or partially unsuccessful without claiming the reason for the misfire.

The definition of a misfired round in this evaluation is that the round is normal with respect to detonation function and initiation sequence. The pull or rock breakage should be estimated to less than 50% of expected advance.

All charges in such round could be considered as fully confined. In this analysis these rounds have been compared to the reference round before and after the misfired round including the re-blasts.

A number of blast round results have been collected over a time period of approx. 10 years. The common ground for the collected rounds was that they all have been classified as misfired rounds. When the background to this project was more clearly formulated additional misfired rounds were traced down. Not only the misfired rounds are documented but also the re-blasted rounds and also reference rounds blasted before and/or after the misfire. Due to today's high demand on quality assurance in tunneling works the documentation from collected rounds is reliable and extensive.

All together 7 misfired tunnel rounds have been studied together with 2 fully confined single shots in a surface bench environment.

## 7.2 Collected data

All seven misfired rounds are tunnel production rounds from four different projects in Sweden. The single shots are conducted in a test setup in Swedish lime stone and has been reported by Jern at the Swedish rock blasting committee in 2010. A summary of the projects is found in Table 2.

Table 2. General geology at the different projects

Project	Type of project	Geology	Misfires no
1	Test facility for underground storage of nuclear waste, the Äspö laboratory	“Äspö diorite” a quartz-monzodiorite	1 and 2
2	Rail tunnel, Citybanan, Södermalmstunneln, Stockholm	Weakly gneissic tonalites cut by minor pegmatites, and "Stockholm granite"	3 and 4
3	Underground train depot, Stockholm	Gneissic granite	5
4	Underground storage of bio- fuel, Stockholm	Gneissic granite	6 and 7
5	Single shot test, Klinthagen, Gotland	Limestone	

All projects except project 5 have been visited and personal contacts with the tunnel staff were established. One of the misfired rounds in project 2 was blasted by one of the authors of this report. Also in project 1 the authors have been involved in the blast design. The data has in general been received from the web based monitoring system which provides easy access to all data.

The reliability and quality of the data from the different rounds are judged to be high.

Example of documentation which is used in the analysis:

- Blast report including details of blast parameters such as co-operating charge, number of holes, drill depth of round etc. The report also presents results of vibration monitoring, active geophones, distances and vibration levels, see Figure 6
- Drilling plan and initiation plan, see Figure 7
- Map of blast and monitoring area, see Figure 8
- Images in some cases



Sprängjournalfilter		ExporteraSkriv utStäng	
Salvnummer	861	Antal hål	120
Entreprenaddel	Fältsburstunneln	Underborrning [m]	
Sektion	57	Håldiameter [mm]	48
Signatur	Johan Hillman	Hållavstånd [m]	
Tid	2012-03-08 10:55:00	Försättning [m]	
Skapad	2012-03-08 10:17:06	Håldjup [m]	1,7
Tidsspänn [s]	300	Typ av sprängämne	eDev
Norr	77276	Antal intervaller	
Öst	100863	Area	37
Z	-3	Salvans volym [m <sup>3</sup> ]	
Antal delladdningar/hål		Täckning typ	
Sprängämne	Patronerat	Täckning antal	
Laddning/tändare [kg]			
Laddning/intervall [kg]			
Laddning/salva [kg]	37		
Samverkande laddning [kg]	0,75		
Specifik laddning [kg/m <sup>3</sup> ]			
Oladdad del			
Notering			

Mätpunkt	Placering	Datum	Värde	Gräns	Andel	Avstånd	Anmärkning
MB006-001 - V	Tella-T S55 Anf SV Sekt.2+555	2012-03-08 10:55:41	0,85 mm/s	70	0,1%		
HG041-001	KV Skaraborgsg 7	2012-03-08 10:55:40	2,45 mm/s	37,1	7%	43	
MB002-001 - V	Södertunneln sektion 1/850berg	2012-03-08 10:55:33	2 mm/s	30	7%	63	
MB002-001 - L	Södertunneln sektion 1/850berg	2012-03-08 10:55:33	1,65 mm/s	30	6%	63	
MB002-001 - T	Södertunneln sektion 1/850berg	2012-03-08 10:55:33	1,4 mm/s	30	5%	63	

Figure 6. Blast report

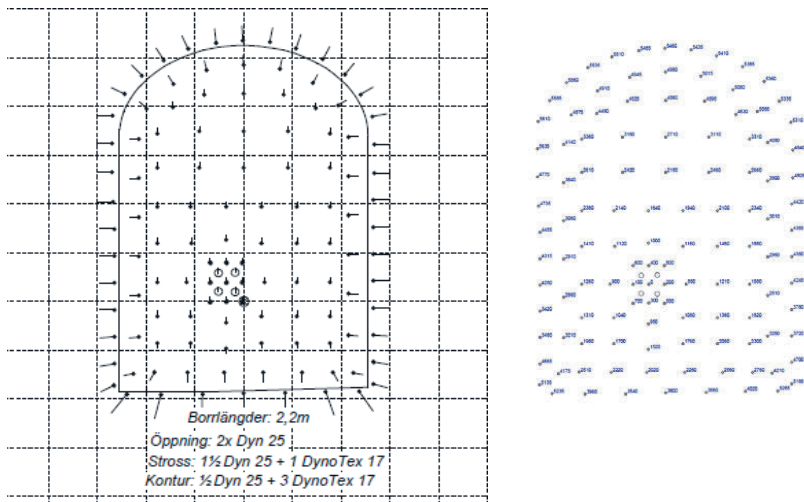


Figure 7. Drilling plan and initiation plan

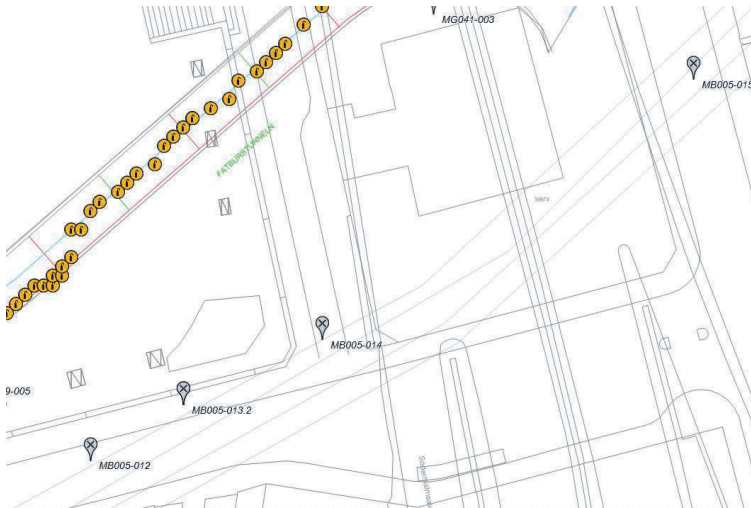


Figure 8. Map of blast rounds and location of geophones

### 7.3 Results

Round 1 to 7 below refers to the misfired rounds which have been followed up. Connected to each misfired round are a varying number of reference rounds and one or more re-blasts. The misfired rounds are named 1 to 7 while all other reference rounds keep their original id-numbers in each project. Reference rounds are blue colored in the graphs, the misfired round is brown and the re-blasts are yellow.

Due to the fact that the compared rounds for each misfire are located next to each other the difference in distance and charge weight is small. However, in most cases these small differences have been normalized by using scale distance ratio to correct the level of vibration in order to make them more comparable.

Square root scaled distance  $SD = \frac{R}{\sqrt{Q}}$  where R is distance (m) and Q is charge weight (kg).

A simplified correction due to the difference in SD value for the rounds is made where the correction factor is SD for the vibration value divided by the SD value for the misfired round:

$$V_{1corr} = \frac{SD_1}{SD_{mf}} \times V_1 \text{ where}$$

$V_{1corr}$  is the corrected value of the measured value  $V_1$

$SD_1$  is the SD value of the measured vibration value

$SD_{mf}$  is the SD value of the measured vibration value of the misfired round

### 7.3.1 Round 1

Round no. 1 from project no. 1 is monitored at two different locations. One is located on left hand side of the blasted tunnel, called fire wall. The other geophone was positioned in the direction behind the tunnel on a transformer. The fire wall geophone was fixed to the rock wall while the transformer geophone was mounted on the foundation of the transformer. For that reason the transformer geophone results are excluded. Figure 9 shows the location of the geophones. Figure 11 show the location of the blast rounds along the tunnel alignment. Round 13 – 17 are included in the graph presenting the results of misfired round 1.

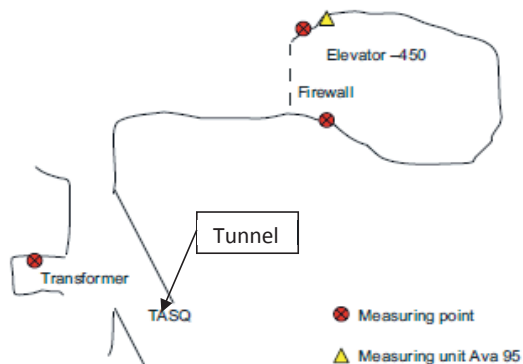


Figure 9. Location of monitoring points and tunnel location

The round consisted of 125 holes. Drill depth was 4.0 m and all charged holes were charged with cartridge dynamite type of explosives. Initiation system was Nonel LP.

Maximum co-operating charge was varying from 2.6 to 3.0 kg. Distances from round 13 to round 17 are 10 to 13 m.

Following can be noted in Figure 10 where the result for round no. 1 is presented. The un-corrected data including distances and charge weight is found in Appendix 2.

Basic data for round 1 is:

Round no.	Distance m	Charge weight kg
13	10	3.0
14	11	2.8
15 MF (misfired)	13	2.0
16 RB (re-blast)	13	2.6
17 RB (re-blast)	13	2.6

The first reference round, 13, is lower than the second reference round, 14, and the misfired round, 15, which are in the same range of vibration level. The first re-blast, 16, is around 30 mm/s. In this project a second re-blast, 17, is reported. The second re-blast is higher than both reference rounds and the misfired round and surprisingly much higher, + 20 mm/s, than the first re-blast.

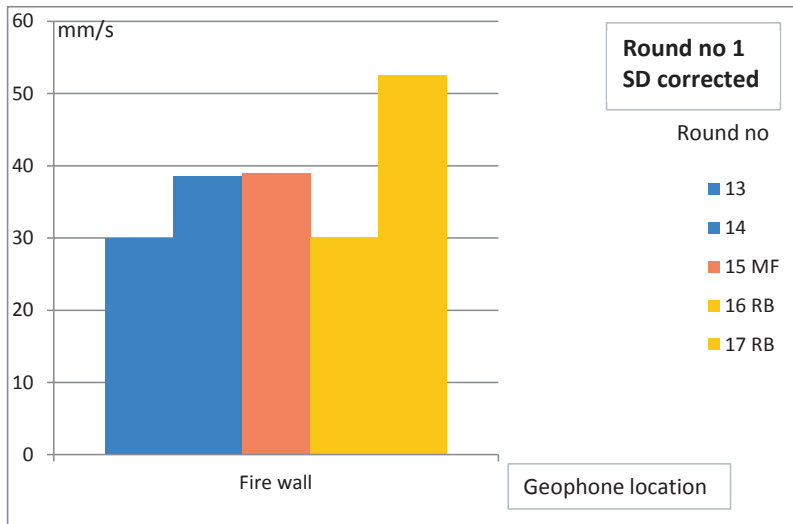


Figure 10. Results from round no 1, data are scale distance corrected

No clear indication that the misfired round is different from the reference rounds can be seen from the results.

### 7.3.2 Round 2

Round no 2 from project no 1 is monitored with the same geophones as in round no 1. The tunnel has now been excavated approx. 10 m more and the distances from the blasted rounds to the measuring have increased.

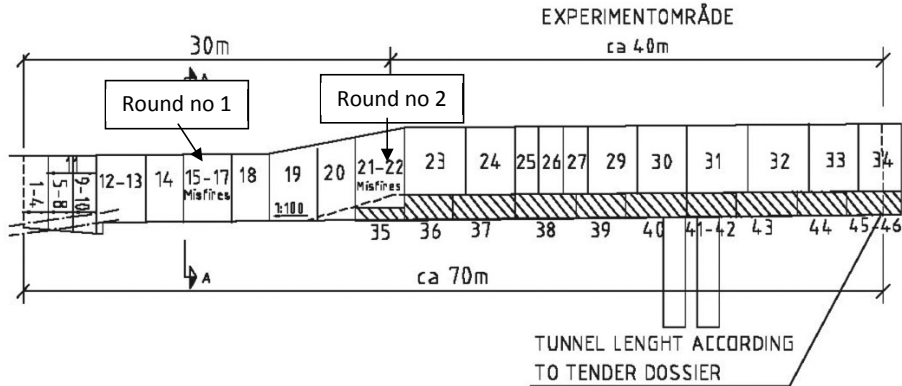


Figure 11. Location of the tunnel rounds

Figure 11 show the location of the blast rounds along the tunnel alignment. Round 20 – 22 is included in the graph presenting the results of misfired round 2.

The round consisted of 138 holes. Drill depth was 4.5 m and all charged holes were charged with cartridge dynamite type of explosives. Initiation system was Nonel LP. Maximum co-operating charge was varying from 2.9 to 3.7 kg. Distances from round 20 to round 23 are 22 to 25 m.

Basic data for round 2 is:

Round no	Distance m	Charge weight kg
20	22	2.9
21 MF	25	3.7
22 RB	25	3.3

Following can be noted in Figure 12 where the result for round no 2 is presented. The un-corrected data including distances and charge weight is found in Appendix 2.

