R-05-27

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Monitoring of vibrations during blasting of the APSE tunnel

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Summary

During the first half of 2003, a 70 m long tunnel named APSE (Äspö Pillar Stability Experiment) was blasted in hard crystalline rock at the Äspö HRL (Hard Rock Laboratory) in Sweden. The goal was to study the pillar stability between vertical canister full-face holes. The APSE tunnel was blasted in 34 top heading rounds and 12 bench rounds from the elevator shaft in N/E direction at level –450 m.

The need to use vibration control during excavation as a safety measure for the facilities led to additional discussions on the possibilities to expand the monitoring program in order to gain further information on the impact of blasting on the rock mass and on the environment. The primary goal was to estimate to what extent blast vibrations can be used in judging the relative extension of an Excavation Damage Zone (EDZ). Possibilities were also given to estimate third-part disturbances.

In order to minimize the EDZ, the contour blast holes were grouped and initiated instantaneously with electronic caps. Instantaneous initiation causes less damage than if the holes are initiated with the normal scatter. The electronic caps time precision was measured during a function control of the last three rounds.

The blast vibrations were also used to detect anomalous blast rounds and to estimate the P-wave velocity and the attenuation in the near and the far field. An attempt was made to find a relation between the vibration levels and water bearing geological structures in the vicinity of the tunnel.

The report presents the vibration measurements and evaluation of three main data sets. The first set of data consists of vertical geophone data for blast optimization and vibration control approximately 10–600 m away from the blast. The data set consists of values from all the 46 rounds. This data set was also grouped into sub sets based on the blasting technique used in order to detect deviating blast rounds.

The second data set consists of accelerometers grouted into gauge holes along the tunnel wall 14–28 m behind the front. This set was primarily used for a function control of the contour blast holes of the three last rounds but the measurements were also used for calculation of the P-wave velocity and the amplitude attenuation along the tunnel wall.

The third data set consists of measurements 600–1,600 m from the blasts for calculation of the far field amplitude attenuation. Seismograph stations on the ground surface were used for collection of these data.

The result shows that the the vibration Peak Particle Velocity (PPV), did not exceed the upper limit 50 mm/s for installations and facilities and that moderate disturbances (0.4–1.0 mm/s, Swedish standard SS 460 48 61) very unlikely will occur above ground 450 m away from the tunnel. Over a range of 350 m distance the mean PPV decreases about 100 times. However, there is a scatter in the mean PPV times a factor of 1/5 to 5 and the PPV average values tends to increase with the total number of blast holes per round.

The acceleration measurement scatter along the tunnel was low and the programmed initiation time intervals for the electronic caps agreed well with the monitored time intervals along the tunnel wall.

The last chapter contains a discussion of the limitations of vibration control as an indicator of the EDZ.

Sammanfattning

Under första hälften av 2003 sprängdes en ca 70 m lång tunnel, kallad APSE (Äspö Pillar Stability Experiment), i kristallint berg i Äspö-laboratoriet. Tunneln drevs med målet att studera pelarstabiliteten mellan vertikala kanisterhål. APSE-tunneln sprängdes med 34 tunnelsalvor och 12 pallsalvor från hisschaktet mot N/E på –450 m nivån.

Nödvändigheten av vibrationskontroll vid känsliga objekt ledde till ett beslut att utvidga vibrationskontrollen för att få ytterligare information för bedömning av sprängskador. Målet var primärt att försöka uppskatta i vilken utsträckning som vibrationer kan användas för bedömning av den så kallade skadezonen EDZ ”Excavation Damaged Zone”. Därutöver gavs möjlighet att följa upp vilken störning på tredje man denna typ av sprängning kan orsaka.

I syftet att minimera EDZ initierades laddningar i konturen momentant i grupper med elektroniska sprängkapslar. Detta ger mindre skador än om laddningar initieras med normal tändspridning. En funktionskontroll av kapslarnas initieringsnoggrannhet genomfördes för de tre sista salvorna.

Vibrationsmätningarna från sprängningarna användes också till att försöka detektera avvikande sprängsalvor och att bestämma P-vågens utbredningshastighet och dämpning både nära och långt ifrån sprängsalvorna. Dessutom gjordes ett försök att finna samband mellan vibrationsnivåerna och vattenförande geologiska strukturer i drivningsområdet.

Rapporten presenterar vibrationsmätningarna och utvärdering av tre grupper av data. Den första gruppen består av mätningar med vertikala geofoner för optimering av salvorna och vibrationskontroll 10–600 m från salvorna. Gruppen innehåller data från alla 46 salvorna. Mätningarna delas också in i undergrupper utifrån använd sprängteknik för att upptäcka avvikande sprängsalvor.

Den andra gruppen utgörs av mätningar 14–28 m från fronten med accelerometrar ingjutna i mäthål utmed tunnelväggen. Mätningar användes först och främst för att kontrollera tiderna för initiering av spränghålen i konturen men användes också för beräkning av P-vågens hastighet och amplituddämpning utmed tunnelväggen.

Den tredje gruppen består av mätningar 600–1 600 m från salvorna för beräkning av amplituddämpningen på stora avstånd. För dessa mätningar användes seismografer utplacerade på markytan.

Den maximala svängningshastigheten, (”Peak Particle Velocity PPV”) för känsliga objekt överskred inte gränsvärdet på 50 mm/s och vibrationsnivåerna kom knappast upp till 0.4–1.0 mm/s (måttlig påverkan enligt svensk standard SS 460 48 61) på markytan 450 m från tunneln. Vibrationsnivån avtar i medeltal ca 100 gånger efter 350 m. Det finns dock en spridning i mätvärdena PPV gånger en faktor 1/5 till 5 och en tendens att vibrationsnivåernas medelvärden ökar med totala antalet spränghål i salvorna.

Spridningen för accelerationsmätningarna utmed tunnelväggen var låg och de förprogrammerade sprängkapslarnas tider stämde väl med de uppmätta tiderna utmed tunnelväggen.

I det avslutande diskussionskapitlet redovisas ett antal begränsningar som försvårar uppskattning av EDZ utifrån vibrationsvärden från sprängsalvor.

Contents

1 Introduction

A new tunnel was driven at the Äspö Hard Rock Laboratory (AHRL) during spring and summer of 2003. The tunnel is located at the –450 m level close to the shaft, see Figure 1-1. It was specifically designed for a rock mechanics experiment, the Äspö Pillar Stability Experiment (APSE) /Andersson 2003/. The tunnel is therefore referred to as the APSE tunnel, whereas the correct ID in the SKB database is the TASQ tunnel.

There were four major considerations for siting the experiment

1. The tunnel should be subjected to the highest achievable in situ stresses at the AHRL. Due to this criterion, the experiment was located at the deeper part of the facility.
2. To achieve the highest possible stresses for the planed experiment, the tunnel had to be orientated perpendicular to the major principal stress and the boundary stress conditions to the tunnel experiment should be understood. This implied the need for a new tunnel, sufficiently long to avoid secondary stresses from existing tunnels or the face of a new tunnel.
3. Available rock mechanics data from the AHRL should be reused as much as possible. The most relevant rock mechanics data came from the Prototype Repository Experiment and from a test of tree different stress measuring methods in two orthogonal boreholes /Jansson and Stigsson 2002/. This brought the siting of a new tunnel to the western part of the 450-m level.
4. The impact on monitoring of ongoing experiments should be as small as possible in order to not change the boundary conditions for some long term monitoring. This criterion led to the conclusion that the tunnel should be placed as far away as possible from the so-called True Block Scale area /Winberg et al. 2002/. This lead to the actual location.

The need for a new tunnel at the AHRL or the planned rock mechanics experiment led to the construction of a new tunnel. Site investigations were carried out by drilling new cores /Andersson 2003/ which provided detailed geological information. The information retrieved from the investigations concluded that the tunnel driving would be performed in varying ground conditions in terms of fracturing, lithological variation, and water bearing fractures. None of the above conditions were unexpected for the conditions at the AHRL and had no significant impact on the possibilities for the construction work. It was however concluded that the construction of approximately 70 m of the tunnel would provide an opportunity for studying the possibilities to control the development of the Excavation Damaged Zone (EDZ) caused by the Drill & Blast operations (D&B).

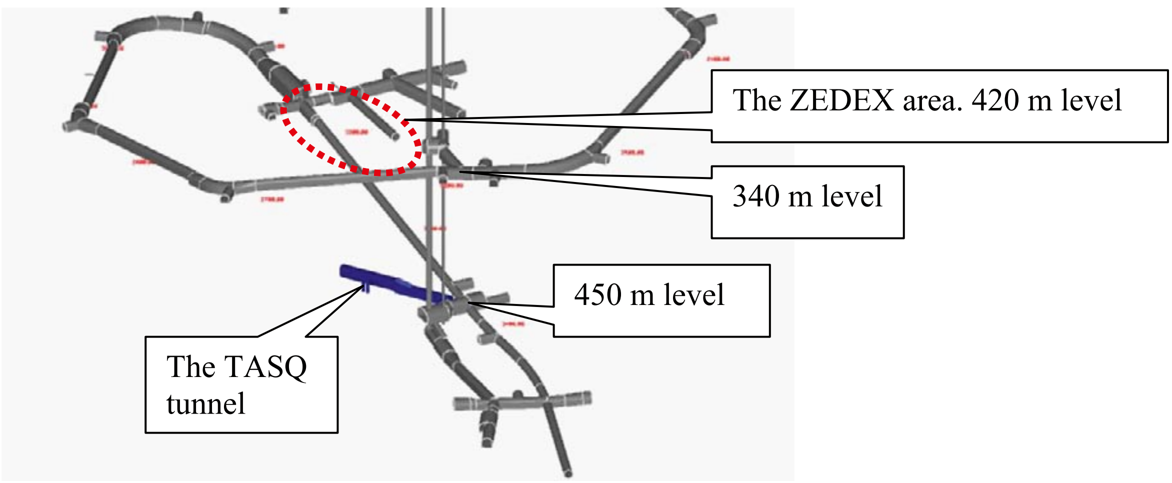

Figure 1-1. Location of the TASQ tunnel.

The new tunnel was located about 300 m away from the ZEDEX tunnel (Figure 1-1), were a study of EDZ caused by D&B and TBM, respectively, was performed /Olsson and Reidarman 1995/. The major question for that project was if the current state-of-art for the D&B method, together with the requirement for the contractor to be extremely cautions in blasting the floor, by taking the lower part of the cross section as a separate bench, could produce a less pronounced EDZ compared to the results obtained 8 years earlier.

In addition, in studies performed primarily in quarries a large number of holes have been blasted and the cracks in the remaining rock have been examined /Olsson and Ouchterlony 2003/. Coupling ratio, spacing, water in the holes, scatter in the initiation, and the influence of different explosives on crack lengths were some of the factors examined. This resulted in the proposition of a new prediction formula. Since the proposed formula should be tested under various conditions, SKB applied the new ideas to the last three rounds of the top heading round.

A discussion was initiated in the planning process regarding the study of the EDZ in the new tunnel. The need to use vibration control during excavation as a safety measure for the facilities led to additional discussions on the possibilities to expand the monitoring program in order to gain further information on the impact of blasting on the rock mass and on the environment. The overall objectives were to:

– Make certain that vibration restrictions on sensitive facilities and installations are not exceeded.
– Provide a tool to assist the contractor in optimising the blast design.
– Follow up to what extent vibration records could assist in judging the relative extension of the Excavation Damage Zone (EDZ).
– Collect vibration data on the surface, far from the excavation.

This report presents the results of monitoring of vibrations during excavation of the tunnel. A parallel report /Olsson et al. 2004/ presents the actual D&B design, describing the outcome of the excavation work, including visible signs of damage caused by the excavation in the floor and walls of the tunnel.

2 Site conditions

2.1 Lithological composition

The dominating rock types in the Äspö area are the plutonic Äspö diorite and Ävrö granite. They belong to the postorogenic phase of the Transscandinavian Igneous Belt (TIB), their ages are around 1.8 Ga. The Äspö diorite is a medium-grained, grey to reddish grey rock. It is generally porphyritic, with K-feldspar megacrysts. Its composition does not correspond to a true diorite, but ranges from granite to granodiorite to quartz monzonite /Rhén et al. 1997, Wikman and Kornfält 1995/. The more felsic Ävrö granite, which is a medium-grained, greyish red rock, is mainly classified as true granite.

Transitions between these two rock types are gradual rather than sharp. The chemical relationship between them indicate that they can be considered as two varieties of the Småland granite /Wikman and Kornfält 1995/. Subordinate rock types intruding the TIB-rocks are mafic rocks, pegmatites and fine-grained granites. Distinguishment between diorite and granite through visual inspection is difficult. Based on density logs from boreholes a density of > 2,700 kg/m^3 has been used to define the diorite /Rhén et al. 1997/.

The TASQ tunnel is dominated by different varieties of Äspö diorite, which is a quarz-monzo-diorite. The major rock volume consists of unaltered Äspö diorite, but relatively large volumes also consist of oxidized or sheared Äspö diorite. This is primarily associated with a ductile deformation zone that strikes in the tunnel orientation and dips approximately 45° to SE. Other rock types present are mafic rocks, pegmatite and fine-grained granite. Rock contacts are generally diffuse, as they are successive transitions from one type of Äspö diorite to another. Contacts between dikes and host rock are sharp, but well healed. Regional metamorphism appears absent or of very low grade in the TASQ rock mass. Occasionally a diffuse foliation can be found in the Äspö diorite, which appears to be associated with the regional foliation pattern. Hydrothermal, low grade alteration appears to some extent in association with the old ductile deformation zone that strikes along the tunnel.