The reference rounds, 20, blasted before the misfired round, 21, has somewhat higher vibration level than the misfired round, 18 to 16 mm/s. The re-blast, 22 is a bit lower than the misfired blast around, 13 mm/s.

No clear indication that the misfired round is different from the reference rounds can be seen from the results.

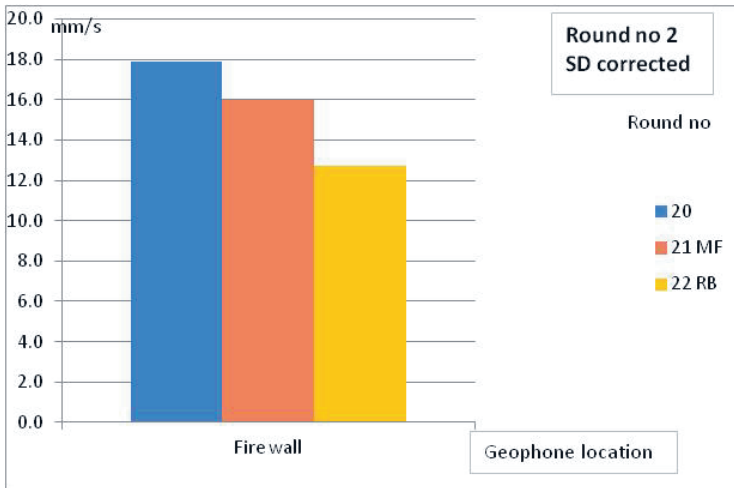


Figure 12. Result from round no 2, data are scale distance corrected

### 7.3.3 Round 3

Round no. 3 from project no. 2 is monitored in a tunnel crossing approx. 20 m below the excavated tunnel. The presented graph in Figure 14 shows vibration values from geophone MB 005-001 to 009 placed in the tunnel roof of the crossing tunnel. MB 005-001 to 003 is to the right of the blasts. MB 005-004 to 006 is in front of the blasts and MB 005-007 to 009 is to the left of the blasted rounds. Figure 13 shows the locations of the 3 rounds and the monitoring locations.

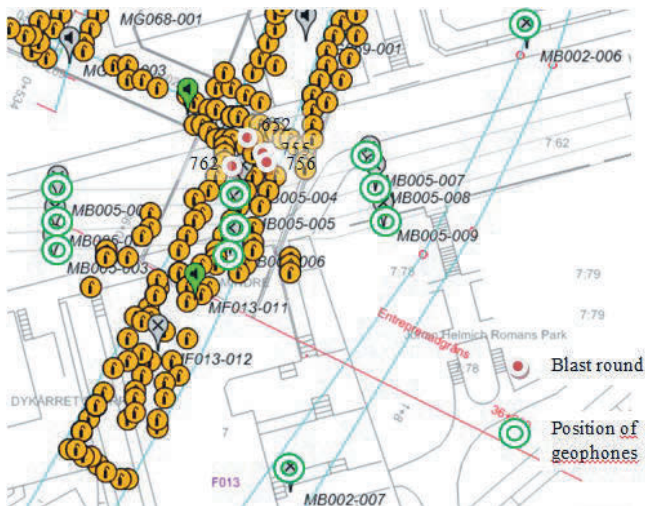


Figure 13. Locations of the 4 rounds and the monitoring locations

The round consisted of only 13 holes and formed the opening cut. The small round was a test blast for the coming crossing of an existing rail tunnel. Drill depth was 1.5 m and all charged holes were charged with cartridge dynamite type of explosives. Initiation system was Nonel. Maximum co-operating charge was 0.7 – 1.3 kg

Basic data for round 3 is:

Round no	Distance m	Charge weight kg
652 MF	19 – 48	0.7
755 RB	20 – 48	0.8
756	19 – 48	1.3
762	19 – 47	1.3

All rounds were monitored at 11 locations with 3-axial geophones. Data is presented as the vector-sum of the three directions.

Following can be noted in Figure 14 where the result for round no 3 is presented.

At many of the measuring points, 8 of them, the vibration levels from the misfired round were in the same range or lower than the reference rounds. In three of them the misfire is lower. The re-blast vibration level is in general the same or lower as the misfired round except in one measuring point where the re-blast was twice as high as the misfired round. This measuring point was located in an opposite direction as the others.

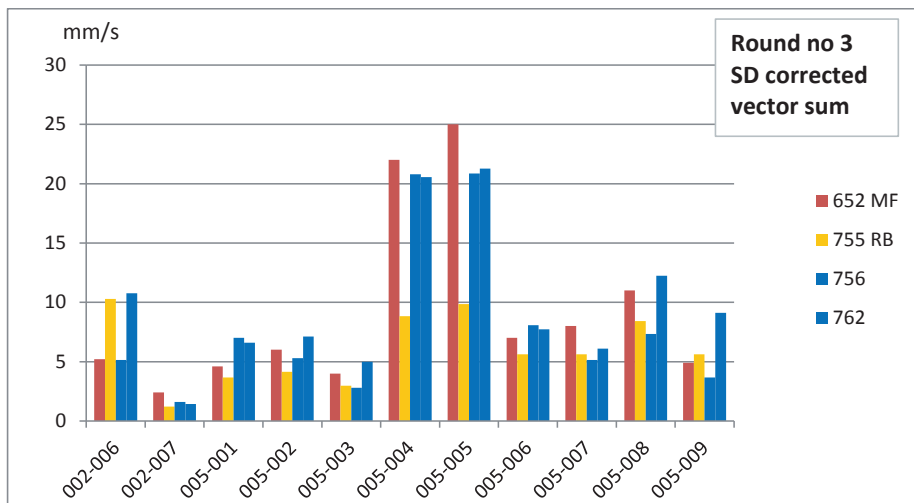


Figure 14. Results from round no 3, data are scale distance corrected

### 7.3.4 Round 4

Round no 4 from project no. 2 is monitored in a parallel tunnel at approx. the same horizontal level. Four different monitoring points were used for evaluation. Geophone MB 005-12 and 005-13.2 were placed in the parallel tunnel abutment facing the excavated tunnel. Location was behind the tunnel faces of the evaluated rounds. Geophone MB 005-014 was also placed in the parallel tunnel abutment facing the excavated tunnel but more perpendicular to the rounds. Geophone MB 005-015 was positioned in the same tunnel as the other geophones but ahead of the tunnel face. Figure 15 shows the locations of the 6 rounds and the monitoring locations.

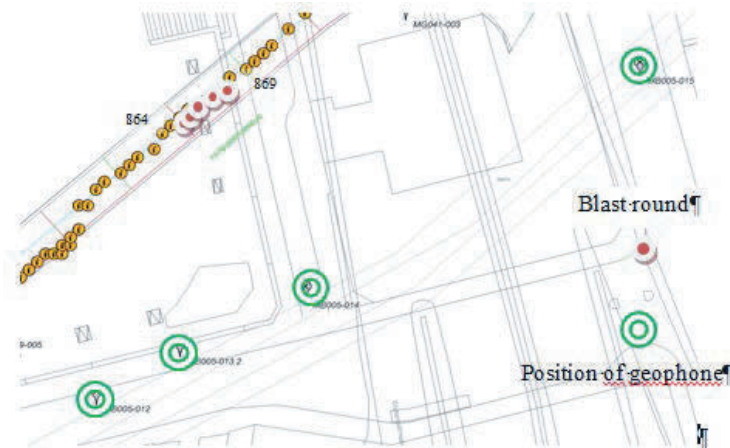


Figure 15. Locations of the 6 rounds and the monitoring locations

The round consisted of 121 holes. Drill depth was 2.2 m and all charged holes were charged with cartridge dynamite type of explosives. Initiation system was electronic detonators, eDev from Orica. Maximum co-operating charge was 1.1 – 1.5 kg.

Basic data for round 4 is:

Round no.	Distance m	Charge weight kg
864	27 – 56	1.3
865	28 – 61	1.1
866 MF	28 – 55	1.1
867 RB	28 – 54	1.1
868	28 - 52	1.5
869	28 – 50	1.4

All rounds were monitored at 4 locations with 3-axial geophones. Data is presented as the vector-sum of the three directions.



The graph in Figure 16 shows 2 reference rounds, 864 & 865, blasted before the misfired round, 866, the re-blast, 867 and two more reference rounds, 868 & 869. As can be seen in the graph all 4 reference rounds are higher in measured vibration level in all measuring locations compared to the misfired round and its re-blast. For geophone MB 005-015 at the longer distance from the blasts, approx. 50 m, the difference is less than for the closer ones, 30 – 40 m. The re-blast is overall lower than the misfired rounds.

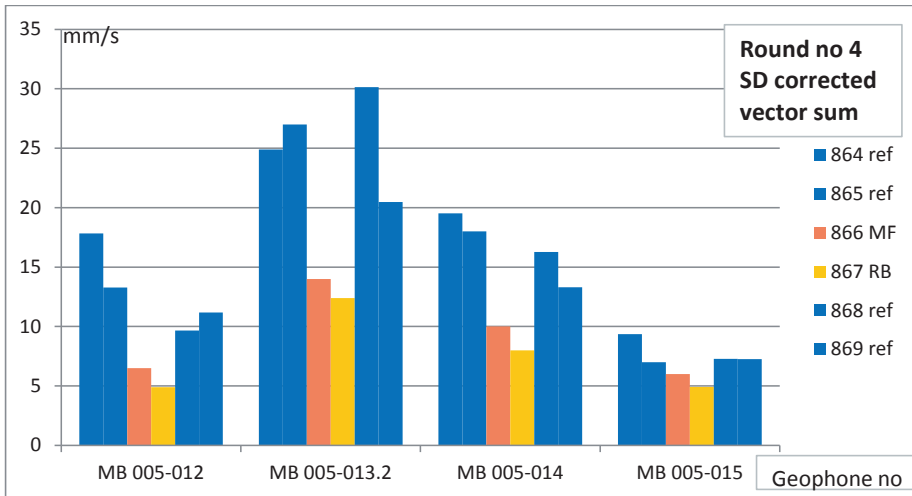


Figure 16. The monitoring results of round 4 in project 2. Data are the vector sum from 3 triaxial measuring points which are scale distance corrected

### 7.3.5 Round 5

Round no. 5 from project no. 3 is monitored at 3 surface locations, 9, 10 and 11. The geophones were mounted on buildings in a residential area at approx. 17 m higher elevation than the blasted rounds. All geophones were vertically positioned. Figure 17 shows the locations of the rounds and the 3 monitoring locations.

The round consisted of 132 holes. Drill depth was 5.8 m and all charged holes were charged with a pump emulsion type of explosives. The initiation used system was Nonel LP. Maximum co-operating charge was 10.5 – 11.5 kg.

Basic data for round 5 is:

Round no.	Distance m	Charge weight kg
13 MF	77 – 145	10.5
14 RB	74 – 141	11.5
15	72 – 138	11.5
16	70 – 135	11.5

As shown in Figure 18 the misfired round, 13, is lower or at the same level as the reference rounds, 15 & 16 with the exception of geophone #9 where the reference round 16 is clearly lower than all other measurements. It can also be noted that the re-blast, 14, vibration level is higher than the misfired round, 13.

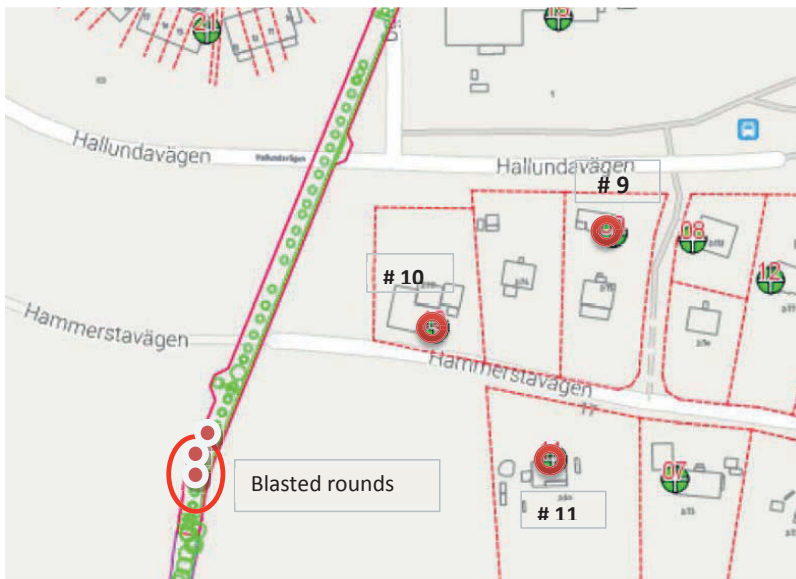


Figure 17. Locations of the rounds and the 3 monitoring locations

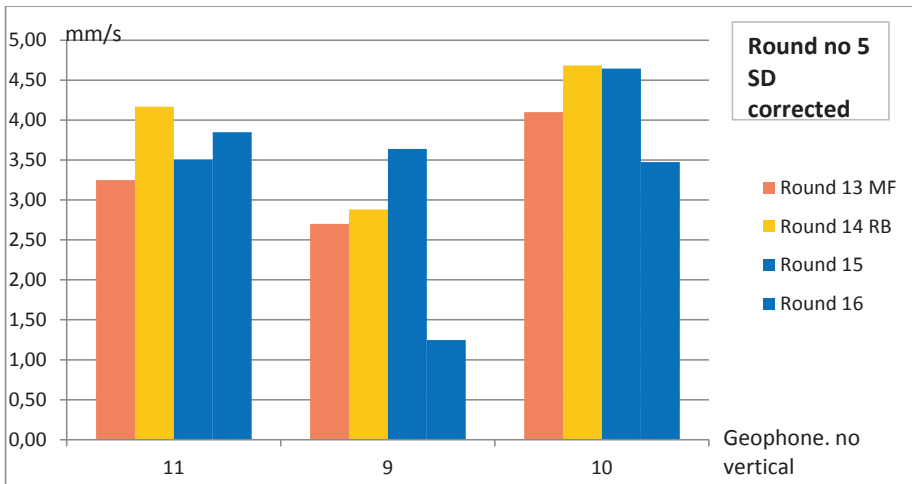


Figure 18. The monitoring results of round 5 in project 2. Data are scale distance corrected

### 7.3.6 Round 6

Round no. 6 from project no. 4 is monitored at one surface location, 206, and one underground location in three directions, 209 L, 210 T & 211 V. The underground geophones were mounted to the rock surface in a parallel rock cavern. The surface located geophone was mounted on to a foundation of a building. Figure 19 shows the locations of the rounds and the underground monitoring location.

The round consisted of 102 holes. Drill depth was 5.2 m and all charged holes were charged with a pump emulsion type of explosives. The initiation used system was Nonel. Maximum co-operating charge was 8.5 kg.



Figure 19. Locations of the 4 rounds and the monitoring location

Basic data for round 6 is:

Round no.	Distance m	Charge weight kg
21	20	8.5
25 MF	20	8.5

As shown in Figure 20 the misfired round, 25, is lower or at the same level as the reference round, 21 with the exception of the longitudinal direction, 209, where the reference round 21 is somewhat lower than the misfired round, 25. No reading from the surface monitoring for round 21 was available. In Figure 21 the vector sum of geophone 209 – 211 is shown. The difference between the reference blast and the misfired blast is very small.

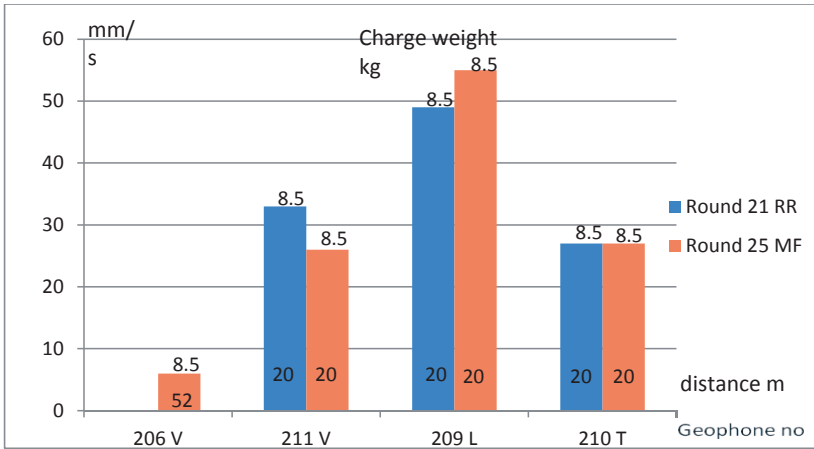


Figure 20. The monitoring results of round 6 in three directions

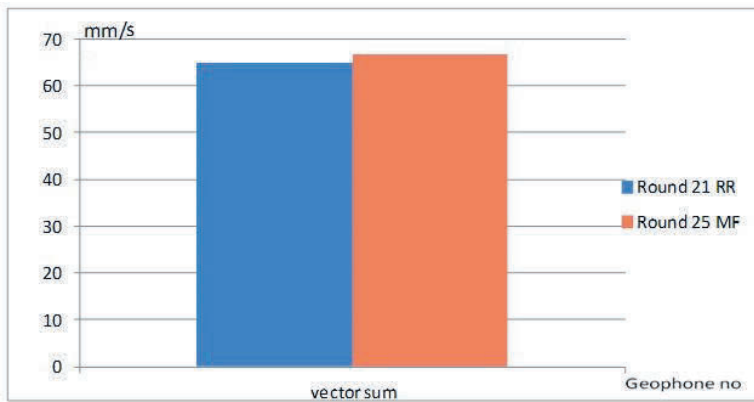


Figure 21. The monitoring results of round 6 as the sum of the three directions

### 7.3.7 Round 7

Round no. 7 from project no. 4 is located and monitored as shown in Figure 19 which is in the same area as round 6. The reference round, 33 was blasted before the misfired round, 37. Blasting parameters are also the same as for round 6.

As shown in Figure 22 the misfired round, 37, has registered lower vibration levels in all three directions compared to the reference round, 33. At the longer distance for the vertically oriented surface geophone, 206, the misfired round shows a higher value of vibration than the reference round, 8 mm/s compared to 4 mm/s. In Figure 23 a vector sum of geophone 206 – 210 is shown. In this case the vibration level of the reference round is higher than the misfired round.

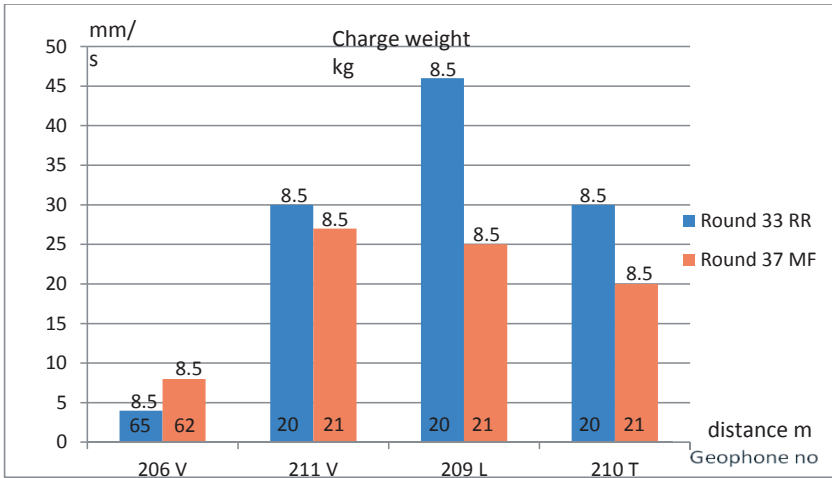


Figure 22. The monitoring results of round 7 in project 4

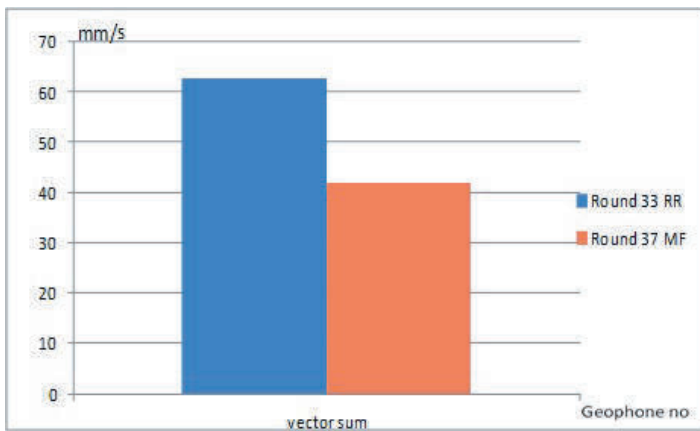


Figure 23. The monitoring results of round 7 as the sum of the three directions

### 7.3.8 Bench test, round 8

At the Swedish rock blasting committee 2013 Jern presented a paper on establishing vibration prognosis for a lime stone quarry in Sweden. Ten single test shots were fired in a bench set up. Charge weights were 12.5 to 52 kg. Two of the charges were blasted with a normal burden. The rest were blasted fully confined with no ability to break the burden. Vibration level was measured at 12 different measuring points at different distances from the bench. Data from that project is used in this study to look closer into the vibration levels from the fully confined charges and the 2 with breakage.

From the 10 shots, 4 shots are selected to the study. All charges are 52 kg, 2 are confined and two are with normal burden. Distances from charge to monitoring location

are from 9 up to 115 m. The locations of the single shots and the monitoring points are shown in Figure 24.

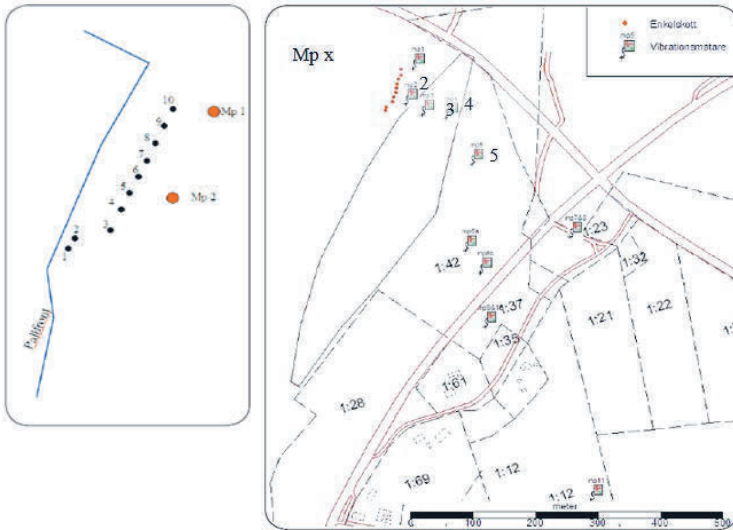


Figure 24. Layout of test site, the 4 monitors are marked 2 – 5

The result of the 4 single shots can be seen in Figure 25.

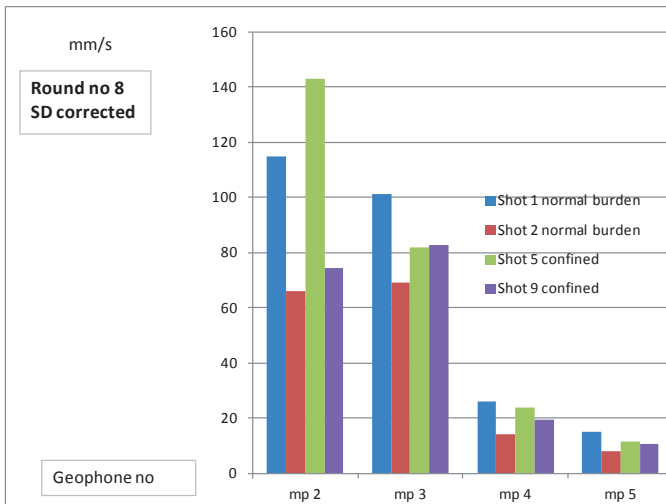


Figure 25. Result from 4 of the closest monitoring points

The result from the 4 single shots measured at 4 locations shows the highest vibration level from shot 1 with normal burden. Second shot, also with normal burden shows a much lower value compared to the first shot. Shot no. 5 which is confined is highest at measure point 2 compared to shot no. 1 but is reduced compared to shot 1 as the distance increases away from the bench. Shot no. 2 with normal burden has a lower vibration level than all others at all measuring locations. Figure 26 shows a regression analysis of the data. No significant difference between the shots can be seen in the graph.

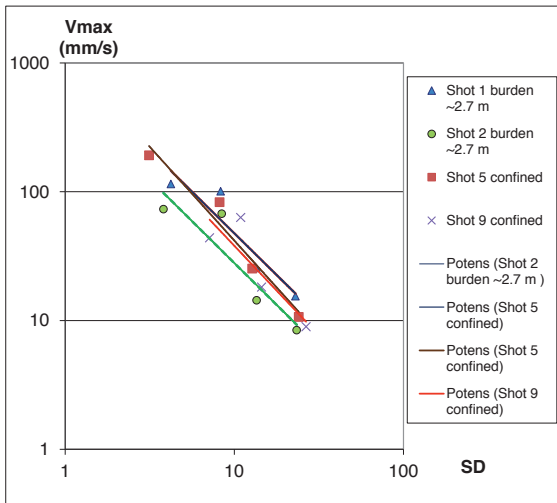


Figure 26. Regression analysis graph from the 4 shots

## 7.4 Summary of results

When looking at the results for the 8 rounds shown in the graphs it is difficult to trace any kind of tendency whether there is relationship between level of vibration and confinement or not.

In five of them, 1, 3, 5, 6, and 8 no tendency could be found at all. In round 2 the misfired round is lower than the reference round and the re-blast is lower than the misfired round. However, the number of data is limited. The graph from round no. 4 shows a clear tendency that the misfired- and the re-blast are lower than the reference blasts. In round no. 7, also limited in data the reference round is higher than the misfired round.

For round no 3 and 4 where more available monitoring data was accessible a statistical analysis of vibration data for misfired rounds was carried out. The analysis is presented more in detail in section 7.5. In this analysis it is shown that all types of rounds, reference-, misfired and re-blasts are within the same population within a 95 %



confidence interval. So what could be seen in the graph of round 4 could not be seen in the statistical analysis.

## 7.5 Statistical analysis of round no 3 and 4

### 7.5.1 Introduction

First a statistical analysis of single component vibration measurements was conducted for 15 blasts in two tunnels. The result was that the one-dimensional nature of single component PPVs and limited number of measurements did not permit any solid conclusion to be drawn. A re-analysis of the vibration data, using the vector PPV (VPPV) of the same blasts, was then done and this is presented and discussed in this section. The VPPVs were calculated from the original recorded signals from triaxial geophones; additionally, more measurement stations were taken into account for the re-analysis.

A summary of the number of blasts and measurements is presented in Table 3.

Table 3. A summary of the number of blasts and measurements

	<b>Citybanan Rail Tunnel Round 3</b>	<b>Fatburs Tunnel Round 4</b>
Total number of Blasts	4	6
Reference Blasts	2	4
Misfired blasts	1	1
Re-Blasts	1	1
Number of geophones	11	6
Total number of VPPV measurements	44	32

### 7.5.2 Aim and method

The main purpose of this analysis is to find out whether the misfired rounds produced vibrations different than the reference blasts, which were blasted normally, and also to check if there are any variations for the re-blasts of misfired rounds.