From the D&B operations perspective, the rock mass is not expected to have large heterogeneities in the location of the TASQ tunnel. The main difference in mineral composition between the Äspö diorite and the Småland granite is the content of quartz versus mafic minerals. The quartz and kalifeldspar contents tend to decrease towards diorite as especially plagioclase and biotite increases, causing the somewhat higher density of the diorite, see Table 2-1. This may cause the diorite to be a little "tougher" for D&B, compared to the granite.

Table 2-1. Estimated mineralogical composition (%) of rock types (QMD = quartz-monzodiorite).

Sample	Äspö QMD	Altered ÄQMD	Ävrö granite	Fine-grained granite
Number of samples	5	1	3	2
Quartz	12	15	25	31
Plagioclase	40 (An 25–30%)	25 (An 0–5%)	28 (An 20–30%)	15 (An 20–25%)
K-feldspar	20	23	32	36
Biotite	18	0.5	7	3
Chlorite	0.3	14	1.0	0.5
Titanite	1.3	1.3	0.4	0.2
Amphibole	0.2	-	-	-
Epidote	4	10	2.5	3
Sericite	4	10	4	10.5
Opaques	0.6	0.4	0.3	1.0

2.2 Structures

Geological structures in TASQ are dominated by three main orientations, all of them related to the regional pattern. In Figure 2-1, the three main orientations are presented in stereographic projections.

1. Set 1 in Figure 2-1 represents a NE-SW steeply dipping set. Fracture filling material in this set is dominated by chlorite. This set is rarely associated with water seepage in the AHRL.
2. Set 2 in Figure 2-1 is striking NW-SE and dipping sub vertically, i.e. perpendicular to the tunnel. It consists of relatively wide continuous brittle fractures and faults. This set is common throughout the whole Äspö HRL and is often associated with water seepage, both in the TASQ tunnel and in the Äspö region in general.
3. The third main structural set is sub horizontal (set 3 in Figure 2-1). Fracture filling minerals in all these orientations are dominated by chlorite, epidote and calcite. This set is rarely associated with water seepage.

An oxidized brittle-ductile shear zone strikes along the tunnel in 030–035º parallel to set No 1. It is dipping to the southeast and is present along the major part of the tunnel. At some locations, this set of structures generates critical surfaces of brittle reactivation with fracture filling of mainly epidote-chlorite. It is however mainly sealed.

The structures striking in the tunnel direction (Set 1) may have some influence on the drilling precision. Especially the partly "softer" rock in the ductile shear zone may have had influence in some boreholes. But the area of the ductile zone is small, compared to the tunnels cross-section area, so this influence is believed to be insignificant.

Water leakage from the fracture set oriented in NW-SE/sub vertical was most pronounced in sections 0/060 and 0/064 of the tunnel. This area was subject to grouting /Emmelin et al. 2004/. Generally the leakage causes damp surfaces or, at most, seepage. Occasionally, however, leakage has been classified as flowing.

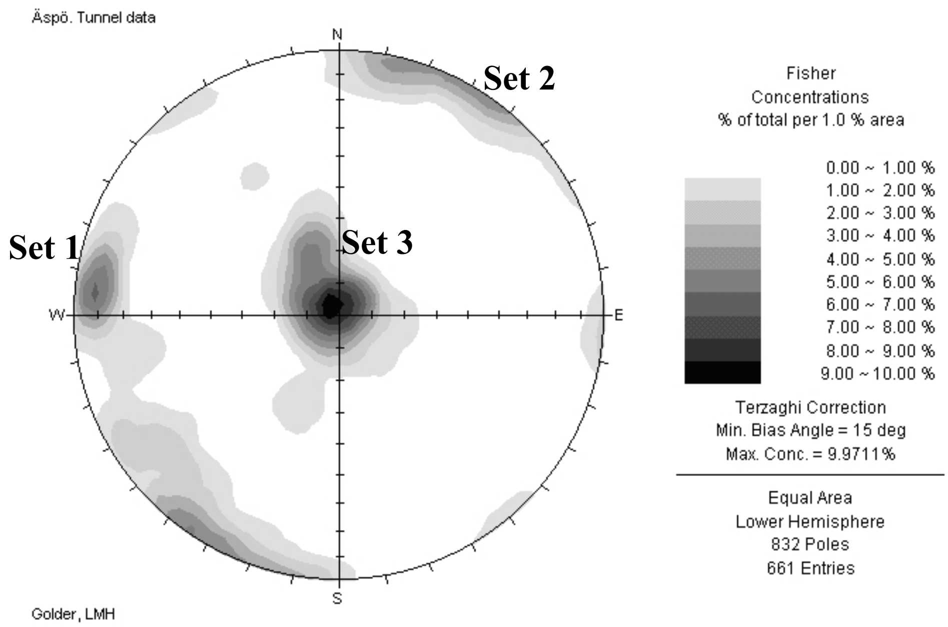

Figure 2-1. *Stereonet contour plot of fractures in Tunnels TASA ch 2,625–2,700, TASF, TASG, TASI, TASJ, and hoist shaft (TASH) from elevation –350 metres to bottom at elevation –450 metres. Picture reproduced from /Hansen and Hermanson 2002/.*

2.3 Mechanic characteristics of the rock mass

The state of stress in the lower part of the AHRL is described by /Jansson and Stigsson 2002/. These data has been confirmed by /Staub et al. 2004/. The principal stresses in the rock mass around the TASQ tunnel are summarised in Table 2-2. There is believed to be an absolute error of roughly 2 MPa in the stress determination. Notice that the major principal stress is almost perpendicular to the TASQ tunnel, and nearly parallel with fracture set 2 in Figure 2-1.

Table 2-2. State of stress around the TASQ tunnel /Staub et al. 2004/.

	Magnitude (MPa)	Trend/Plunge (degrees)
Sigma 1	27	310/07
Sigma 2	15	090/83
Sigma 3	10	208/00

The mechanical properties are summarised by /Andersson 2003/ and reproduced in Table 2-3. The lower uniaxial strength is associated to some portions of altered diorite that occur to a smaller extent.

Table 2-3. Mechanical properties of the rock.

Parameter	Mean value	Unit	Standard deviation
Uniaxial compressive strength, low	130	MPa	
Uniaxial compressive strength, high	210	MPa	
Crack initiation stress	121	MPa	
Crack damage stress	204	MPa	
Young's modulus, intact rock	76	GPa	6.5 GPa
Young's modulus, rock mass	55	GPa	
Poisson's ratio, intact rock	0.25	-	
Poisson's ratio, rock mass	0.26	-	
Friction angle, intact rock	49	Degrees	
Friction angle, rock mass	41	Degrees	
Cohesion, intact rock	31	MPa	
Cohesion, rock mass	16.4	MPa	
Tensile strength	14.3	MPa	
Thermal conductivity	2.60	W/m, K	
Volume heat capacity	2.10	MJ/m^3, K	
Thermal linear expansion	7.0E-06	I/K	
Density	2.731	g/cm^3	
Initial temperature of the rock mass	15	°C	

2.4 Summary on conditions for excavation

The rock mass is very competent, with few heterogeneous sections that could influence the excavations. The density of the rock is a little higher than that of average crystalline rock in Sweden.

The structures form a relatively "blocky" rock mass. However, the rock conditions are good due to the low fracture frequency. For example, the Q-index rating is in the range of "good to very good rock", see Figure 2-2. The only fracture set of any significance for the excavations is the NW-SE trending, steeply dipping fracture set. This set is partly open and water bearing. Because the tunnel is orthogonal to this set the tunnel face tends to be parallel to the partly open fractures, causing a tendency for a drummy face. The actual state of stress contributes to this phenomenon.

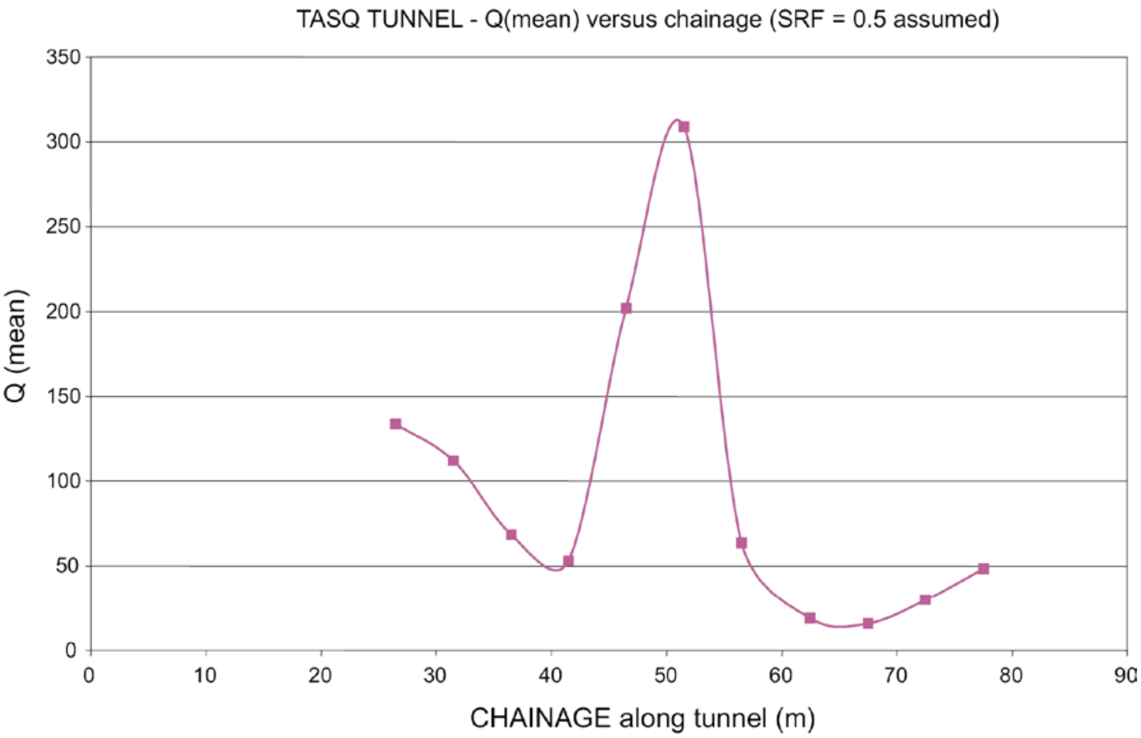

Figure 2-2. *Distribution of Q index along the TASQ tunnel. /Barton 2003/.*

3 Monitoring programs

Three different working groups (Section 3.1–3.3) have been involved in the monitoring program.

Section 3.1 describes the geophone network and instrumentations both in the tunnel system and above ground for drift optimisation and risk assessment. The geophones registered vibrations generated by 46 blast rounds at distances of approximately 10–600 m. Bergsäker AB performed the geophone network monitoring during the late spring and early summer of 2003.

Section 3.2 deals with near field blast vibration data primarily collected for the blast function control. The reason for checking the blast function is that the timing of the contour holes is believed to influence the contour damage zone /Olsson and Bergqvist 1997/. Swebrec, Swedish Blasting Research Centre at Luleå University of Technology monitored three rounds in two gauge holes during 2003-07-01 and 2003-07-02 in order to make a function control of the electronic detonators used in the tunnel contour.

Section 3.3 describes the layout of far field measurements with three mobile seismic stations positioned above ground. The measurements were performed to estimate the attenuation of P-waves generated by two rounds. The fieldwork was carried out by Uppsala University, Department of Earth Sciences during 2003-06-30 and 2003-07-01.

3.1 Production

The main objectives of the geophone network measurements were to:

- Monitor vibration levels at installations and other facilities according to the recommendations in earlier performed risk assessment.
- Optimize the drill depth, the firing patterns, and the charge diameter so that the vibration levels could be kept below the recommended limits.
- Determine the vibration Peak Particle Velocity (PPV) dependence as a function of distance and charge weight.

Figure 3-1 shows a geophone mounted on the rock surface using an 8 mm brass anchor placed in a borehole which is drilled directly in the hard rock. As for the transformer, the borehole is drilled in the concrete foundation. All geophones measured the vertical velocity components.

The software system (AvaNetXT, AvaNet and AvaNT) is described in the specifications (see Appendix.1). Figure 3-2 shows the recording unit Ava95 and geophones that can record events and their full wave forms for up to 70 seconds at a sampling rate of 3,000 samples/seconds. The recorder can be set in piling mode i.e. recording only single values over a time period or in blasting mode for storing a time series. The instrument meets the requirements of the Swedish Standard SS 460 48 66. According to the standard, all recordings were filtered i.e. frequencies over 350 Hz were filtered out.

1. AvaNet XT: Figure 3-3 shows the geophone positions below the 340 m level (the geophones PD0016B01) that were used for vibration underground level control on installations and constructions. Note that ID code PA3514B01 in Table 3-2 has three geophones. All geophones (channels) were set with a rather low trigger level (0.2 mm/s) to guarantee that no data were missing. Three of the geophones were used to check the vibration levels at the firewall towards the 450 m level shaft station and the nearby transformer i.e. two on each side of the firewall and one at the transformer. The geophones were connected to a measuring server for data storage in a container under ground via three Ava95 units and modem cables. The data was also transferred via modem cables to a PC at an office above ground. By this installation it was possible to double-check the blast data.