The provided data for the re-analysis consist of blast identification information in addition to specifications of the blast (total charge, distance to geophones, detonators type, etc.) and their corresponding vector PPVs calculated from triaxial measurements at each geophone.

For the convenience, REF, MF and RB abbreviations is used to refer to Reference blasts, Misfired blasts and Re-blasts respectively. The squared root scaled distance (SD) to the geophone has been calculated to normalize the VPPVs according to the charge

weight and distance from the sensor. The method for the statistical analysis is ANCOVA, Univariate Analysis of Variance.

### 7.5.3 Results

#### Citybanan Rail Tunnel Round 3

The pairwise comparison of three groups is presented in Table 4. The critical value for significance is 0.05, i.e. 95% confidence. In other words, significance values smaller than 0.05 represent significant differences between groups. The standard error and mean difference between groups are also included as well as the upper and lower bounds for the 95% confidence interval.

Tabell 4. Pairwise comparison of logPPV data for Citybanan Tunnel Round 3 (Pairwise Comparisons. Dependent Variable: logVPPV)

(I) Blast	(J) Blast	Mean Difference* (I-J)	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
MF	RB	0.160	0.083	0.176	-0.048	0.367
	Ref	0.123	0.078	0.329	-0.072	0.318
RB	MF	-0.160	0.083	0.176	-0.367	0.048
	Ref	-0.037	0.077	0.951	-0.227	0.154
Ref	MF	-0.123	0.078	0.329	-0.318	0.072
	RB	0.037	0.077	0.951	-0.154	0.227

Based on estimated marginal means

\*. The mean difference is significant at the 0.05 level.

According to Table 4 all significance values for any pair of blasts are larger than 0.05, meaning that none of them can be considered different than the others and all measurements can be assumed as one population. The graphical illustration of the results in Tabel 4 is presented in Figure 27. The dashed line represents the 95% confidence interval for the reference blasts, which includes almost all of the measured VPPV values of misfired and re-blast rounds.

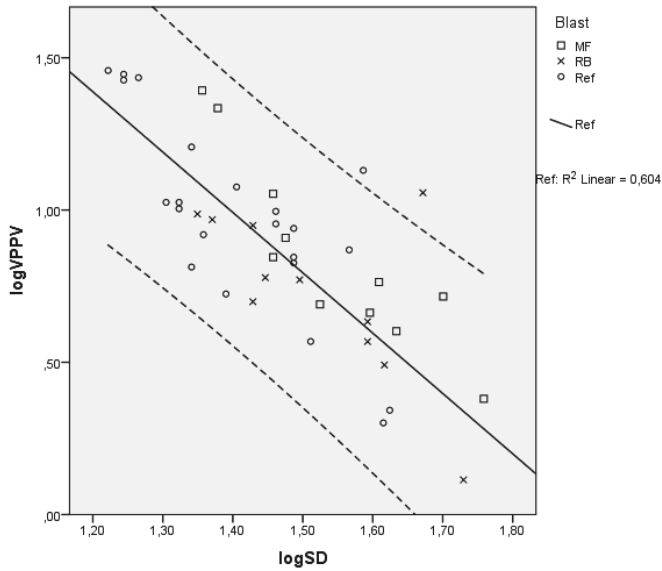


Figure 27. Logarithmic plot of scaled distance (SD) versus VPPV (the solid line is the regression line for reference blasts with the dashed lines showing its 95% confidence interval)

Figure 27 visually confirms that the VPPVs produced by the misfired round and its re-blast are not significantly different from the reference blasts.

#### Fatburs Tunnel Round 4

The results of pairwise comparison of three groups of data are presented in Table 5.

Table 5. Pairwise comparison of logPPV data for Fatburs Tunnel Round 4 (Pairwise Comparisons Dependent Variable: logVPPV)

(I) Type	(J) Type	Mean Difference* (I-J)	Std. Error	Sig.	95% Confidence Interval for Difference	
					Lower Bound	Upper Bound
MF	RB	0.082	0.151	0.931	-0.302	0.466
	Ref	-0.053	0.116	0.957	-0.347	0.241
RB	MF	-0.082	0.151	0.931	-0.466	0.302
	Ref	-0.135	0.116	0.582	-0.430	0.159
Ref	MF	0.053	0.116	0.957	-0.241	0.347
	RB	0.135	0.116	0.582	-0.159	0.430

Based on estimated marginal means

\*. The mean difference is significant at the 0.05 level

Similar to the results of the Citybanan tunnel, Table 5 shows rather large significance values for all pairs of data. In other words, none of the groups can be considered as different from the others. The large values of significance, e.g. 0.9 with the significance limit of 0.05, shows that the misfired and the re-blast are actually rather close to the regression line of the reference blasts, implying their close correlation. The regression line and its corresponding 95% confidence interval are plotted in Figure 28.

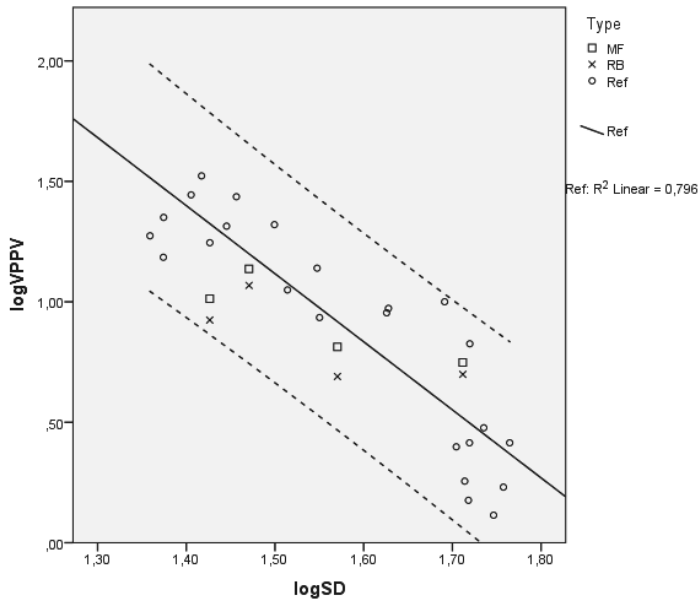


Figure 28. Logarithmic plot of scaled distance (SD) versus VPPV for Fatburs tunnel round 4. The solid line is the regression line for reference blasts with the dashed lines showing its 95% confidence interval

As seen in Figure 28, all the VPPV values of the misfired round and the re-blast lie within the confidence interval of the reference blasts, and interestingly, they are rather close to the regression line for the reference blasts.

#### 7.5.4 Discussion of the statistical analysis

In the first part of the analysis, single component PPVs together with limited number of data resulted in ambiguous results whether the misfired rounds produced vibration different from the normal blasts. In the second part, the vector PPVs were extracted for a larger number of sensors and a re-analysis of the data was conducted. Larger number of measurements led to better statistical understanding of the data; in addition, due to

3D characteristic of PPV vector, no comparison of different components and their contribution were required.

*The statistical analyses indicated no significant variation with type of blast, i.e. normal, misfired or re-blast.* According to the presented results, in both tunnels the vibrations for misfired, re-blast and reference blasts were considered similar with respect to their corresponding deviation.

Altogether, it can be concluded that the misfired rounds and their re-blasts did not produce vibrations different from the reference blasts. However, such set of data is not sufficient to generalize this conclusion to all blasts.



## 8 DISCUSSION AND CONCLUSION

The small number of blast rounds in this study is of course limiting the possibility to draw a far-reaching conclusion. All data are collected from production tunnel blasts except round 8 which is picked from a test blast set up. Misfires are extremely unwelcome events in tunneling and therefore by definition the number of available objects for the study is limited.

The quality of collected data from blast reports and vibration monitoring is judged as fairly reliable. Vibration data is received from a site adapted monitoring system. The system keeps track of the blast geometry, the blast parameters and the vibration results. This is stored in a data base accessible for all involved parties. Used monitoring systems are the Swedish systems Avanet, NCvib and Vipnet.

### *Vibration measurements*

In the area of round 3 and 4 the tunnel under construction crossed over an existing underground tunnel which was under heavy surveillance due to the ongoing public transportation in the underground tunnel. An array of triaxial geophones was mounted directly to the rock face by expander bolts which are the normal way in tunnel projects. Frequencies measured were up to 250 Hz. The coupling between rock and geophone was at a few occasions deteriorated but not during the monitoring of the rounds in this study. A change in coupling conditions could normally be observed in the vibration signal.

### *Distance between blast and geophones*

The distance between the blast and the monitoring location was calculated based on the coordinates for each location. The monitoring point was registered when mounted and the coordinate for the blast round was registered by the blasting engineer when filling in the blasting report form. This could be done either by marking the round on a map or by using the coordinates from the tunnel line as input to the blast report. Either way of registering the coordinates could create differences between correct and reported location. Especially with large rounds and short distances to monitoring points this error could differ quite a lot depending from what part of the round the distance was measured. All blasts in round no.3 were pilot blasts and limited in size to approx. 5 x 5 m. For round no. 4 the width of the tunnel was 7.5 m and the closest distance to the monitoring locations positioned parallel to the constructed tunnel was 27 m. The distance was usually measured from the gravity center of the round but the individual charges in the blast were located at distances varying from 23 to 31 m away from the measuring point.

### *Charge weight*

Another source of error is the registration of maximum cooperating charge in the round which is also an important input in this study. In some of the rounds due to high restrictions in vibration level, cartridge explosive was used. Using sticks and pipe charges makes it easier to calculate the consumption compared to the use of bulk explosives. For some rounds where pump emulsion explosives were used and the holes were fully charged the amount in each hole could be checked by simply checking hole size and hole length.

### *Conclusion*

No evidence for a relationship between degree of charge confinement and vibration level could be found in this study. Both, the main part of the single observations and the statistical analysis of round 3 and 4 confirm the independency.

The practical aspect of this result will hopefully be that confined charges will not get all blame for causing unwanted vibration peaks in the future. It can also be the other way round that one cause for a plausible explanation of high vibration levels is taken away from the tray of speculations.

A next step, phase 2 of this work is already planned and presented in section 9. It will be based on test shots and not on production tunnel rounds. Not on misfires but on single hole shots.



## 9 PHASE 2. PROPOSAL OF PRACTICAL TESTS

The result of this pre-study has pointed out that:

- there is no clear evidence in the literature study of an increase in the vibration level due to confinement
- there seems to be no evidence from a number of identified misfired rounds that confinement increase the vibration level

To investigate this further a second step, phase 2 is proposed. Phase 2 includes a number of controlled field studies of bench and tunnel blasts and registration of vibration levels.

This pre-study does not cover details for the field tests. However, there are a number of important factors to be aware of like:

- constant geology conditions if possible
- careful and accurate drilling
- careful and exact charging
- accurate positioning of holes and geophones/accelerometers
- the geophones/accelerometers are solid casted in the measure holes
- electronic detonators for exact timing

### 9.1 Bench blasting

The bench blasting tests includes the following steps:

1. A number of holes, all with different burden, are drilled in a quarry. The blast holes are charged with the same type of explosive and with constant charging weight. The vibrations are measured at different distances behind the blasting holes. In Figure 29 the distance from the blasting holes to the measure point is constant.

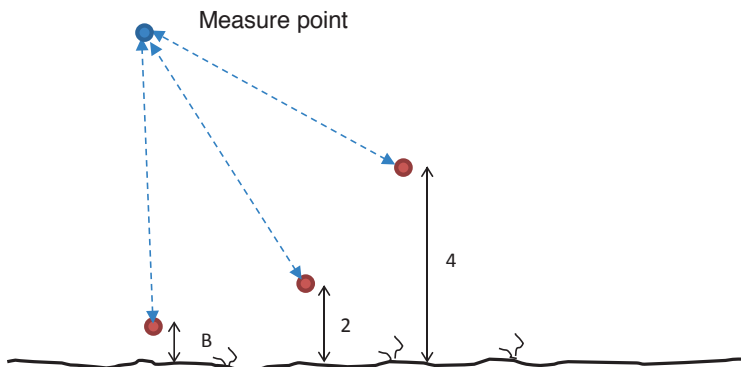


Figure 29. Example of the experimental set up

2. The tests are repeated 5-10 times
3. The vibration signals are analyzed with respect to amplitude and frequency
4. The result is evaluated and reported

## 9.2 Tunnel rounds

The main difference between a tunnel-and quarry blasts is that only one free face is available in a tunnel blast. In that sense the blasting is more confined and a free face must be created constantly. In tunneling this starts up with an uncharged large opening hole as the first free surface, see Figure 30. The charged holes are then blasted towards an increased surface. It is very important that the delay between the holes is long enough to allow time for breakage and throw of rock before the next hole is blasted.

The principle structures of the tests with tunnel rounds are:

1. Tunnel rounds with deliberate strange initiation sequences are blasted. As an example the initiation sequence in the opening holes could be reversed. Another example could be a change in the sequence of the stopping holes.
2. The vibration levels are measured from blasting of the rounds at a constant distant. The vibration curves are analysed to see what hole that cause the highest vibration level. The vibration levels from the test blasts are then compared with the vibration level from ordinary tunnel blasts in the same rock. The tests are repeated 5 times.

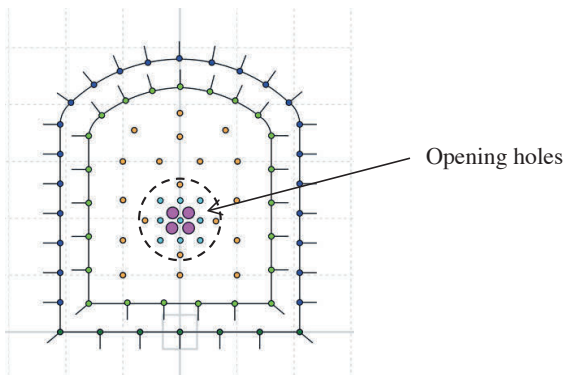


Figure 30. Example of a tunnel layout

**Evaluation and compilation**

A total evaluation from all of the tests should be done with respect to vibration level, distance, rock structure and charge weight. It's very important to keep hole diameter, charge weight, type of explosive, decoupling and measurement equipment constant. The variables should only be the confinement and local changes in the rock type.