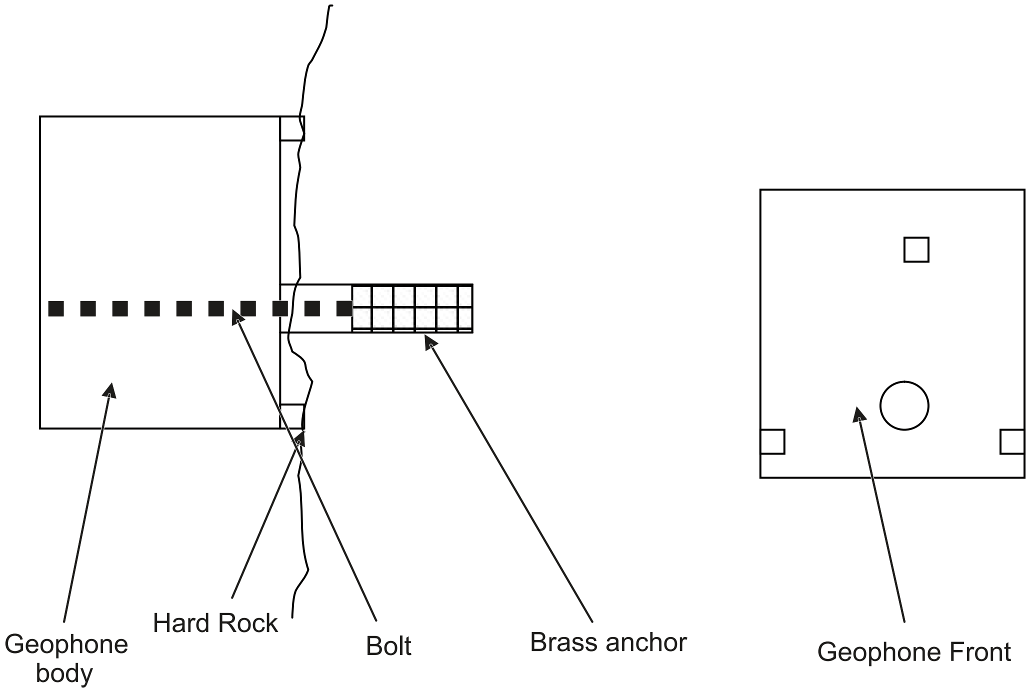

Figure 3-1. *Layout of standard geophone mounting.*

Figure 3-2. *Recording unit Ava95 and geophones for vibration measurement.*

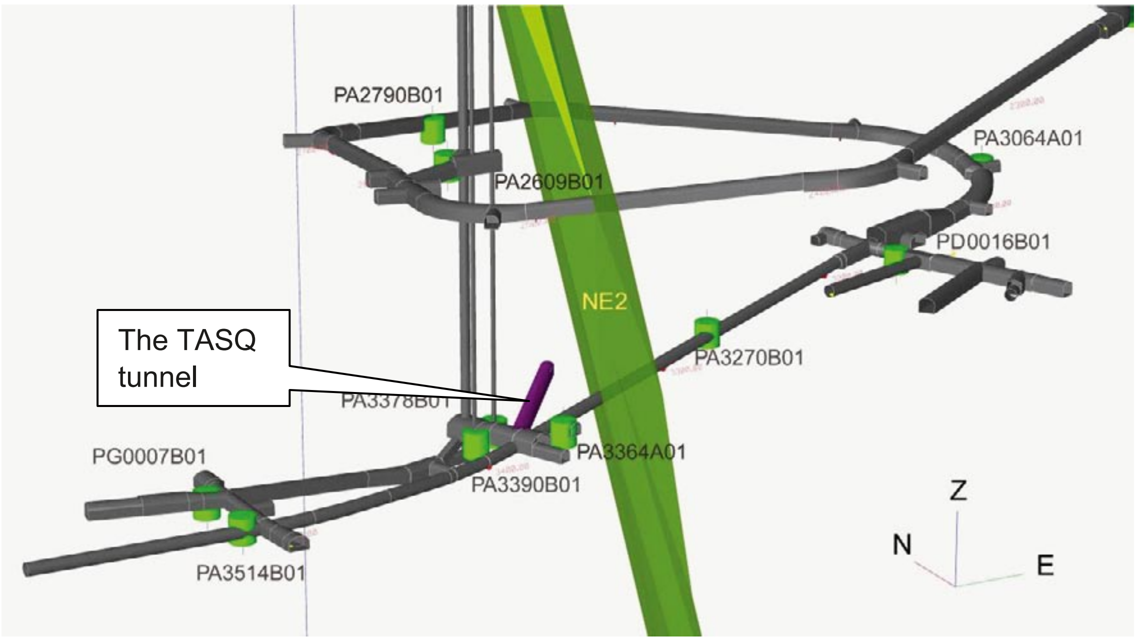

Figure 3-3. The underground geophone network. Note that PA3514B01 is a 3D geophone position. All other positions have 1D vertical component geophones. Deformation zones in accordance to /SKB 2004/.

Tables 3-1 to 3-3 show identification codes, geophone coordinates and tunnel section positions used for the drift optimisation and risk assessments.

Figure 3-4 shows a close up view for instrumentation at the elevator, the firewall and the transformer. The recommended maximum velocity was 50 mm/s at both the firewall and the elevator. At the transformer, the acceleration peak value was calculated to 30 m/s^2. The initial velocity was of 35 mm/s.

Table 3-1. Blast 1 to 46 during the period 2003-04-07 to 2003-07-18.

ID CODE	X	Y	Z	Position
PD0016B01	7295.393	2289.857	-417.715	Tunnel D Sektion 0/016.8
PA3364A01	7272.68	2100.559	-444.395	Tunnel A Sektion 3/364.2 Transf. v
PA3390B01	7287.878	2070.839	-446.54	Tunnel A Sektion 3/390.8 Elev. -450

Table 3-2. Blast 1 to 34 during the period 2003-04-07 to 2003-07-03.

ID CODE	X	Y	Z	Position	
PG0007B01	7298.798	1956.55	-447.702	Tunnel G Sektion 0/007	measur. Cont
PA3514B01	7267.745	1950.951	-447.023	Tunnel A Sektion 3/514.6 PROTOTYPE L	
PA3514B01	7267.745	1950.951	-447.023	Tunnel A Sektion 3/514.6 PROTOTYPE T	
PA3514B01	7267.745	1950.951	-447.023	Tunnel A Sektion 3/514.6 PROTOTYPE V	

Table 3-3. Blast 5 to 46 during the period 2003-04-24 to 2003-07-18.

ID CODE	X	Y	Z	Position	
PA3270B01	7297.229	2191.71	-429.616	Tunnel A Sektion 3/270.2	
PA3378B01	7292.513	2082.788	-445.665	Tunnel A Sektion 3/378.2 Firewall -450	

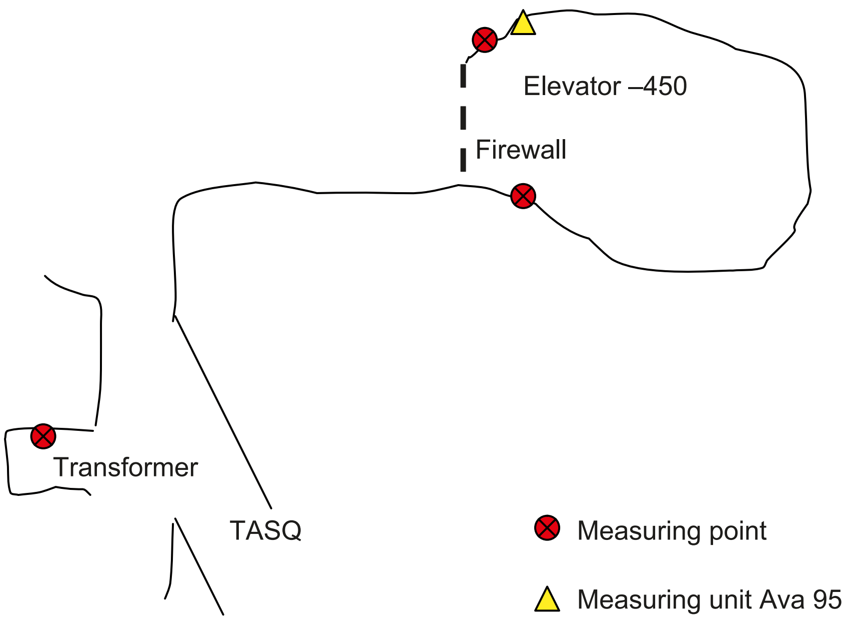

***Figure 3-4.** Plan view of area for measurement of vibration levels with vertical 1D-geophones.*

2. AvaNet: Tables 3-4, 3-5 and Figure 3-5 show the geophone ID-codes and the locations above ground. Each location had three geophones, i.e. one vertical and two horizontal components pointing in North-South and East-West. The geophones above ground were more sensitive in the lower frequency range (from 1 Hz) than the ones used under ground (from 5 Hz) due to the long distances from the blast location.

As for the underground measurements, the geophones were connected to Ava 95 units with a connection to the AvaNet via GSM-modem. Due to the very low vibration levels the recording units were set in piling mode i.e. the instrument was programmed to record the highest vibration levels within a period of 10 minutes.

Table 3-4. Measuring period 2003-05-27 to 2003-07-03 (Blast 25 to 34).

ID CODE	X	Y	Z	Position
PKT OJ 15	7309.537	1988.323	6.65	West Office V

Table 3-5. Measuring period 2003-06-10 to 2003-07-03 (Blast 25 to 34).

ID CODE	X	Y	Z	Position
PKT OJ 15	7309.537	1988.323	6.65	West Office V
PKT OJ 14	6961.426	2074.026	4.624	West KAS02 (Lillbåten) V
PKT OJ 14	6961.426	2074.026	4.624	West KAS02 (Lillbåten) N/S
PKT OJ 14	6961.426	2074.026	4.624	West KAS02 (Lillbåten) E/W
PKT OJ 15	7309.537	1988.323	6.65	West Office V
PKT OJ 15	7309.537	1988.323	6.65	West Office N/S
PKT OJ 15	7309.537	1988.323	6.65	West Office E/W
PKT OJ 16	7650.911	1936.66	13.007	West KAS04 (Äspöstigen) V
PKT OJ 16	7650.911	1936.66	13.007	West KAS04 (Äspöstigen) N/S
PKT OJ 16	7650.911	1936.66	13.007	West KAS04 (Äspöstigen) E/W

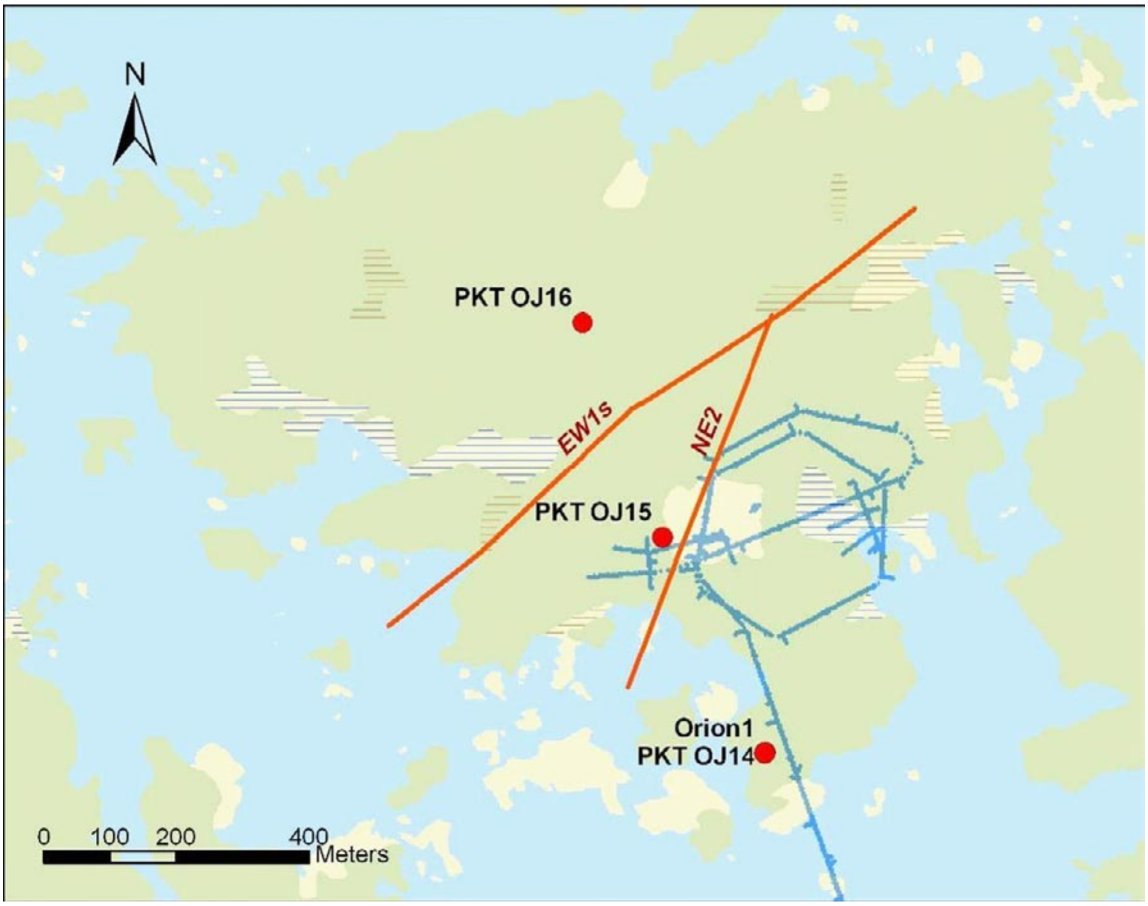

Figure 3-5. *Locations for geophones above ground. Each group has one vertical and two horizontal gauges (North-South and East-West). The deformation zones are in accordance to /SKB 2004/.*

3. Ava NT: In Figure 3-6, the six geophones from PA3064A01 and upwards were used to record and store data on a Laptop. Two geophones were used for the blasting control of another project (Table 3-6). In this case the instrument was set in blasting mode with a trigger level at 2 mm/s. The other four geophones (Table 3-7) were set in piling mode for recording of the highest vibration level every hour.