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## 12 APPENDIX 1. LITERATURE STUDY

The effect of blast confinement on ground vibrations has been an area of interest for many studies. However, most of the early research works were based on a prevailing assumption which is “as the burden increases, vibrations increase as well”. Anderson et al. (1985), Wiss and Linehan (1978), Persson et al., (1994), Siskind et al. (1980) and several other researchers have studied the factors affecting vibrations and almost all of them have reported moderate to significant effect of burden on vibrations. According to Jimeno et al. (1995), if the confinement or burden is extensive, the explosive energy has too much resistance for effective fracturing and displacement of the rock. As a result, part of the energy becomes seismic and intensifies the vibrations. In a more or less similar reasoning, Hagan and Kennedy (1977) state that in case of large burdens, the pressurized gases, which are products of explosive detonation will be bottled up within the hole for more than the optimum time. The energy of the explosive not utilized in fragmentation and throw will cause an increase in ground vibration (Hagan and Kennedy, 1977).

On the other hand, the studies carried out recently have come up with different conclusions and controversy swirls about whether ground vibrations are affected by confinement/burden. Ramulu et al. (2002, 2005), Ramulu (2010), Bergmann et al. (1973), Liu and Ludwig (1996) and Heilig et al. (1997) have investigated such effect and believe that the vibrations increase as burden increases; but a study by Uysal et al. (2007) resulted in adverse effect of burden, i.e. vibrations decrease as burden increases. Blair and Armstrong (2001) and Blair and Birney (1994), on the other hand, believe that burden has insignificant effect on vibration levels and believe that the studies that resulted in burden effect are subject to methodological and scientific objections.

Ramulu et al. (2002) conducted 2 series of trials in order to investigate the effect of individual blast parameters on ground vibrations in a limestone quarry. The first series consisted of 5 trials with burdens varying from 3 m to 8 m. The optimum burden for those particular strata was 4 m. Each round consisted of 10 holes and 2 holes were blasted in each delay. The vibration was monitored by three seismographs placed at 3 different distances in the same direction from the blast. Bench height and blast hole diameter were 6 m and 150 mm respectively for all trials. They also adjusted the spacing in order to have a constant specific charge of  $0.39 \text{ kg/m}^3$  for all trials. The results of this series of trials showed that the vibration is insensitive to the burden at larger scaled distances (Figure 1). It was observed that the influence of the burden was predominant only at lower scaled distances.

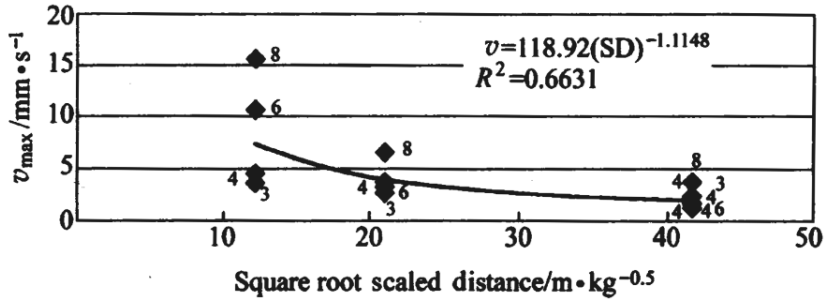
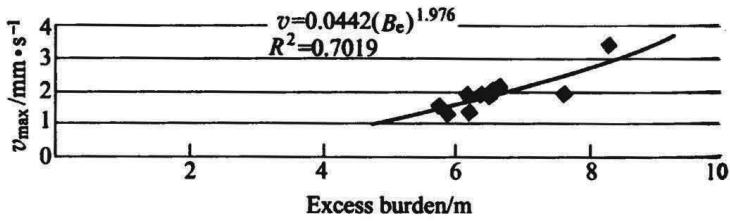
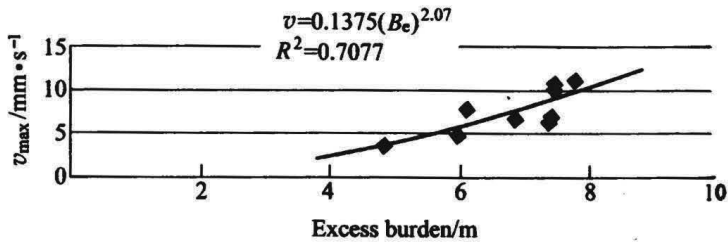


Figure 1: Peak particle velocity versus square root scaled distance for vibration data of the first series of trials of Ramulu et al.; after Ramulu et al. (2002).

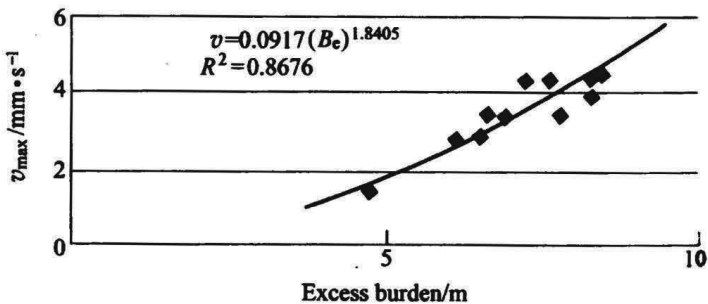
In their second series of trials, Ramulu et al. (2002) used a more or less similar setup with a different approach. The monitoring stations were fixed in 3 directions to the blast site. The seismographs were installed in a strategic way to maintain constant scaled distance in each direction. The peak particle velocity (PPV) was then correlated to the excess burden, which is any burden larger than the optimum burden (4 m in their case). The results, in three directions with three different scaled distances, clearly indicated that the burden has a considerable influence over level of vibration (Figure 2). Ramulu et al. (2002) concluded that there is a considerable relationship between burden and vibrations.



(a)



(b)



(c)

Figure 2: Effect of excess burden on the PPV in: a) N-E direction with scaled distance of  $50 \text{ m/kg}^{0.5}$ , b) East direction with scaled distance of  $15\text{-}16 \text{ m/kg}^{0.5}$  and c) S-E direction with scaled distance of  $23\text{-}25 \text{ m/kg}^{0.5}$ ; after Ramulu et al. (2002).

As part of a study on blast damage and dynamic behavior of hanging walls in underground bench stopping, Villaescusa et al. (2004) measured peak particle velocity for two layouts with 1.5 m and 3 m of burden in stope blasts. They used two explosive types, i.e. ANFO and ISANOL, and adopted a number of triaxial geophone arrays to measure the PPV for each monitored event. They reported that limited data and poor correlations in 3 m burden configuration made it difficult to draw a solid conclusion whether the PPV was being affected by burden confinement. However, a review of their

raw data showed that in the case of 3 m burden, larger PPV amplitudes were being experienced at similar distances and for the same explosive type (Villaescusa, 2004).

Ramulu et al. (2005) carried out investigations in three open-cast mines to establish the effect of the burden on ground vibrations and vibration frequencies. Their method was similar to their previous study (Ramulu et al., 2002) with seismographs. A total number of 30 trial blasts were conducted. An optimum burden was assigned for each open-cast mine and the burdens varied from 4 m to 13 m in different mines. From the results of all trials, they concluded that the influence of burden on peak particle velocity is very significant and the burden is directly proportional to the PPV levels within the range of optimum burden to twice the optimum burden. Some observations with suboptimum burdens indicated that there is a decrease in vibration levels with a decrease of burden. They also reported that the influence of burden on vibration frequency is insignificant. However, their conclusions are debatable from an analytical point of view. It is mentioned that the poor correlation coefficient (i.e.  $R^2=0.28$ ) of the combined PPV and scaled distance in the regression analysis of the raw data owes to scattering of PPV levels for one of the mines. It was assumed that the scattering of PPV levels might be due to the influence of excess burden for some of the trial blasts. Based on the aforementioned assumption, the correlation was improved by separating PPV data with respect to burden. Even after separation, the correlation for the data with excess burden is relatively poor ( $R^2=0.51$ ). Once more, it was assumed that the scattering of PPV levels may be due to the differing influence of excess burden at various distances and hence, the PPV levels were separated again according to the scaled distance. Still, after such categorization the correlation is poor for one out of two distances ( $R^2=0.44$  for 300 m distance). Therefore, the conclusions of Ramulu et al. (2005) should be viewed with some level of discretion.

Uysal et al. (2007) carried out single blast hole trials in two open-pit mines in Turkey (namely SLE and GLE respectively) in order to investigate the effect of burden on blast-induced vibrations. They conducted 20 trial blasts with burdens of 4, 10, 12 and 14 m in SLE mine with 10 m long blast holes. At GLE mine, with blast hole length of 8.5 m, they carried out 16 trial blasts with burdens of 3, 4, 5 and 6 m. Similar to the study by Ramulu et al. (2005), they analyzed the data in 2 stages. In the first stage the classical methods were utilized to correlate PPV to scaled distance (Figure 3).

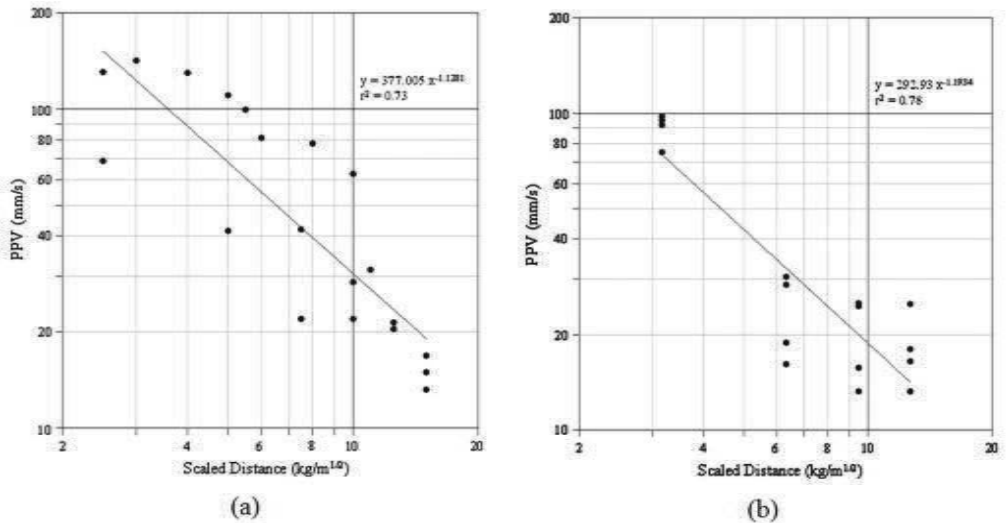


Figure 3: Relationship between PPV and scaled distance, a) SLE mine and b) GLE mine; after Uysal et al. (2007).

In the second stage the data were categorized and evaluated on the basis of burden for the purpose of identifying the effect of burden over particle velocity (Figure 4).

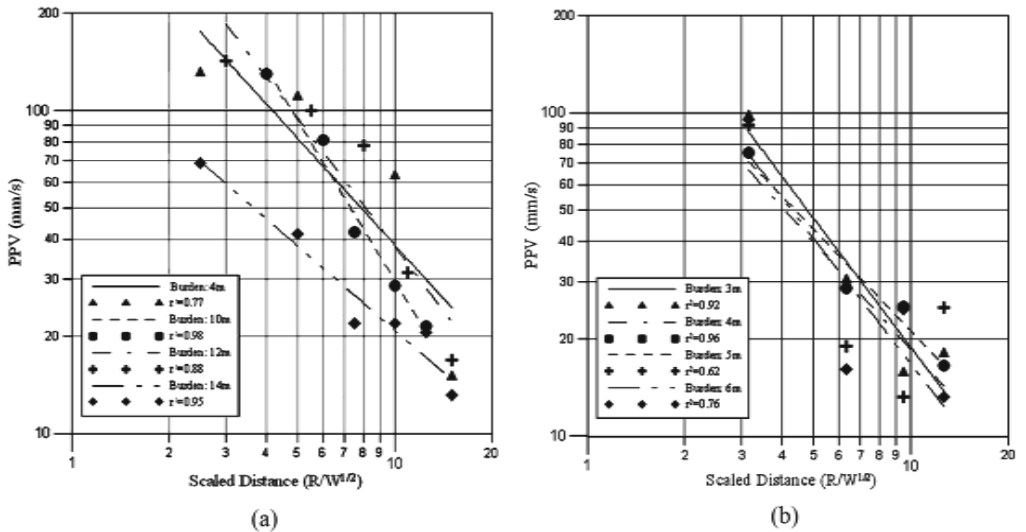


Figure 4: Data of Uysal et al. (2007) classified based on burden; after Uysal et al. (2007).

Uysal et al. (2007) concluded that particle velocity decreases as burden increases, which is contrary to the results of Ramulu et al. (2002, 2005). However, it should be reminded

that this conclusion is based on an assumption of PPV dependency on burden size; so the correlations were improved by categorizing the data, therefore their conclusion should also be viewed with caution.

On the other hand, Blair and Armstrong (2001) argue that there is no convincing evidence for the influence of burden on blast-induced vibrations. In addition to a detailed review of the literature, they conducted trials to investigate whether the vibration is affected by blast confinement. They concluded that vibration is insensitive to burden, but it is influenced by rock mass condition (i.e. the degree of damage). Blair and Armstrong (2001) questioned the methodology and conclusions of several researchers regarding the effect of confinement on vibrations.