Table 3-6. Measuring period 2003-04-07/2003-04-24 to 2003-07-03.

ID CODE	X	Y	Z	Position
PA1685B01	7305.736	2072.259	-225.08	Tunnel A Sektion 1/685.2 Elevator -220
PA1635A01	7272.753	2019.872	-225.006	Tunnel A Sektion 1/635 Transformer v

Table 3-7. Measuring period 2003-04-07 to 2003-07-03.

ID CODE	X	Y	Z	Position
PA2201A01	7180.897	2303.51	-295.343	Tunnel A Sektion 2/201.5
PA2609B01	7303.1	2069.972	-341.734	Tunnel A Sektion 2/609.7 Elevator -340
PA2790B01	7432.363	2159.158	-369.969	Tunnel A Sektion 2/790.4
PA3064A01	7350.099	2388.288	-408.219	Tunnel A Sektion 3/064.1 LTDE

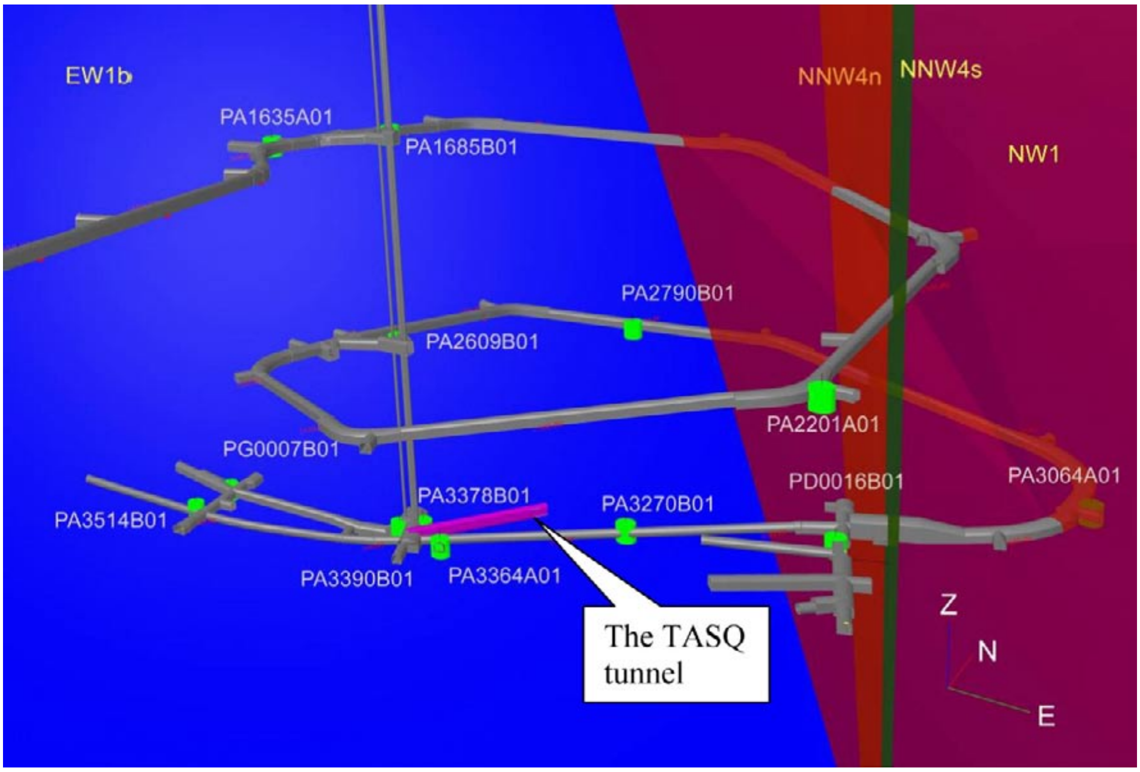

Figure 3-6. *The upper six 1D-geophones were used for recording in blasting mode and piling mode respectively.*

3.2 Function control

The objectives of the blast function control were:

– To measure the electronic cap time intervals for initiation of the contour holes.

– To monitor the entire blasting sequence.

3.2.1 Mounting of accelerometers

Accelerometer stations were grouted into drilled holes along the tunnel wall to monitor the blast sequence. The technique was used earlier in Södra Länken, Stockholm for estimation of damage on rock support from blast-induced vibrations /Reidarman and Nyberg 2000/.

Figure 3-7 to 3-9 shows the layout of the 3D-accelerometer mounting. Tubes of PVC were use as casing, fitted into the holes with an aluminium anchor at the bottom. The holes of approximately Ø 90 mm and 1 m long were drilled with an angle of 45 degree to the wall and approximately 1.5 m above the floor. The accelerometer mounting and testing before each round were made in steps:

– Mixing concrete and pumping it into the holes. Then pressing the anchors to the bottom of the hole, thereby filling the free volume around the anchors and the casings with concrete, and checking the anchors orientations.

– Screwing the accelerometer plates on to the grouted anchors after the concrete had cured.

– Connecting the coaxial cables and making a signal connection test just before the blast.

The concrete (Optiroc type EXM711) is designed for a short curing time, to expand 0.5–2% and to have a compressive strength of minimum 20 MPa after 24 hours. The curing time between grouting and blasting was approximately 10 hours for the first round. For the two other rounds the curing time was 24 hours or more. Depending on the working conditions in the tunnel, the choice of using EXM711 was a compromise between concrete with extremely short curing time and standard concrete.

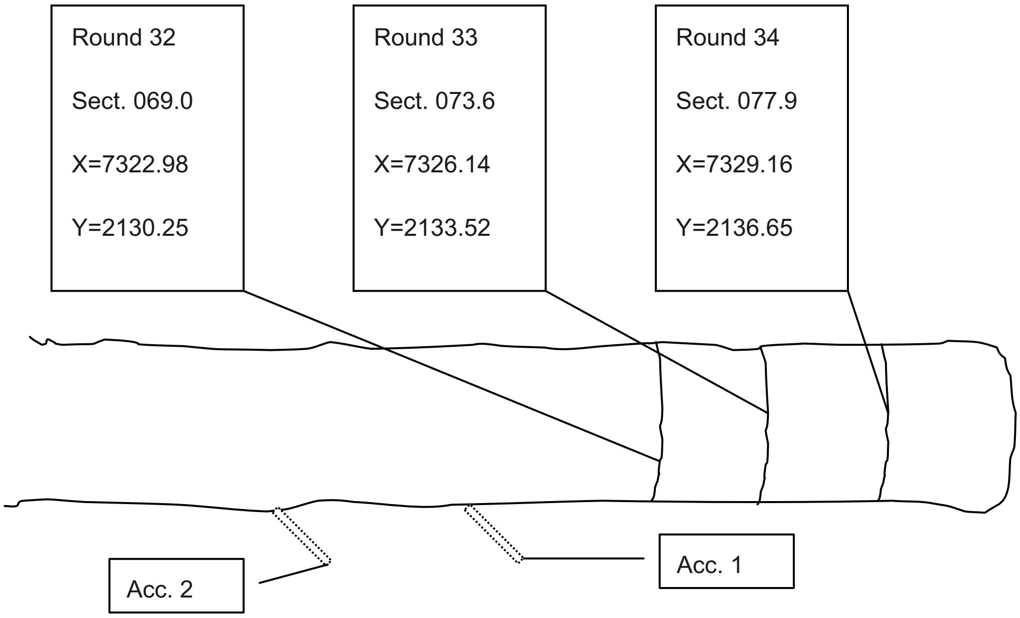

Figure 3-7. *Layout of the accelerometer gauge holes and the sections along the tunnel wall (Figure not to scale).*

Figure 3-8. *Photo of accelerometers, base plate and anchor (from right to left).*

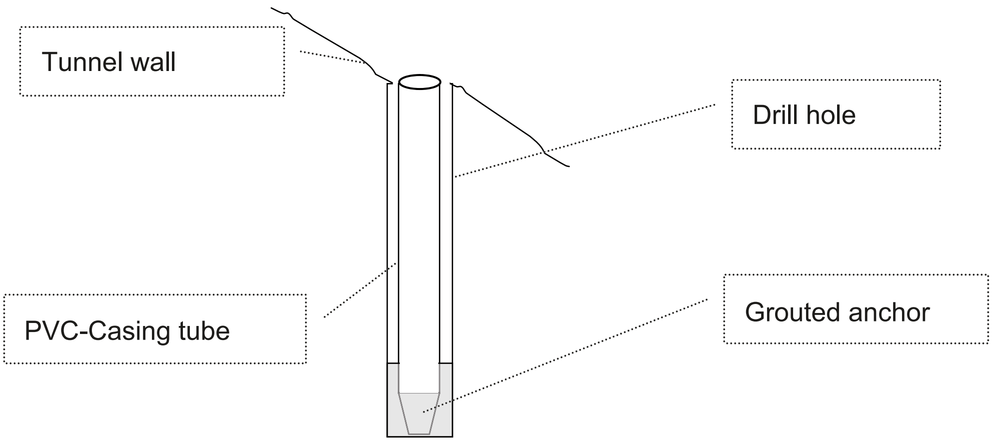

Figure 3-9. *Top view of a gauge hole, the anchor is grouted to the drill hole wall.*

The distances between the rounds and the gauge holes in Table 3-8 varied from approximately 14 m to 28 m, se /Olsson et al. 2004/. Note that in the first round one sensor at 9.5 m was not in use since damage to the sensor and cables were suspected.

Figure 3-8 shows the accelerometers, base plate and anchor. The anchor is fitted into the gauge hole in Figure 3-9 using the PVC casing.

3.2.2 Blast initiation system

The contour holes were initiated at "exact time delay intervals" programmed with detonators from Orica "i-kon" /www.oricaminingservices.com/. All other blast holes i.e. the cut, the production holes and the helpers were initiated by standard Nonel LP initiation system and pyrotechnic detonators developed for long delay time www.dynonobel.com.

According to the product specifications /Ouchterlony 1992/ the functional time precision for the Nonel LP detonators must be less than 1/3 of the delay intervals. For example, an LP 25 has a delay interval of 500 ms and a scatter of ±150 ms, which is also the scatter for the time delays of 2,500–6,000 ms.

3.3 Far field

The purpose of the seismic measurements was to calculate the far field amplitude decay from the TASQ rounds in the Äspo hard rock laboratory.

Three mobile seismic stations where positioned on the surface to measure the amplitude from two shots. The instruments are highly sensitive and are used as temporary stations of the Swedish National Seismological Network (SNSN). The SNSN operates on the same principles as the SIL-system on Iceland /Bödvarsson et al. 1999/. The two blasts Round 32 (FoU 1) and Round 33 (FoU 2) (Table 3-9) were recorded at distances of about 0.5 to 1.5 km (Table 3-10) and (Figure 3-10 and 3-11).

The instruments used were three component Lennartz LE-3D/5s geophones /Lennartz 1990/ and Nanometrics "Orion" data logger (Figure 3-12 and 3-13). The Orion instruments features a 24-bit digitizer providing sufficient dynamic range. The bit resolution of the Orion is 2 nV/bit and the gain of the geophone is 400 V/(m/s), which yields a station sensitivity of 0.5 nm/s.

Table 3-8. Distances between round sections and gauges along the TASQ-tunnel, see Figure 3-7.

Round (/Olsson et al. 2004/)	Section	Distance Acc. 1 (m)	Distance Acc. 2 (m)
32	0/069.0	(9.5)	19.5
33	0/073.6	14.05	24.05
34	0/077.9	18.4	28.4

Table 3-9. Blasts used in the experiment.

Blast	Blast Time
Round 32	2003 06 30 00°29'32''
Round 33	2003 07 01 01°17'24''

Table 3-10. Positions (X, Y, Z) of far field stations transformed from RT90 to Äspö 96 coordinate system.