Liu and Ludwig (1996) measured the blast vibration for a series of blasts with various charge weights and burdens; they used a 4-parameter model to fit a scant data set of 9 observed values and concluded that vibration depends on burden. Blair and Armstrong (2001) argue that Liu and Ludwig (1996) have *assumed* a dependence of vibration on burden and their raw data includes a significant amount of scatter, in addition to that the raw data show no convincing evidence of an influence of burden (Figure 5).

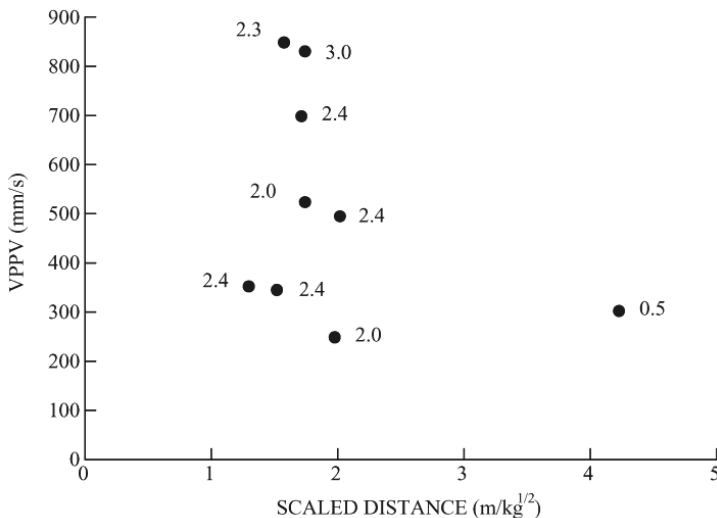


Figure 5: The raw experiment data of Liu and Ludwig (1996) plotted as a function of scaled distance. The burden (in m) is shown for each data point; after Blair and Armstrong (2001).

Bergmann et al. (1973) conducted trial blasts in small granite blocks, but instead of geophones or accelerometers they used pressure gauges to measure the induced



vibration (Figure 6). These authors, too, assumed that vibration is affected by burden and incorporated this effect into a 9-parameter model.

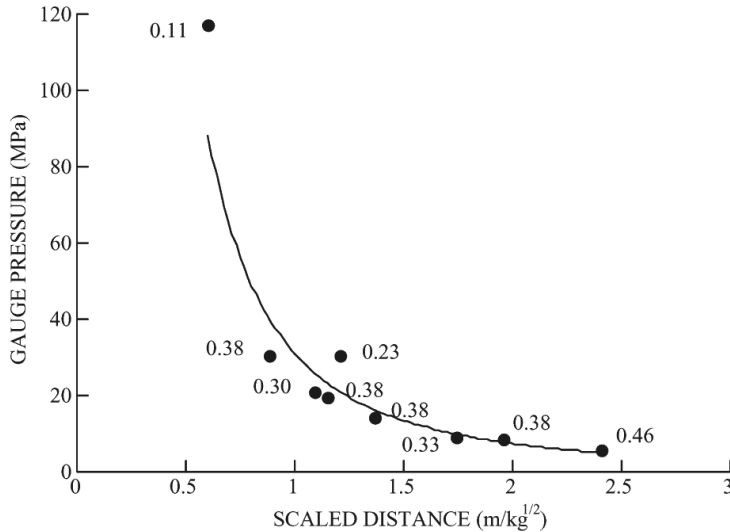


Figure 6: The raw experiment data of Bergmann et al. (1973). The burden (in m) is shown for each data point; after Blair and Armstrong (2001).

Blair and Armstrong (2001) reviewed the raw results of Bergmann et al. (1973) and argued that there is no convincing evidence of an effect of burden on blast vibration (gauge pressure in this case). Blair and Armstrong (2001) believe that the most common sense interpretation of Bergmann et al. (1973) data is that all the data may be fit by the usual power curve, irrespective of burden.

Blair and Armstrong (2001) also mention the study by Heilig et al. (1997), who monitored a series of blasts in a quarry with free face and confined conditions. The scaled distance for the confined blasts in the study of Heilig et al. (1997) was approximately twice that of the unconfined blasts; Blair and Armstrong (2001) stated the comparison of those data sets as “statically unwise”. Additionally, by applying more suitable statistical methods, Blair and Armstrong (2001) argue that there is no convincing evidence that confined blasts produce vibrations different to those from unconfined blasts.

In addition to the detailed review of previous studies, Blair and Armstrong (2001) studied the effect of burden by means of direct experiments as well as a Dynamic Finite Element Model (DFEM) for the vibration produced from an explosive source located near free faces. They argue that the blast hole does not ‘know’ the extent of the burden until a wave has travelled out to the face and then returned. Thus there is a time delay

between the detonation in the blast hole and its reaction off the face. Neglecting any role of explosive gases, Blair and Armstrong (2001) believe that the influence of burden on blast vibrations should be analyzed from a viewpoint of travelling waves. By comparing two simple single-blast systems, one with a free face present and the other with infinite burden, they state that the only difference between two cases is the reflected wave from the free face. They then argue that there are at least four reasons to suspect that the reflected wave might not be of any significance. The four reasons would be:

- The most dominant reflection occurs for plane waves normally incident on a planar free face. However, the three-dimensional geometry and the finite velocity of detonation (VoD) of the explosive lead to a conical wave hitting the face at non-normal incidence.
- The direct wave travels towards the face through ground that is usually more damaged than ground at an equal distance behind the blast hole.
- The rugged (non-planar) face will promote incoherent back-scattering of the energy rather than simple reflection.
- The back-scattered wave travels back to the blast hole and beyond through ground that is even more damaged by the direct wave.

The models of Blair and Armstrong (2001) included a spherical source with finite VoD fired near one or two faces and monitored at 50 m from the spherical source. The wave mode conversion upon reflection at each boundary was accomplished by a modified method of images. Material attenuation (viscoelasticity) was also modeled approximately. Figure 7 shows the results of the model.

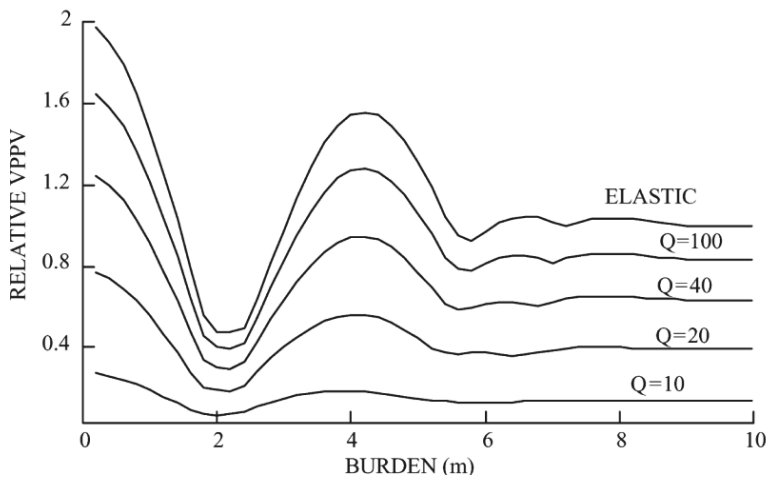


Figure 7: Results of the model of Blair and Armstrong (2001) showing the vibration as a function of burden in materials of varying attenuation ( $1/Q$ ); after Blair and Armstrong (2001).

According to this simple model, Blair and Armstrong (2001) concluded that the vibration can never increase by more than a factor of 2.0 due to the burden. Ironically, the model also showed that, under certain conditions, the vibration decreases with increasing burden, which is precisely opposite to the belief of Ramulu et al. (2002, 2005), but agrees with findings of Uysal et al. (2007).

Blair and Armstrong (2001), finally, reported a series of trial blasts with varying burdens conducted in an open pit mine. They used 125 kg to 150 kg of Energan 2640 explosive in 10.2 m long blast holes of 165 mm diameter. To monitor the vibrations, triaxial accelerometers were bonded directly to rock in an approximate line that was approximately normal to the bench face. The standard burden in the mine was 5.2 m and the trials were conducted with burdens of 0.5, 1.0 and 2.0 times the standard burden. Additionally, they measured the vibrations produced by two blast holes initiated in virgin (undamaged) ground. Their results are presented in Figure 8 in terms of vector peak particle velocity.

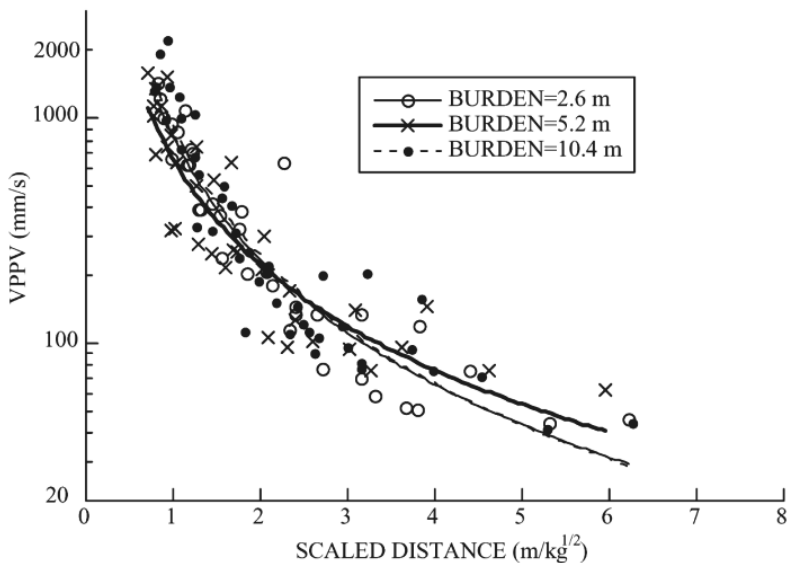


Figure 8: Results of single blast hole trials of Blair and Armstrong (2001) showing the VPPV as a function of burden; after Blair and Armstrong (2001).

It is quite obvious from Figure 8 that the burden has an insignificant effect upon the blast vibration, in fact the fitting curves for the 2.6 m and 10.4 m burdens are practically indistinguishable. Moreover, a formal statistical analysis of the data showed that all the data is best treated as a single data set rather than categorized by burden. It is worthwhile to mention that the statistical analyses showed that the vibration produced

from blast holes fired in undamaged ground was significantly larger than the vibration produced by blast holes from the burden trials (Blair and Armstrong, 2001).

Blair and Armstrong (2001) also cited a confidential study by Blair and Birney (1994) in which trial blasts were conducted with burdens of either 3 m or 6 m. The single blast holes were fired 900 m below the surface vibration detectors. The results are reproduced in Figure 9 below. It is quite obvious that this data for underground blasting also show no convincing evidence of a dependence of vibration on burden (Blair and Armstrong, 2001).

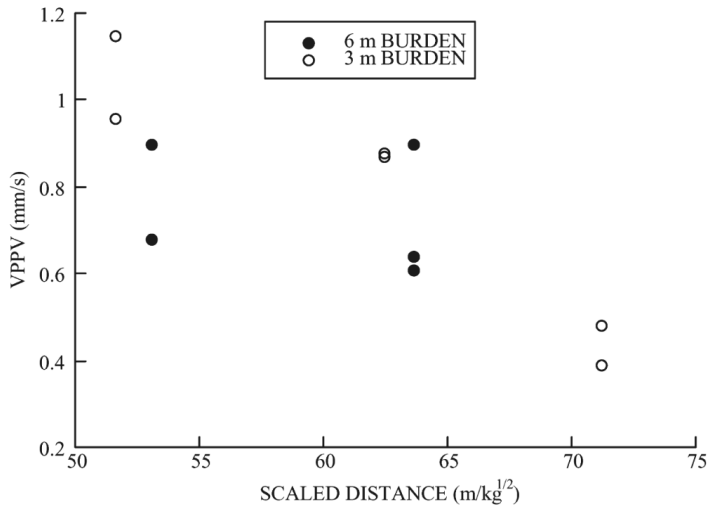


Figure 9: The VPPV data of Blair and Birney (1994) vs. scaled distance; after Blair and Armstrong (2001).

On the other side of the contradiction about the effect of confinement on vibrations, Ramulu (2010) put a step further and introduced a new blast vibration prediction model incorporating burden variations. Ramulu (2010) argued that the conclusions of Blair and Armstrong (2001) were based on early peak (the arrival of the P-wave) of the vibration and the maximum value, which was shown later, was ignored. Overlooking the critique of Blair and Armstrong (2001) about previous studies (Liu and Ludwig, 1996; Bergmann et al. (1973); Heilig et al. (1997); etc.), Ramulu (2010) considered the burden-effect as a fact and implemented the burden variations in a new vibration prediction model. For that purpose he viewed the ground vibration through two phases, the phase of vibration generation due to direct wave system, called as direct phase, and the phase of vibration generation due to reflected wave system, called as indirect phase. He looks at these two phases independently and then combines them to implement both of them into a model that takes into account the burden size in vibration prediction.

For the direct phase, Ramulu (2010) utilized the results of Mortazavi and Katsabanis (2001), who studied the effect of burden on blast hole chamber pressure. An optimum burden and an optimum pressure were assumed and the burdens were correlated in terms of burden to optimum burden ratios. A regression equation was developed for burden ratios and pressure ratios. Finally as the blast hole chamber pressure is directly proportional to vibration, the chamber pressure ratio was replaced by the vibration ratio, see Eq.1 (Ramulu, 2010).

$$\frac{v_2}{v_1} = \left( \frac{B_2}{B_1} \right)^{0.6}$$

Eq.1

Where  $B_1$  and  $v_1$  are the optimum burden and its corresponding vibration, respectively, and  $B_2$  and  $v_2$  are the non-optimal burden and its corresponding vibration respectively.