Station	Serial number	X [m]	Y [m]	Z [m]	Hypo centric distance [m]	Epicentre distance [m]
Orion 1	122	6,965.512	2,072.942	4.252	579.5	373.3
Orion 2	125	6,303.804	2,197.685	5.842	1,118.1	1,025.8
Orion 3	118	5,804.383	2,224.757	6.062	1,589.5	1,525.9

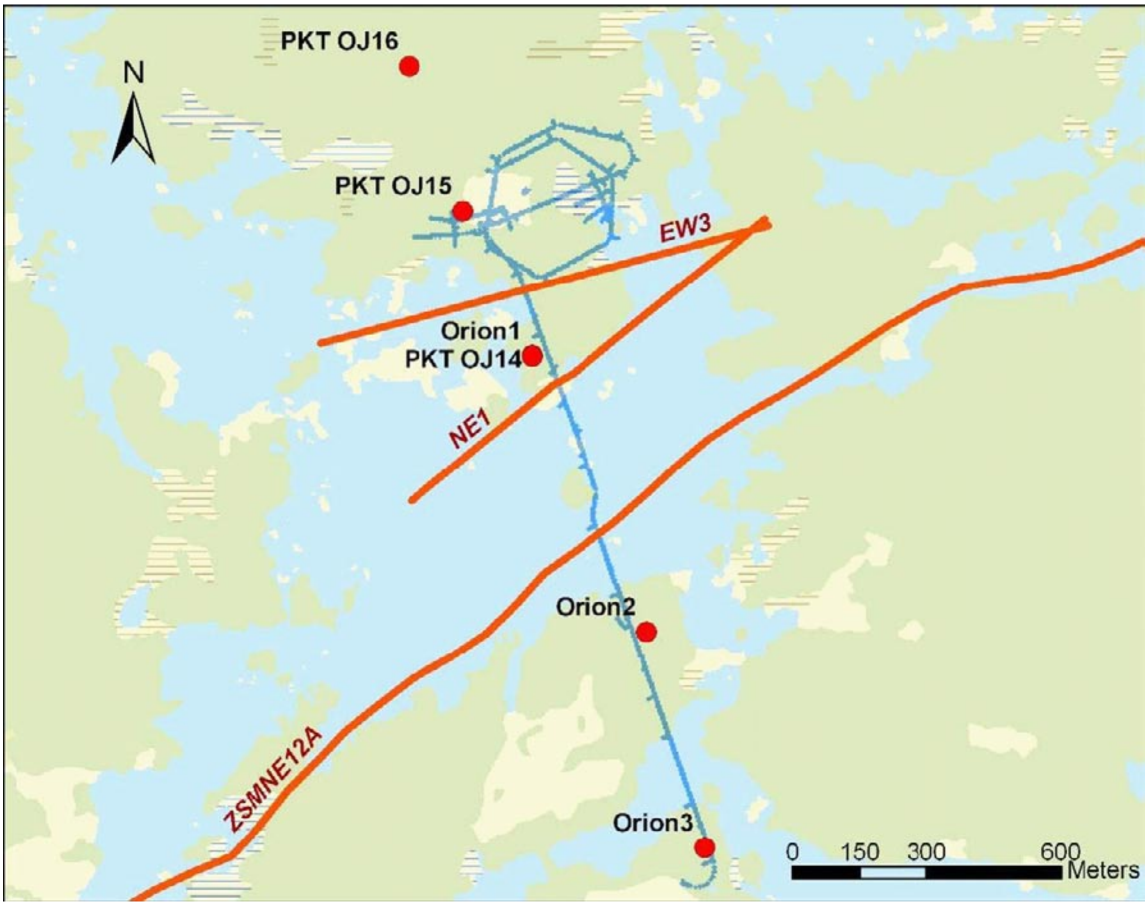

Figure 3-10. Top view of far field 3D seismic stations Orion 1, 2 and 3 and standard 1D geophone stations OJ14, OJ15 and OJ16. The deformation zones are in accordance to /SKB 2004/.

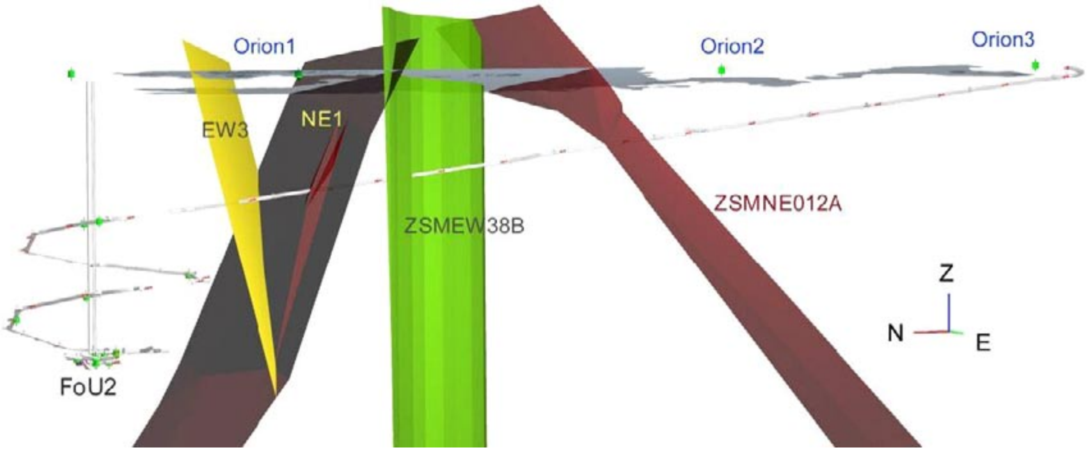

Figure 3-11. Vertical view of far field seismic 3D stations. Depth and horizontal (epicentre) distance from rounds to stations are shown in Table 3-10. Round 32 were located within 10 meters of Round 33 (FoU2). The deformation zones are in accordance to /SKB 2004/.

Figure 3-12. Lennartz LE-3D/5s geophone with Ø95 mm and height 165 mm.

Figure 3-13. *Nanometrics Orion Data logger.*

3.4 Limiting factors of detectors

Three types of detectors were used: Accelerometers, standard geophones and high sensitive seismological stations. This section provides some comments on the use of the detector- recording units.

Accelerometers

- Designed for recording shock wave data
- Dynamic range ± 5,000 g and low gain (1 mv/g)
- Frequency Response ± 5% from 1 alt. 5 to 10,000 Hz

Comments: Must be strongly coupled to the rock

High time resolution

Standard geophones

- Designed for vibration level control at installations and constructions
- Band limited recordings 0.3–350 Hz

Comments: Good for vibration measurements at medium distances

Data may be biased due to high frequencies close to the blast (over 350 Hz, which is the high cut filter frequency)

Seismological stations

- High resolution
- High sensitivity

Comments: High quality far field vibration data

4 Results

This chapter presents the geophone network monitoring of 46 rounds (at approximately 10–600 m distance from blast), acceleration monitoring of 3 rounds behind the blast in gauge holes along the tunnel wall and seismograph station monitoring of 2 rounds above ground (at approximately 600–1,600 m from the blast).

Figure 4-1 below shows an example of a geophone recording with different blast intervals. The blasting sequence covers about 6.3 s of vibrations from a vertical geophone at the firewall, 56 m from the round. The maximum value (9.4 mm/s) is defined as the Peak Particle Velocity or PPV, as shown in Figure 4-1.

Figure 4-2 below shows the PPV dependence on distance for all rounds and all recording units including the PPV-values from the integrated acceleration recordings and the seismographs.

It is clear that the PPV from the integrated acceleration recordings are higher than the standard geophone PPV at the same distances. This is probably due to the 350 Hz high cut filter for all the geophone recordings in the Figure below. The seismograph PPV is roughly independent of distances in the range 600–1,600 m.

According to the Swedish standard SS 460 48 61 a PPV of 0.4–1.0 mm/s will give moderate environmental disturbance. The 1 mm/s line is shown in Figure 4-2 and velocities over 1.0 mm/s will probably cause disturbances. This occurs closer than 300 m to the blast. The tunnel depth is however 450 m.

Note that vibrations from blasting in general scatter a lot depending on rock type, fractures, breakage, vibration gauge mounting and the time scatter in the pyrotechnic initiation.

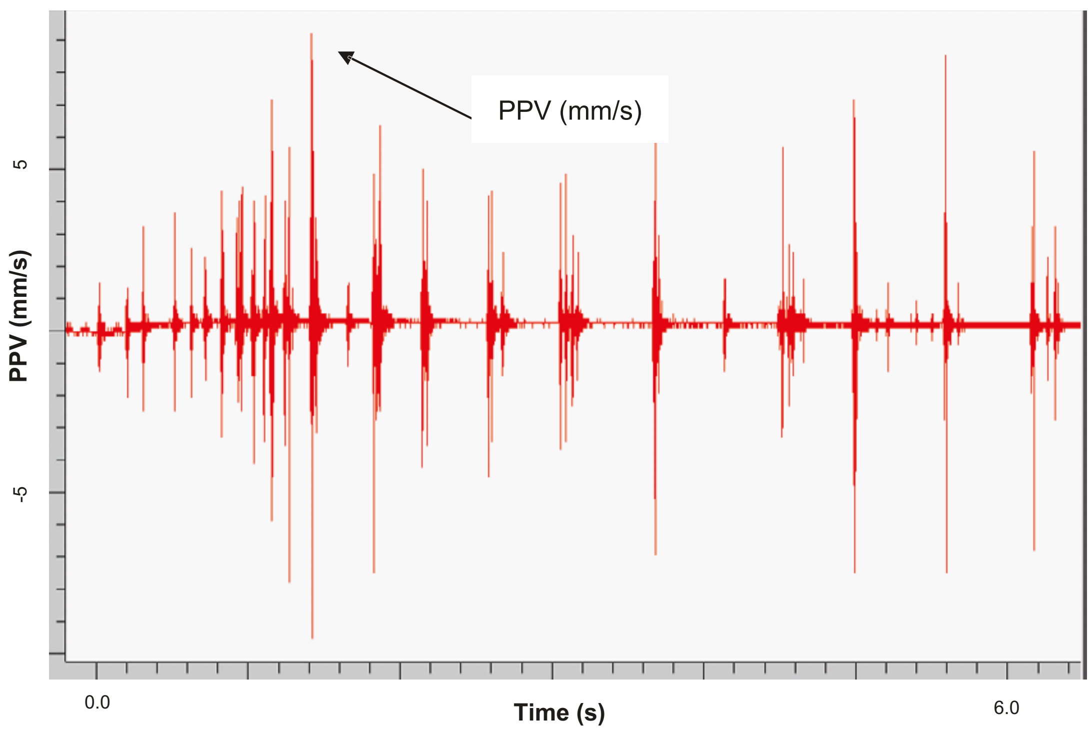

***Figure 4-1.** Event from a blasting round with the maximum vibration value defined as PPV (mm/s). Data from top heading blast round 32.*

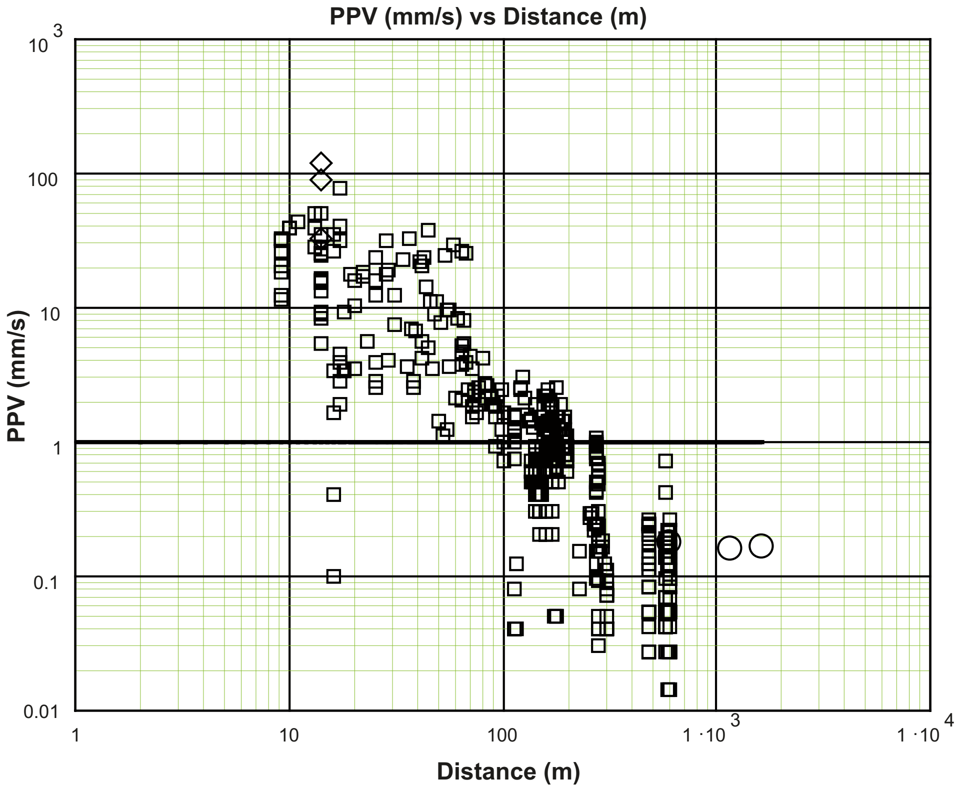

Figure 4-2. *Maximum PPV for each rounds vs. distance. The 1 mm/s level is reached at about 300 m from the blast. Symbols: □ Geophone 1 D data, ○ Seismograph 3 D data and ◊ Accelerometer 1 D data.*

4.1 Geophone measurements

The data were collected at 18 positions for the top heading rounds and the bench rounds at distances from about 10 m to 600 m. The positions were distributed at different levels and at sensitive installations.

There is some uncertainty about data recorded at the elevator –340 m (PA2609B01), at tunnel A (PA2790B01) Section 2/7909 and at the transformer (PA3364A01) which was vibrating with a low frequency during every blast.

Appendix 2 and 3 shows the measured PPV data, the amount of explosives and the distances to the monitors for all the rounds. Figure 4-3 shows PPV and charge weights for rounds 5–34 from the vibration level control at the fire wall.

The maximum PPV was 49 mm/s at a 13 m distance from round 17. The maximum allowed PPV at the elevator was 50.0 mm/s.

For the transformer the maximum measured Peak Particle Acceleration (PPA) was 37.2 m/s^2 from round 16. The maximum allowed PPA was given as 30 m/s^2. The limit defined in the risk assessment was reached only once during the whole blasting operations. No damage of the transformer was found.

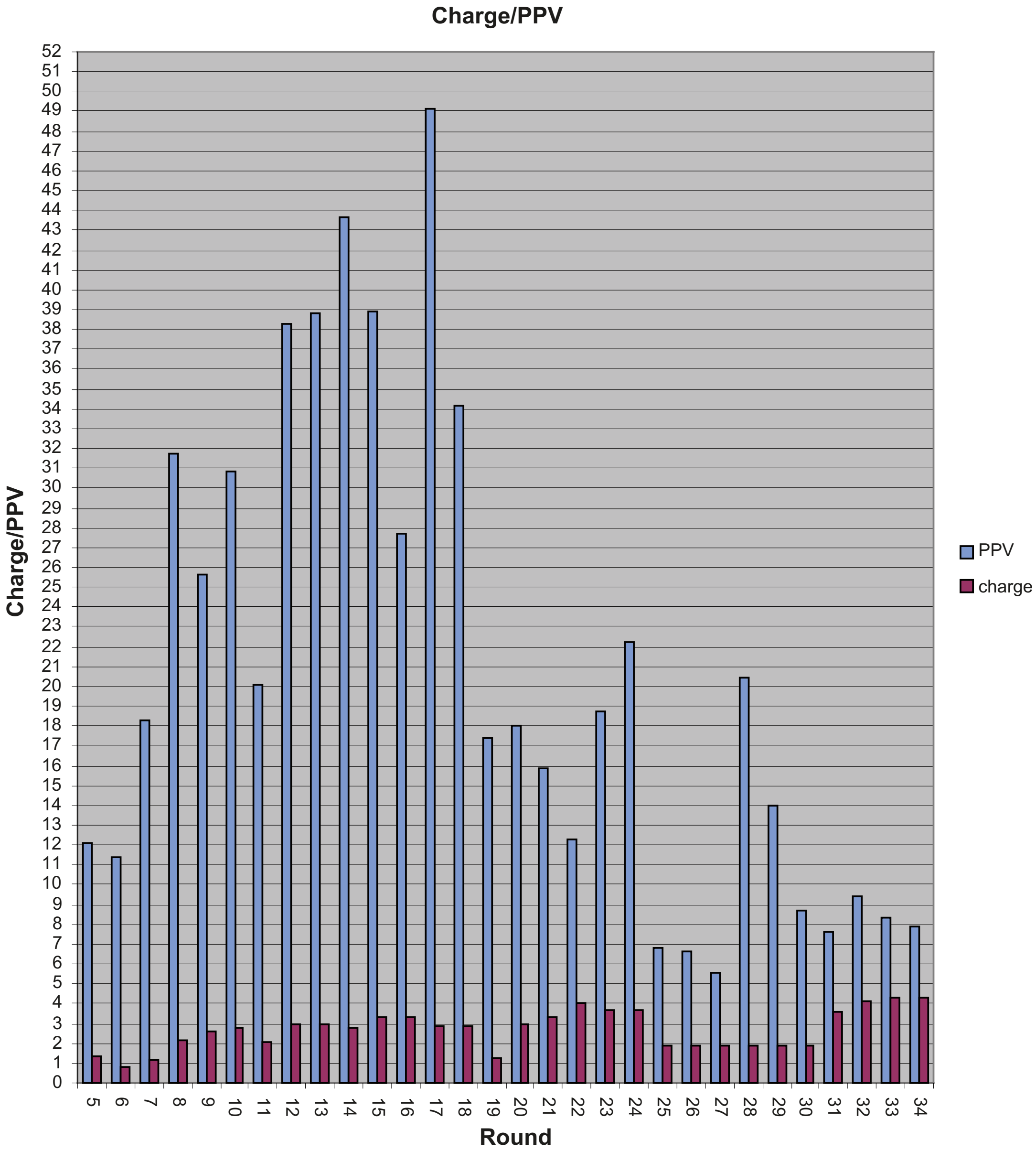

Figure 4-3. *PPV (mm/s) and amount of charge (kg) for rounds 5–34 at distances 9–65 m from the firewall. The maximum PPV/ round were measured during round 17.*

4.1.1 Amplitude-distance dependence

The amplitude-distance dependence was computed in terms of the site constants A and β in a scaling law of the general form 4-1,

$$PPV(R, q) = A \cdot q^{\alpha} / R^{\beta} \quad \text{(Eq. 4-1)}$$

with R (m) as the distance from charge to receiver and q (kg) as the weight of a single charge. The law can often be simplified to square root scaling, 4-2,

$$R^{\beta}/q^{\alpha} \approx (R/q^{0.5})^{\beta} \quad \text{(Eq. 4-2)}$$

by setting $\beta/\alpha = 0.5$. This is often a good approximation. The same law is usually used for a blast round with several charges initiated during the same delay. The maximum co-operating charge weight q_m (kg) per delay is used and the square root scaling law can be written as in 4-3

$$PPV(R, q_m) = A/(R/q_m{}^{0.5})^{\beta} \qquad \text{(Eq. 4-3)}$$

with intercept A, slope β and ($R/q_m{}^{0.5}$) as the scaled distance. The values for q are taken from Appendix in the D&B report /Olsson et al. 2004/ for the type of holes (production holes, lifters etc) that were generating the PPV. A reduction factor for q_m of 1/6 was used for delay number 14–60 for the top heading rounds. No reduction was done for the bench blasting rounds. The delay times are known from the recording instrument delay time log. The PPV(R)-values are taken from the Appendix 3 in this report. Despite some limitations for the charge weight scaling law that will be discussed more in chapter 5.2.1, we have used most of the data over the entire range up to 600 m for a comparison test.

Each data set below is fitted with a least squares linear curve in log-log scale and each data point is the maximum PPV as shown in Figure 4-1 above. Because of the scatter about the nominal time delay for the pyrotechnic detonators, a varying charge weight may randomly contribute to the PPV. This explains some of the scatter associated with the use of the scaled distances ($R/q_m{}^{0.5}$).

Figure 4-4 shows the reference data set for rounds 1–34 with all 419 values including the three test rounds. The inner 95% confidence bounds apply to the "true value" and the outer bounds to the 95% prediction intervals i.e. the next blast will generate a mean PPV times a factor of 1/5 to 5 with 95% probability. Six outliers from test rounds 1 and 2 and from round 21, 22 and 23 were excluded from the original data set to make it conform to a Gaussian distribution.

Two of the objectives were to test if anomalous rounds could be detected and to compare the top heading rounds with the bench blasting rounds.

Firstly, Figure 4-5 shows the regular 370 values (rounds 5-34) i.e. three rounds with misfires and four test rounds were excluded from the reference data set. Table 4-1 shows that the intercept A and slope β calculated from this data set are not significantly different from the reference ones. This indicates that the test rounds and misfire rounds had no strong effect on the PPV. Note that the scatter may mask the effect of the anomalous rounds.

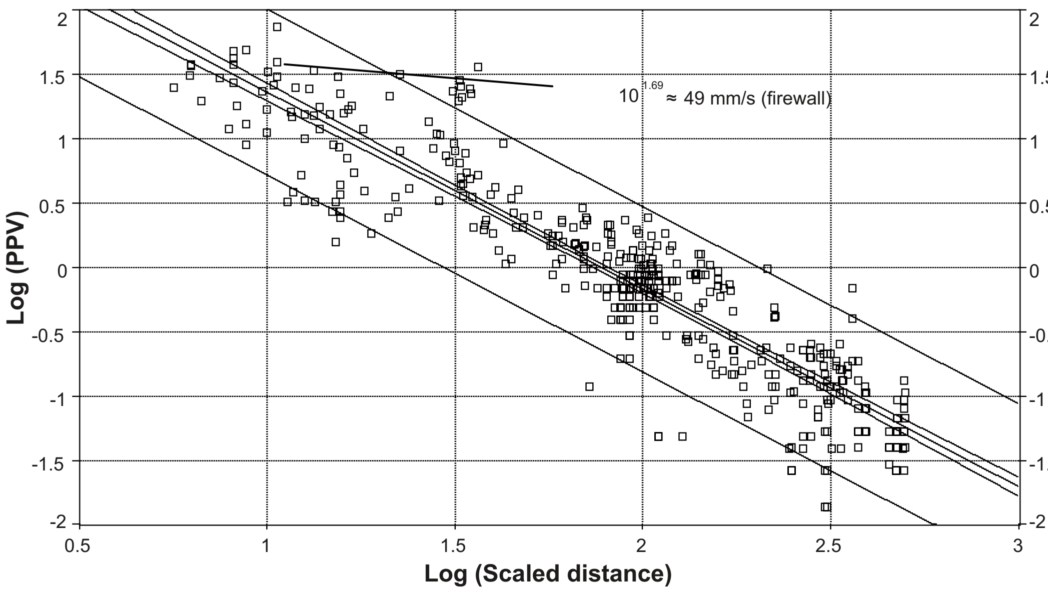

Figure 4-4. *Log PPV (mm/s) as a function of log scaled distance ($R/q_m{}^{0.5}$) for 419 top heading rounds data. The inner lines show the 95% confidence limits for the "true value", the outer lines show the 95% confidence limit for a simple prediction.*

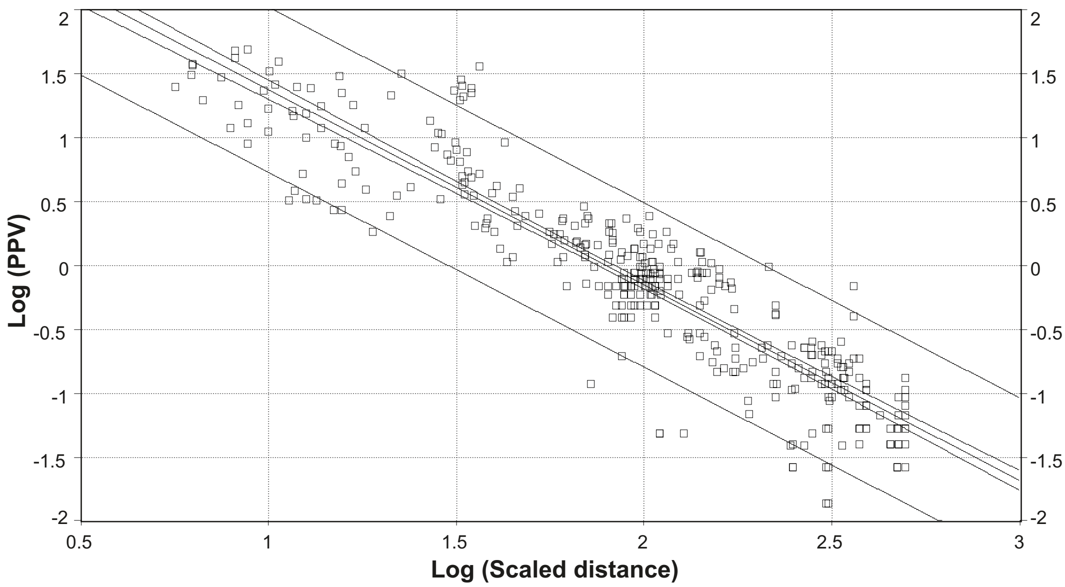

Figure 4-5. *Log PPV (mm/s) as a function of log scaled distance ($R/q_m^{0.5}$) for 370 values. Round 1–4, 15, 16 and 21 are excluded.*

In order to test whether the total number of blast holes per round has any influence on the PPV, all top heading rounds with a maximum of 92 blast holes were selected and marked with light circles (Figure 4-6). It is seen that rounds with fewer blast holes generate somewhat lower PPV-values, especially at long distances. /Blair 1990/ has modelled the PPV as a function of the number of blast holes. He found that the PPV tend to increase with the number of blast holes due to vibration overlap.

To see if the difference is significant the rounds with a maximum of 92 blast holes, i.e. approximately ¼ of the values, were excluded. Figure 4-7 shows 299 values from the full blast rounds with 100–138 blast holes and Table 4-1 shows that the intercept A is higher and the slope -β is steeper. The values are significantly higher than the values for the reference set.

Secondly, the top heading rounds were compared with the bench rounds. The number of PPV:s in the reference data set was reduced to 192 PPV:s for a comparison over the same distance range 25–181 m (Figure 4-8).

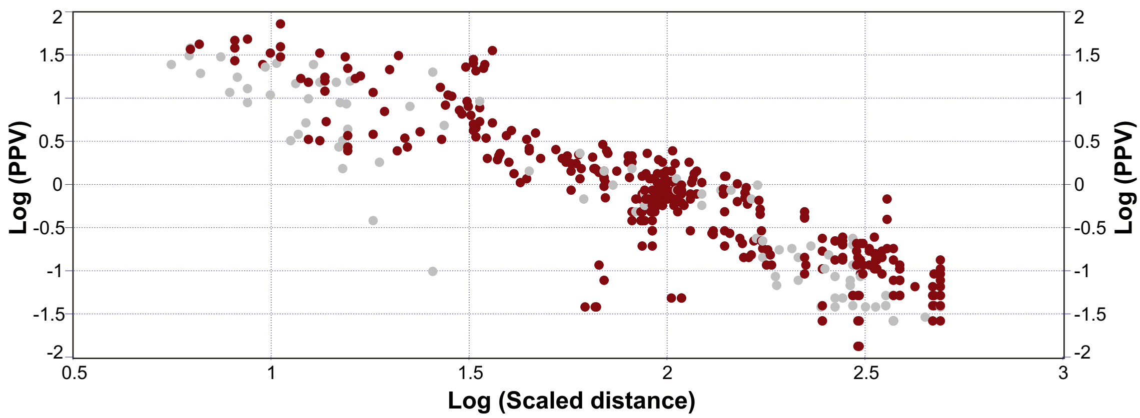

Figure 4-6. *Log PPV (mm/s) as a function of log scaled distance ($R/q_m^{0.5}$). The top heading rounds with maximum 92 blast holes are marked with grey circles. Full top heading rounds, 100–138 blast holes, are marked with red darker circles.*