For the indirect phase, Ramulu (2010) refers to previous studies (Jimeno et al., 1995; Wathen et al., 1996; Du Pont, 1997; etc.) and concludes that the excess burden leads to reduced specific charge, which leads to increased levels of vibration. He then assumes that for the case of excess burden, the portion of the explosive energy that cannot be utilized for rock fracturing, would be used for increasing the intensity of vibrations, he also neglects the increase/decrease in the levels of airblast and throw. Ramulu (2010) used the results of small-scale experiments in single-hole blasts by Rustan and Linn (1983) to calculate the vibrations; the aforementioned experiments were carried out to investigate the explosive energy for different burdens. He then used energy ratios and burden ratios for the regression analysis and presented an equation for the indirect phase with regression coefficient of  $R^2=0.88$ , see Eq.2.

$$\frac{v_2}{v_1} = \left( \frac{B_2}{B_1} \right)^{0.4}$$

Eq.2

To find out the combined effect of burden on vibration, Ramulu (2010) calculated that the phase difference between the direct and indirect phases would be 3-6 ms. He then referred to Ramulu et al. (2004) and stated that the peak cycle of the particle vibration in the near field condition of a typical bench blast takes around 15 to 25 ms. Therefore, the phase difference of 3-6 ms cannot be treated as a separate delay and the two effects can be added together to get the net effect. By such justification, Ramulu (2010) derived an equation to calculate the vibrations due to non-optimal burden as

$$v_d = v_0 \left[ 2 \left( \frac{B_d}{B_0} \right)^{0.5} - 1 \right]$$

Eq.3

where,

$v_d$  – Vibration due to deviated burden,

$v_0$  – Vibration due to optimum burden,

$B_d$  – Deviated burden and

$B_0$  – Optimum burden.

Ramulu (2010) also conducted a total number of 14 trial blasts in two mines in order to validate the burden based vibration prediction model. Seven trial blasts were conducted at an open pit coal mine with burdens varying from 6 to 13.5 m, i.e. burden ratios varying from 1 to 2.25. Seismograph stations were used at a fixed location to monitor the vibrations. Figure 10 presents the regression analysis of the burden ratios and vibration for all the observations. As seen, the trends of curved drawn for measured and predicted vibrations are very close; Ramulu (2010) states that some deviations in both the curves may be due to possible variations in the medium due to progression of blast location at a particular bench.

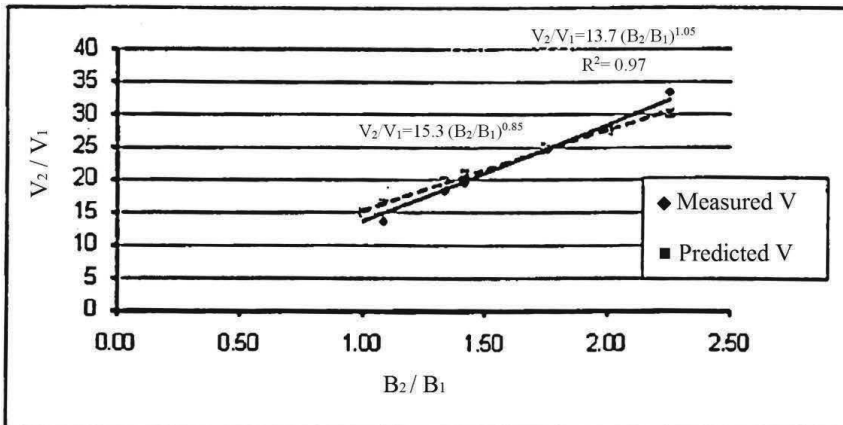
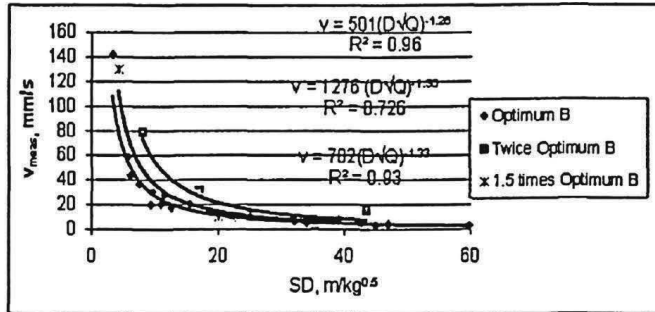
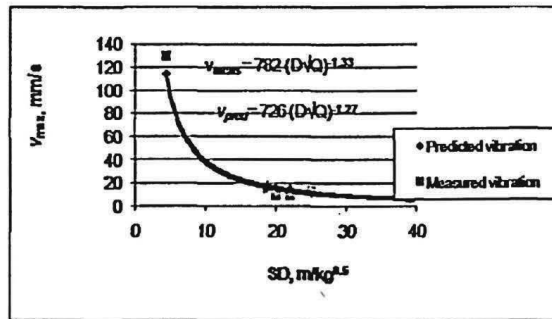


Figure 10: Predicted and measured vibration versus burden ratios for Ramulu's (2010) trials; after Ramulu (2010).

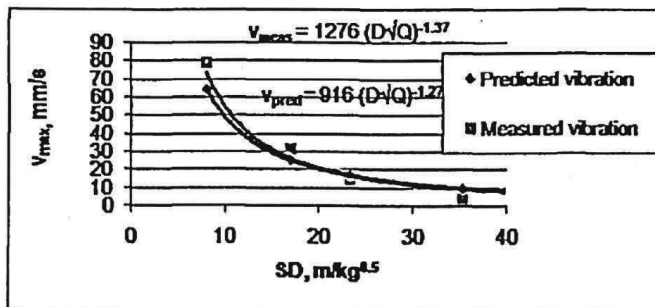
In another coal mine, Ramulu (2010) conducted 7 more trial blasts, of which 5 were blasted with optimum burden (8 m) and 2 were blasted with excess burden (12 m and 16 m). The results are shown in Figure 11.



(a)



(b)



(c)

Figure 11: Results of the second series of trials by Ramulu (2010), a) Measured vibrations vs. scaled distance, b) Measured and predicted vibrations vs. scaled distance with increased burden by one and half times the optimum burden and c) Measured and predicted vibration vs. scaled distance with increased burden by twice the optimum burden; after Ramulu (2010).

The regression analysis in Figure 11a shows that the measured vibrations increase as the burden increases from optimum to 1.5 times optimum and 2 times optimum burden. Figure 11b and c show that the predicted vibrations are almost in line or very close to the measured vibrations, which means that the prediction model is valid for that range of burden ratios (Ramulu, 2010).

Rodgers (2003), in a study to investigate the effect of confinement on vibration amplitude, introduced a conceptual model of a typical bench blast. The model, illustrated in Figure 12, includes a bottom primed vertical blast hole, which is stemmed sufficiently with a vertical free face nearby. He then defines the vibration components of stress wave and rock response by describing the mechanisms of different stages during the blast. He states that the P-wave amplitude is the remainder of the initial pressure transferred to the rock minus the energy consumed in crushing, compressing and fracturing the rock within the crush zone. According to Szuladinski's (1993) calculations (as cited by Rodgers, 2003), 20.1% of the explosive energy is consumed in this manner; the stress wave energy will be only a fraction of the remaining 80% of the explosive energy. This stress wave energy then radiates as the P-wave from near the borehole at the velocity of sound in the rockmass and surrounding medium. Measured P-wave amplitude and pulse width could be very sensitive to free face geometry as well as any preconditioning of ground in the form of opened fractures from previous blasting (Rodgers, 2003).

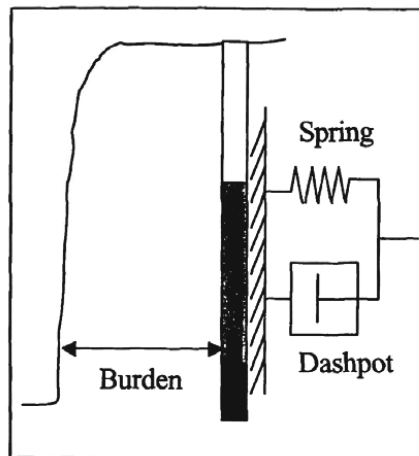


Figure 12: Conceptual model of vibration origin; after Rodgers (2003).

In his conceptual model, Rodgers (2003) assumes the rockmass in the form of a compressible spring-dashpot system that will continue to store potential energy (borehole pressure) in the form of strain until one of two limiting factors occurs.



1. A post-stress wave balance point is reached where the outward expansion force from the pressured gases is countered by an equal force from the confining rockmass.
2. The rockmass begins to expand towards the free face, which leads to rapid reduction of borehole pressure.

The model requires the burden to move in the direction of the existing free face. However, the pressurized borehole cannot sense the presence of a free face until such information is relayed back to it. This means that a signal must travel from the borehole to the free face and back to the borehole, which introduces a time component to the model (Eq.4).

$$T_{\min} = \frac{2 \times B}{V_{cr}}$$

Eq.4

Equation 4, with  $B$  representing the burden and  $V_{cr}$  as the maximum crack propagation velocity, determines the minimum wave travel time and hence the maximum potential energy that can be stored prior to release of the burden rockmass (Rodgers, 2003). In other words, since the pressure in the blast hole increases over time and  $T_{\min}$  in Eq.4 depends on burden distance, the vibrations are affected by the size of the burden. This effect is in such way that increased burdens lead to longer time for the wave to travel from the blast hole to the free face and back, which provides more time for the energy to be stored in the spring (borehole pressure) and hence, larger vibration amplitudes.

To illustrate the conceptual model, Rodgers (2003) conducted a trial with two 152 mm diameter blast holes positioned on a bench of 24 m height with burdens of 4 m and 7 m respectively. The holes were drilled to 24.7 m and loaded with identical explosive loads. Both holes had 4.9 m of stemming to assure that stemming ejection was not a factor. The lightly burdened blast hole was located on a corner with 2 free faces available and the heavily burdened blast hole was located 8.2 m away with only 1 free face and it was fired 650 ms after the lightly burdened blast hole. Ground vibrations were measured at two points, with 10.7 m and 71 m distances respectively (Figure 13).

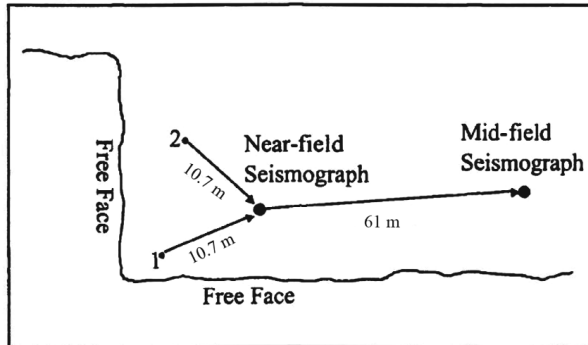


Figure 13: Plan view of Rodgers' (2003) test layout; after Rodgers (2003).

Figure 14 shows the time-corrected data of the near-field recordings by Rodgers (2003), with zero time set to the time of detonation for each hole. It is clear that the heavily burdened blast hole produced vibration of significantly larger amplitude than that of the lightly burdened blast hole. Indeed, the two waveforms appear very unlike.

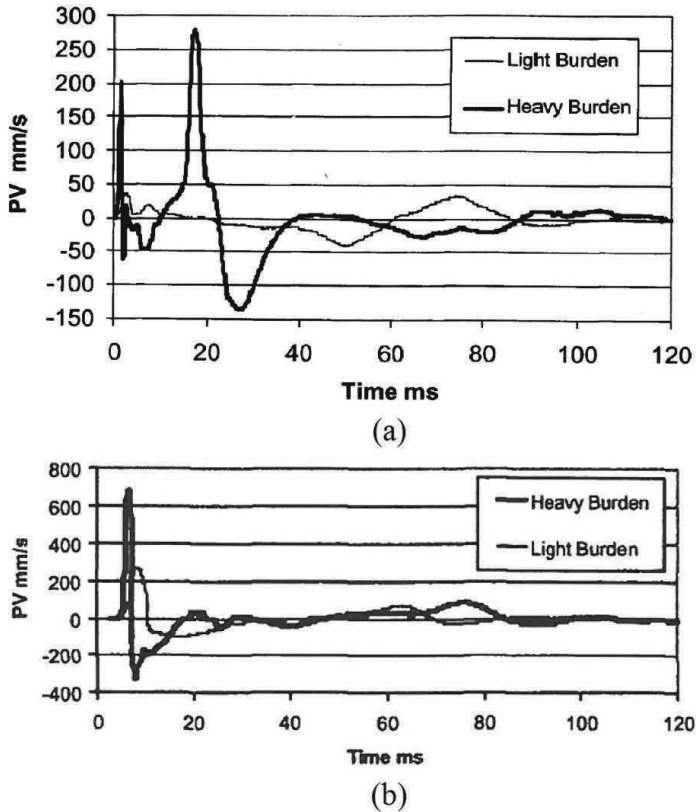


Figure 14: Time corrected near-field vibrations of Rodgers' (2003) trial blast, a) Radial vibration, b) vertical vibration; after Rodgers (2003).

Figure 15 shows the separated components (stress wave and rock response) of the results. Rodgers (2003) interpreted the faster rise-time and much higher amplitude of heavily burdened stress wave component of the trial (Figure 15a) a result of detonation in solid unaffected rock with higher dynamic tensile strength. The smaller amplitude and slower rise-time of the lightly burdened hole was explained by pre-conditioning of the rock due to the previous blast.