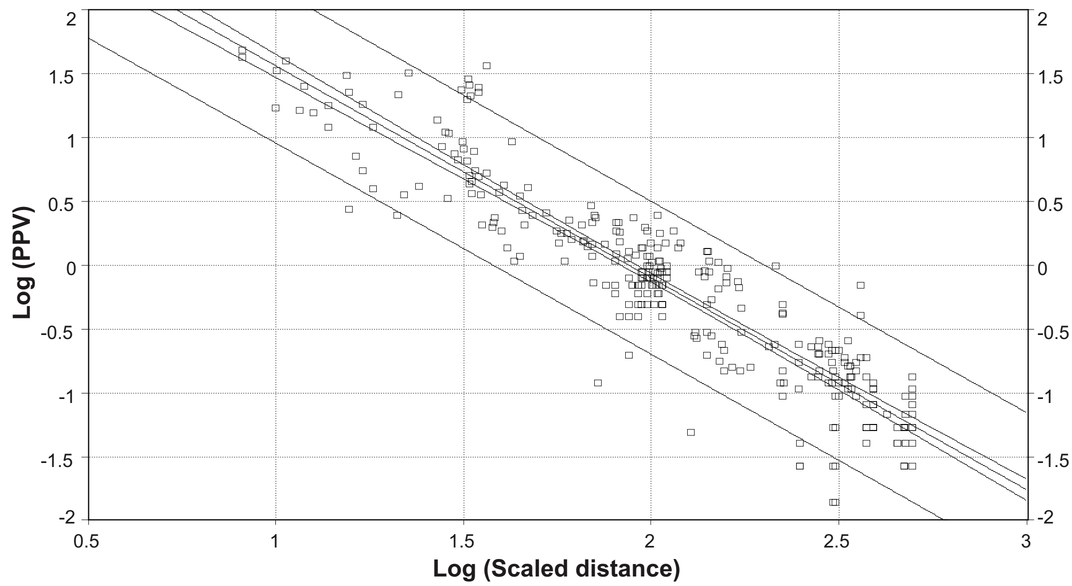

Figure 4-7. *Log PPV (mm/s) as a function of log scaled distance ($R/q_m^{0.5}$) for 299 values from the top heading full blast rounds.*

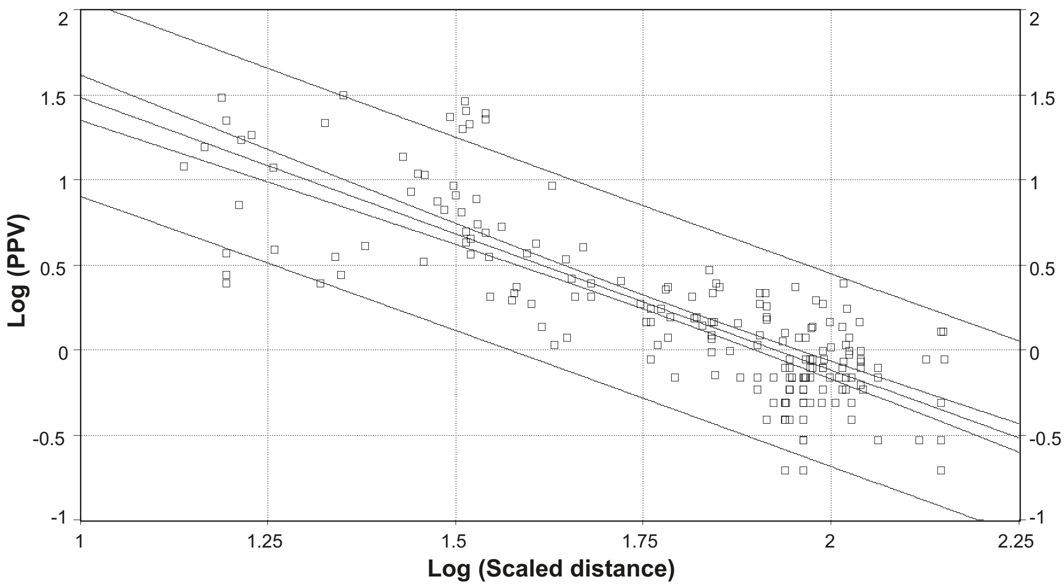

Figure 4-8. *Log PPV (mm/s) as a function of log scaled distance ($R/q_m^{0.5}$) for the reduced reference set with 192 values from the top heading rounds.*

Figure 4-9 shows the 58 values in the bench rounds. The comparison shows no significant difference between top heading rounds reduced reference set and bench rounds. Note that the coefficients of determination r^2 are relatively low in this test.

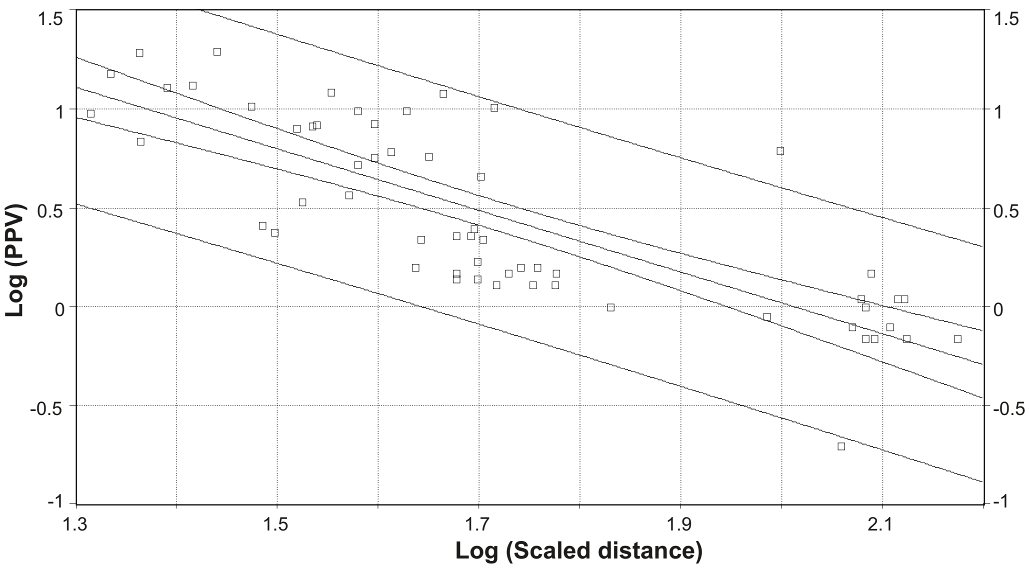

Figure 4-9. *Log PPV (mm/s) as a function of log scaled distance ($R/q_m^{0.5}$) for 58 values from bench blasting the rounds.*

Table 4-1. Fitting parameters for log PPV data with 95% prediction confidence limits for intercept A and slope -β.

Data set	Parameters	Mean	Lower limit	Upper limit	r^2
Top heading Rounds 1–34	Log A	2.90	2.77	3.04	0.84
Reference data set	β	1.53	1.47	1.60	
419 values					
Top heading Rounds 5–34	Log A	2.91	2.77	3.05	0.84
All regular rounds	β	1.53	1.46	1.60	
370 values[1)]					
Top heading Rounds 14–34	Log A	3.23	3.05	3.39	0.85
Full blast rounds	β	1.66	1.58	1.74	
299 values[2)]					
Top heading 25–181 m	Log A	3.09	2.81	3.38	0.67
Reduced reference data set	β	1.60	1.45	1.77	
192 values					
Bench 25–181 m	Log A	3.14	2.59	3.69	0.63
58 values	β	1.56	1.24	1.87	

[1)] Test rounds and misfired rounds are excluded.

[2)] Full blast rounds with 100–138 blast holes.

Table 4-1 above summarizes the curve fits. The results are:

- The most representative parameters for the entire blasting operation are the 419 values from the reference top heading rounds. The parameters are A=813 mm/s and slope β=1.53.
- The parameters for the full blast rounds are A=1,698 mm/s and slope β=1.66.
- The PPV seems to increase with the total number of holes in the blast.
- If one wishes to predict the PPV accurately for a particular blast, the parameters A and β must be known for the relevant type of blast.

– The comparison of the parameters for the bench blasting rounds with the parameters for the top heading rounds shows no difference. This is also true for the top heading rounds with all data included compared with when the misfire rounds and test rounds are excluded.
– The coefficient of determination is relative low for the comparison of the bench rounds with the top heading rounds.

In practical work e.g. in populated areas and for protection of sensitive installations some maximum allowed vibration must be determined. This can for example be done, by simply using an upper 95% ($\approx$+2 σ) confidence line instead of the least square fit line.

In Figure 4-4 with the parameters log A = 2.90, (A= 813 mm/s) and β = 1.53 the PPV for a 4 kg charge decreases from about 30 mm/s to about 3 mm/s over the distance 17 m to 76 m or a factor of 10 over about 60 m distance. The statistics say that a 95% prediction interval spans over a mean PPV times a factor of 1/5 to 5. In this case a predicted value of 3 mm/s will span from 0.6 to 15 mm/s.

Over a 350 m distance the mean PPV will decrease to about 100 times or the 30 mm/s value at 17 m will drop about 0.3 mm/s.

4.1.2 Effect of rock structures and water on vibrations

In an attempt to trace how the PPV varies due to changes in the rock structure, four geophones were selected for monitoring of the bench blasting rounds. The bench blasting rounds were selected due to the lower number of blast holes per interval and the nearly constant charge weights.

Decoupled charges generate a lower blast hole pressure than if the charges are fully coupled to the blast hole wall /Nie 1999/. In this test the holes were loaded with Ø 17 mm and Ø 22 mm explosives in Ø 48 mm holes i.e. the charges were decoupled.

Geological mapping and hydraulic tests has shown that natural fractures cross the tunnel between 43–74 m with a gap with almost no fractures between approximately 52–57 m.

The largest inflows are found for the gauge numbers (positions) 7, 8, 9 and 11 /Emmelin et al. 2004/. These inflow positions correlate to some extent with the blasting positions for rounds 35–38.

One can assume that the blast holes that cross fractures are filled or partly filled with water especially if the holes are horizontal or dipping downwards into the rock.

If the blast holes are filled with water, the acoustic coupling between the charges and the blast hole walls increases as well as the PPV at the gauges.

Each of the data sets below contains one PPV-value per blast monitored by a single geophone. The upper plot in each Figure shows PPV vs distance and the lower shows PPV vs log (scaled distance, $R/q_m^{0.5}$) with q_m (kg/hole) for the explosives from Table 4-2.

Figure 4-10 shows from the left, the vibrations for the elevator in the range 38 –76 m for rounds 35, 36, 37 etc with a drop at round 39. Figure 4-11 shows the vibrations for the firewall in the range 27–63 m. These two geophones were mounted behind the blasts and therefore the distance from the blast to the geophones increases with increasing round number in both data sets.

Figure 4-12 below shows from the right, the vibrations for the elevator in the range 63 –82 m for rounds 35, 36, 37 etc with a less obvious drop at round 39. Figure 4-13 shows the vibrations for the firewall in the range 153–181 m. The geophones were in these cases in front of the blasts so the distance decreases with increasing round number.

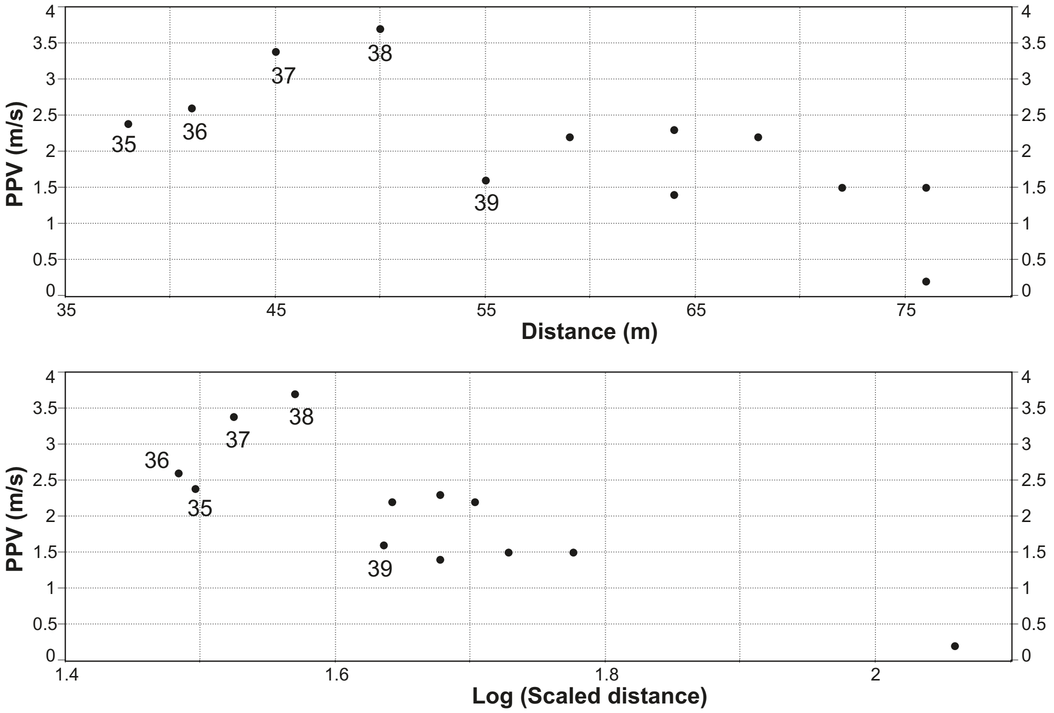

__Figure 4-10.__ Vibrations at the elevator. The upper figure shows PPV (mm/s) vs distance (m). The lower shows PPV (mm/s) vs log scaled distance ($R/q_m^{0.5}$). Note the relative shift of the points due to the different charge weights.