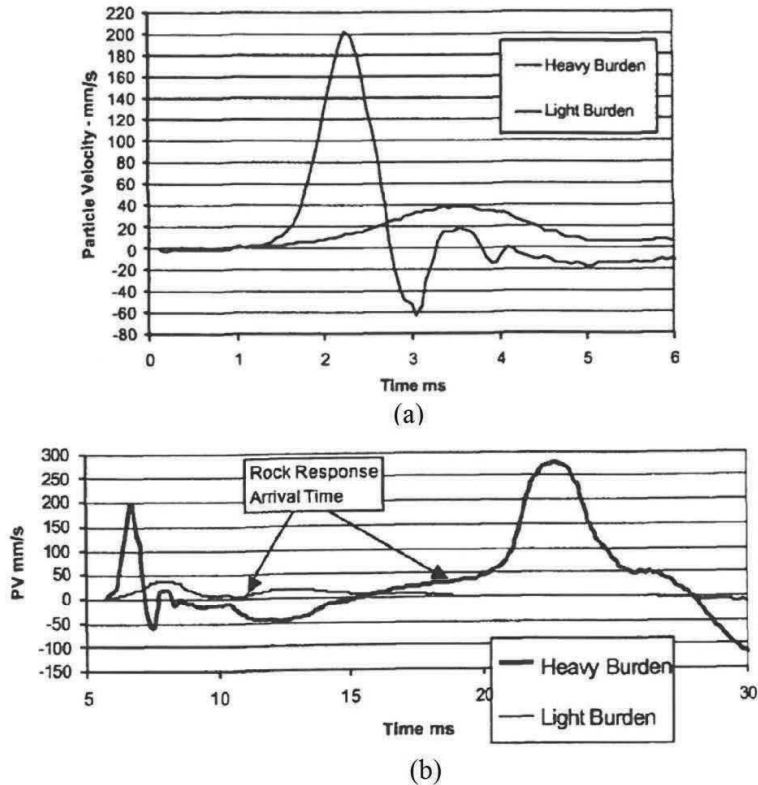
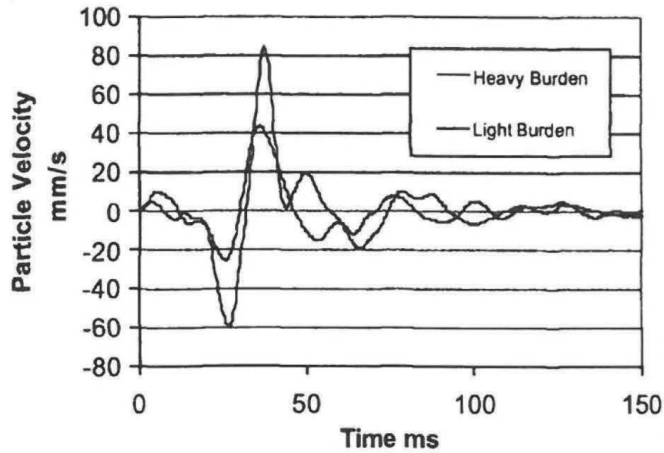


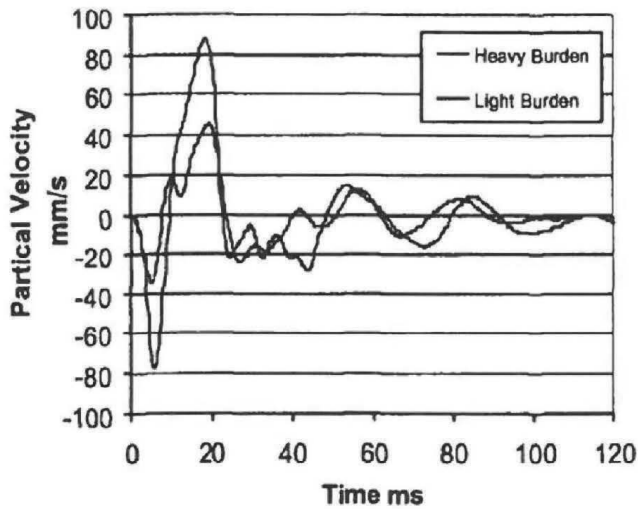
Figure 15: Separated components of the near-field results of Rodgers (2000): a) Radial stress wave component, b) arrival of radial rock response component; after Rodgers (2003).

According to calculations of  $T_{min}$  by Rodgers (2003), the arrival of rock response for both blast holes (Figure 15b) has a time difference of 7.88 ms, which referring to his conceptual model means that the heavily burdened hole's rockmass spring, i.e. explosive detonation gases, were compressed for an additional 7.88 ms. The actual amount of potential strain energy stored is a function of the elastic rock properties, the peak borehole pressure and the time of depressurization. In such case the rebound or response component would be expected to be much larger for heavily burdened hole than that of the lightly burdened hole (Rodgers, 2003).

The transverse and vertical mid-field measurements are presented in Figure 16. The body and surface shear wave phases show approximately twice the amplitude for the heavily burdened hole as compared to the lightly burdened hole.



(a)



(b)

Figure 16: Mid-field (71 m distance) vibrations for trial blast of Rodgers (2003), a) transverse vibration, b) vertical vibration; after Rodgers (2003).

Rodgers (2003) had also set up a recording station at a distance of 305 m from the blast holes, for which the data was lost. However, the remaining paper printout of the recording shows that the lightly burdened hole produced roughly half the vibration amplitude as that of the heavily burdened hole (Rodgers, 2003).

According to the mentioned studies, many trials have been conducted in order to investigate the effect of burden on vibrations. However, various experimental and

statistical methods utilized by researchers have led to entirely contradictory results. Altogether, a confident conclusion cannot be drawn about the effect of confinement on blast vibrations. Such controversy is partly due to different theories behind vibration production and partly owes to different experimentation approaches and divergent presumptions about the effect of confinement.

## 13 APPENDIX 2. DATABASE

Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
<b>1 Äspö lab. TASQ tunnel</b>											
13	2003-05-10			48	Cartridged Dyn.	3	Nonel	50 39	14 10	Transformer Fire wall	
14	2003-05-13			48	Cartridged Dyn.	2,8	Nonel	26 44	16 11	Transformer Fire wall	
15	2003-05-14	4	125	48	Cartridged Dyn.	3	Nonel	31 39	17 13	Transformer Fire wall	
16	2003-05-14		100	48	Cartridged Dyn.	2,6	Nonel	76 28	17 13	Transformer Fire wall	
17	2003-05-19			48	Cartridged Dyn.	2,6	Nonel	40 49	17 13	Transformer Fire wall	
<b>2 Äspö lab. TASQ tunnel</b>											
20	2003-05-23	4	133	48	Cartridged Dyn.	2,9	Nonel	23 18	25 22	Transformer Fire wall	
21	2003-05-24	4,5	138	48	Cartridged Dyn.	3,7	Nonel	18 16	28 25	Transformer Fire wall	
22	2003-05-25		102	48	Cartridged Dyn.	3,3	Nonel	31 12	28 25	Transformer Fire wall	

Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
<b>3 Rail tunnel Citybanan</b>											
652	2011-09-19	1,5	13	48	Cartridged Dyn.	0,7	Nonel	5,2	42	Tri	MB 002-006
							Nonel	2,4	48	Tri	MB 002-007
							Nonel	4,6	33	Tri	MB 005-001
							Nonel	6	34	Tri	MB 005-002
							Nonel	4	36	Tri	MB 005-003
							Nonel	22	20	Tri	MB 005-004
							Nonel	25	19	Tri	MB 005-005
							Nonel	7	24	Tri	MB 005-006
							Nonel	8	25	Tri	MB 005-007
							Nonel	11	24	Tri	MB 005-008
							Nonel	4,9	28	Tri	MB 005-009
755	2011-11-23	1,5	13	48	Cartridged Dyn.	0,8	Nonel	11	42	Tri	MB 002-006
							Nonel	1,3	48	Tri	MB 002-007
							Nonel	3,7	35	Tri	MB 005-001
							Nonel	4,3	35	Tri	MB 005-002
							Nonel	3,1	37	Tri	MB 005-003
							Nonel	9	21	Tri	MB 005-004
							Nonel	10	20	Tri	MB 005-005
							Nonel	6	24	Tri	MB 005-006
							Nonel	6	25	Tri	MB 005-007
							Nonel	9	24	Tri	MB 005-008
							Nonel	6	28	Tri	MB 005-009



Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
756	2011-11-24	1,5	134	48	Cartridged Dyn.	1,3	eDev	7	42	Tri	MB 002-006
							eDev	2,2	48	Tri	MB 002-007
							eDev	9	35	Tri	MB 005-001
							eDev	7	35	Tri	MB 005-002
							eDev	3,7	37	Tri	MB 005-003
							eDev	27	21	Tri	MB 005-004
							eDev	27	20	Tri	MB 005-005
							eDev	11	24	Tri	MB 005-006
							eDev	7	25	Tri	MB 005-007
							eDev	10	24	Tri	MB 005-008
762	2011-11-25	1,5	150	48	Cartridged Dyn.	1,3	eDev	5	28	Tri	MB 005-009
							eDev	14	44	Tri	MB 002-006
							eDev	2	47	Tri	MB 002-007
							eDev	9	33	Tri	MB 005-001
							eDev	10	33	Tri	MB 005-002
							eDev	7	35	Tri	MB 005-003
							eDev	28	20	Tri	MB 005-004
							eDev	29	19	Tri	MB 005-005
							eDev	11	23	Tri	MB 005-006
							eDev	8	26	Tri	MB 005-007
eDev	16	25	Tri	MB 005-008							
eDev	12	29	Tri	MB 005-009							

Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
<b>4 Sercice tunnel Citybanan</b>											
864	2012-02-09	2	120	48	Cartridged Dyn.	1,3	eDev	21	36	Tri	MB 005-012 MB 005-013.2 MB 005-014 MB 005-015
865	2012-03-13	2,2	120	48	Cartridged Dyn.	1,1	eDev	14	37	Tri	MB 005-012 MB 005-013.2 MB 005-014 MB 005-015
866	2012-03-13	2,2	121	48	Cartridged Dyn.	1,1	eDev	6,5	39	Tri	MB 005-012 MB 005-013.2 MB 005-014 MB 005-015
867	2012-03-14	1,4	115	48	Cartridged Dyn.	1,1	eDev	4,9	39	Tri	MB 005-012 MB 005-013.2 MB 005-014 MB 005-015
868	2012-03-14	2,2	120	48	Cartridged Dyn.	1,5	eDev	11	40	Tri	MB 005-012 MB 005-013.2 MB 005-014 MB 005-015

Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
869	2012-03-15	2,2	121	48	Cartridged Dyn.	1,4	eDev eDev eDev eDev	9 21 15 9	42 33 28 50	Tri Tri Tri Tri	MB 005-012 MB 005-013.2 MB 005-014 MB 005-015
<b>5 Access tunnel Norsborg depot</b>											
13	2013-05-07	5,8	132	48	Emulsion	10,5	Nonel Nonel Nonel	3,25 2,7 4,1	116 145 77	Surface Vert Surface Vert Surface Vert	11 9 10
14	2013-05-10	5,8	132	48	Emulsion	11,5	Nonel Nonel Nonel	4,4 3,1 5,1	115 141 74	Surface Vert Surface Vert Surface Vert	11 9 10
15	2013-05-15	5,8	132	48	Emulsion	11,5	Nonel Nonel Nonel	3,7 4 5,2	115 138 72	Surface Vert Surface Vert Surface Vert	11 9 10
16	2013-05-16	5,8	126	48	Emulsion	11,5	Nonel Nonel Nonel	4,1 1,4 4	114 135 70	Surface Vert Surface Vert Surface Vert	11 9 10

Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
<b>6 Värtan 1</b>											
21	41361	5,2		48	Emulsion	8,5	Nonel	33	20	Surface Vert	206
							Nonel	49	20	V	211
							Nonel	27	20	L	209
							Nonel	27	20	T	210
25	41368	5,2		48	Emulsion	8,5	Nonel	6	52	Surface Vert	206
							Nonel	26	20	V	211
							Nonel	55	20	L	209
							Nonel	27	20	T	210
<b>7 Värtan 2</b>											
33	2013-04-10	5,2	102	48	Emulsion	8,5	Nonel	4	65	Surface Vert	206
							Nonel	30	20	V	211
							Nonel	46	20	L	209
							Nonel	30	20	T	210
37	2013-04-11	5,2	102	48	Emulsion	8,5	Nonel	8	62	Surface Vert	206
							Nonel	27	21	V	211
							Nonel	25	21	L	209
							Nonel	20	21	T	210

Round no	Date	Drill depth m	Nos holes	Diameter mm	Expl type	Max charge weight kg co-op	Detonators type	Max vib. mm/s	Distance m	Location	Geophone no
<b>8 Bench test Gotland Nitro Consult</b>											
shot 1			1	76		52		115	30	Surface Vert	mp1
			1	76				101	60	Surface Vert	mp2
			1	76				25,6	97	Surface Vert	mp3
			1	76				15,47	166	Surface Vert	mp4
shot 2			1	76		52		73,3	28	Surface Vert	mp1
			1	76				67,5	61	Surface Vert	mp2
			1	76				14,35	98	Surface Vert	mp3
			1	76				8,41	169	Surface Vert	mp4
shot 3			1	76		52		192	23	Surface Vert	mp1
			1	76				83	59	Surface Vert	mp2
			1	76				25,3	92	Surface Vert	mp3
			1	76				10,67	174	Surface Vert	mp4
shot 4			1	76		52		43,9	52	Surface Vert	mp1
			1	76				63,2	79	Surface Vert	mp2
			1	76				18,2	105	Surface Vert	mp3
			1	76				8,97	192	Surface Vert	mp4

# BeFo



Box 5501  
SE-114 85 Stockholm

[info@befonline.org](mailto:info@befonline.org) • [www.befonline.org](http://www.befonline.org)  
Visiting address: Storgatan 19

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