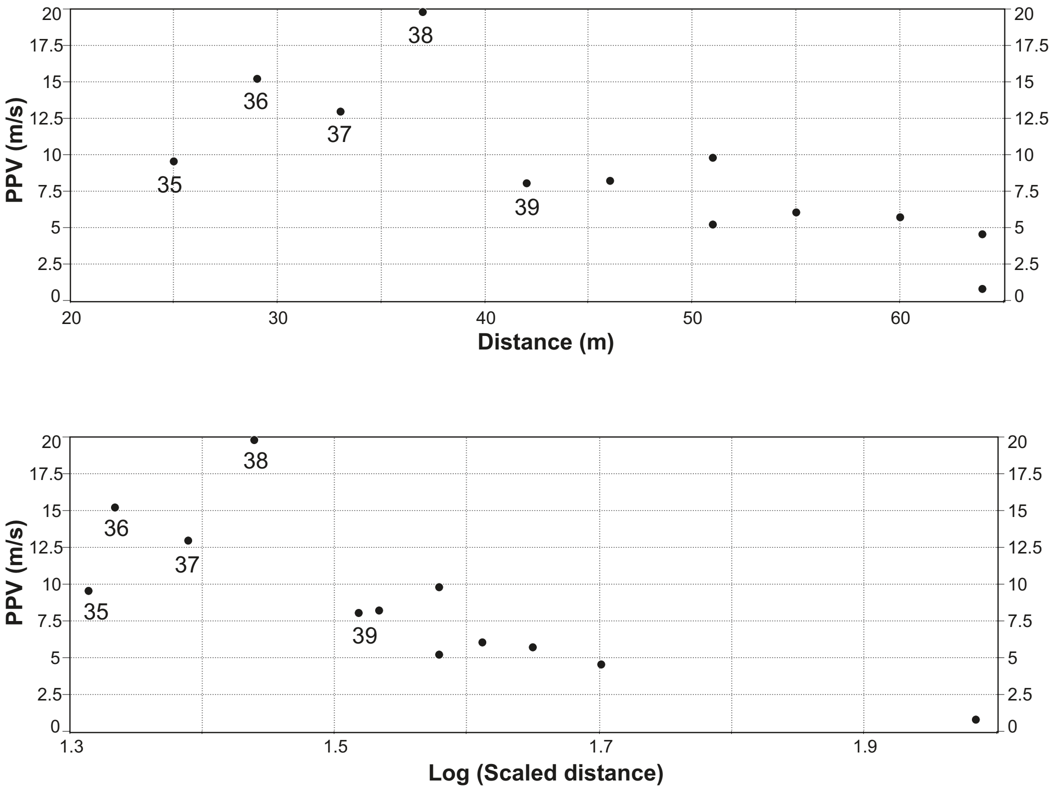

__Figure 4-11.__ Vibrations at the firewall. The upper figure shows PPV (mm/s) vs distance (m). The lower shows PPV (mm/s) vs log scaled distance ($R/q_m^{0.5}$).

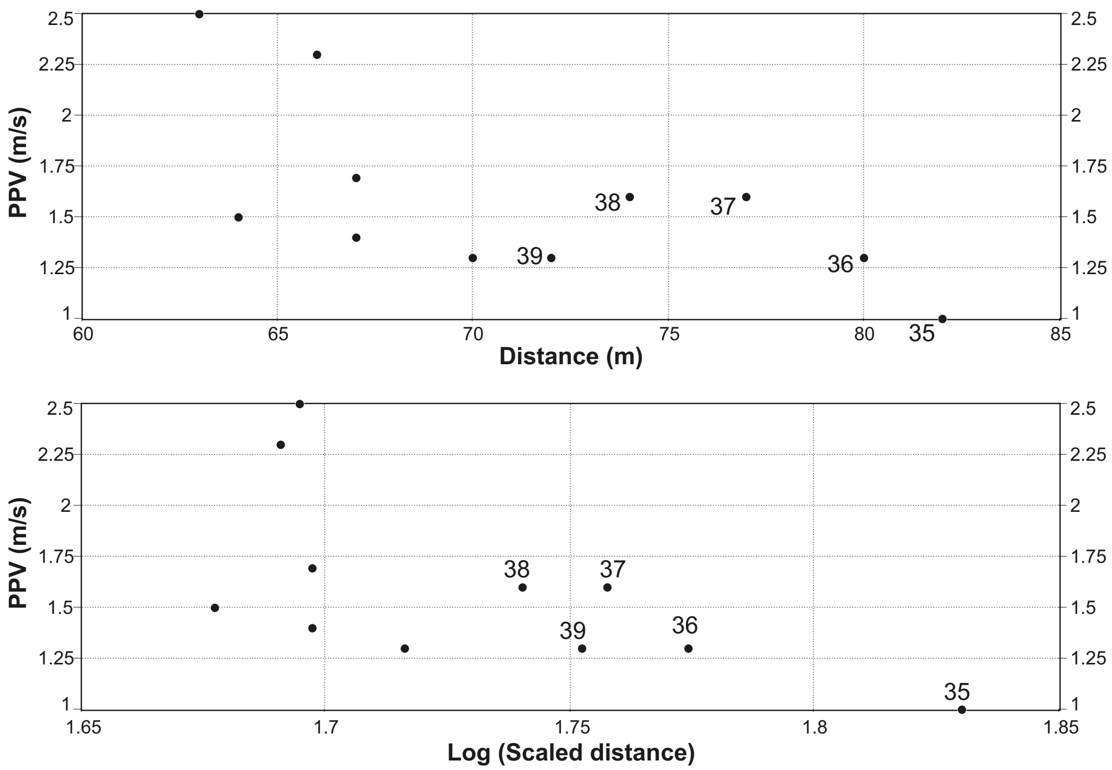

Figure 4-12. *Vibrations at tunnel A. The upper figure shows PPV (mm/s) vs distance (m). The lower shows PPV (mm/s) vs log scaled distance ($R/q_m^{0.5}$).*

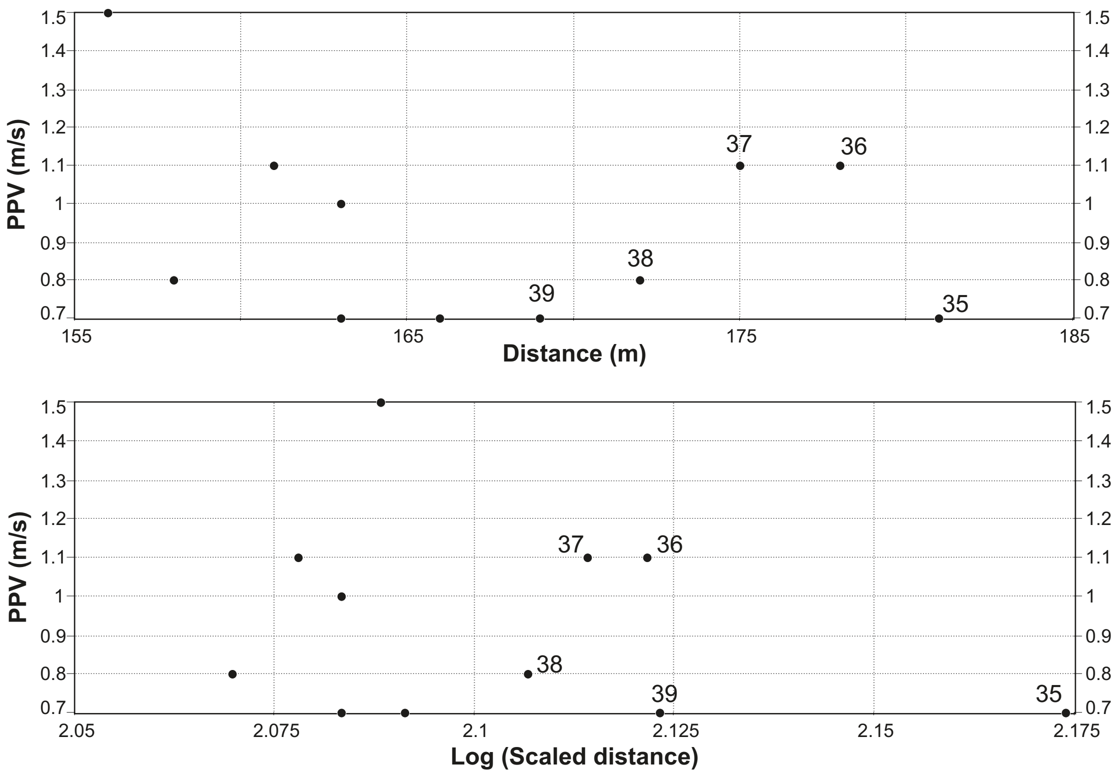

Figure 4-13. *Vibrations at tunnel D. The upper figure shows PPV (mm/s) vs distance (m). The lower shows PPV (mm/s) vs log scaled distance ($R/q_m^{0.5}$).*

Table 4-2. Amount of explosives for the bench rounds. Reduced values are underlined.

Round	Production (kg)	Helper (kg)	Contour (kg)	Charge q (kg/hole)
35		5.9	13.1	1.47
36	7.2	13.0	20.2	1.81
37	7.2	13.0	20.2	1.81
38	7.2	13.0	20.2	1.81
39	3.2	13.0	20.2	1.62
40	5.4	9.7	18.2	1.81
41	3.4	11.3	18.2	1.81
42		3.2	10.1	1.81
43	5.4	13.0	17.2	1.81
44	5.4	13.0	17.2	1.81
45	4.9	11.3	4.4	1.62
46				0.44

The PPV from the 4 gauges shows the same pattern independent on the direction from blasts to gauge positions.

The mapping of conductive features that cross the tunnel indicate that water can flow into the blast holes. The charges in this case are not decoupled and therefore the PPV increases at the gauges for rounds 35–38.

The PPV-drop for rounds 39–45 may be related to:

– Reduced number of holes in the production (Table 4-2).

– Decoupled charges due to fewer fractures and less water inflow between 52–57 m /Emmelin et al. 2004/.

4.2 Accelerometer measurements

Near field vibration recordings from blasting have proven to work well if accelerometers are grouted in gauge holes /Nyberg and Fjellborg 2000, Ouchterlony et al. 2003/. The grouting causes a strong coupling of the accelerometer to the ground.

4.2.1 Electronic time delayed contour holes

Experiences from earlier investigations show that the time precision for initiation of the explosives within an interval has an influence on the damage zone /Olsson and Bergqvist 1997/. Therefore, electronic detonators from Orica /www.ikonsystem.com/ with "exact initiation time" were used for testing of a new damage zone model /Olsson and Ouchterlony 2003/. The model is dependent on a number of factors. One factor is the instantaneous initiation of contour holes.

Table 4-3 below shows the explosives used (kg/blast hole) in the 3 test rounds. In the contour a maximum of 5 holes were initiated simultaneously with the electronic time delay system e.g. 5 holes · 1.01 kg/hole = 5.05 kg per interval. The drilling, charging pattern and the time setting for the contour holes and for the bottom holes are shown below in Figure 4-14.

Table 4-3. Charge concentration for the test rounds. Contour holes initiated with i-kon electronic detonators.

Blast holes	Round 32: charges (kg/hole)	Round 33: charges (kg/hole)	Round 34: charges (kg/hole)
Cut	4.10	4.34	4.34
Stop holes	3.15	3.75	3.75
	2.83	2.68	2.68
	2.88		
	3.04		
	3.20		
Helper	1.76	1.76	1.76
Contour holes$^{(i\text{-}kon)}$	1.01	1.01	1.01
Bottom holes$^{(i\text{-}kon)}$	1.44	1.44	1.44

Appendix 3 shows that the time intervals Δt for the i-kon caps monitored at the gauge holes are very close to the time intervals that were programmed in advance. The measured differences between programmed and monitored time intervals are due to time picking uncertainties and different wave travelling paths.

The time resolution 15–30 m from the front is 1–10 ms. Thus, for round 32 the contour holes at time 5,000 ms, 5,010 ms and 5,020 ms could be separated but the holes for round 34 at 7,010 ms, 7,011 ms etc could not.

The initiation plan and acceleration recordings that are used for the blast function control are shown in Figure 4-14 to 4-17. Each recording is shifted to the left with the first arrival at time 0 (s). The intervals are separated in time due to the nominal initiation time and cap scatter.

It is clear that some intervals are missing. For round 32 (Figure 4-15) two intervals in the opening, LP1 and LP4, are missing. All other intervals were identified except for some contour holes at the left tunnel wall. A time shift of 25 ms delay is related to LP0.

For round 33 (Figure 4-16), LP0 was not used, instead the time shift is related to LP1 with a 100 ms delay. For this round LP2 and LP3 in the opening were missing as well as LP 18 and LP 20 later in the blasting sequence.

For round 34 (Figure 4-17) the initiation sequence was altered. The opening was initiated with MS caps (25 ms between the delays). Thus intervals 1-19 with MS delay corresponding to time delays of 75–475 ms.

The main conclusion from this section is that the programmed initiation time intervals for the electronic caps, agree well with the monitored time intervals along the tunnel wall. This indicates that the contour damage for these rounds should be minimal because of the positive effect of instantaneous cap initiation /Olsson and Bergqvist 1997/.

4.2.2 Wave velocity along the tunnel

The wave velocity V_p was calculated along the tunnel wall. Acceleration data from round 33 (24 values) and round 34 (17 values) were used. All the time/distance data are shown in Appendix 4. Figure 4-18 below defines how the time arrivals were picked at two gauge holes approximately 0.7 m deep and 10 m apart.

In the ZEDEX-project /Olsson et al. 1996/, the average P-wave velocity through the rock between the D&B tunnel and the TBM tunnel (Section B4–B2) was about 6,060 m/s ± 100 m/s from tomography. From downhole measurements the values varied between 5,800 m/s and 6,300 m/s.

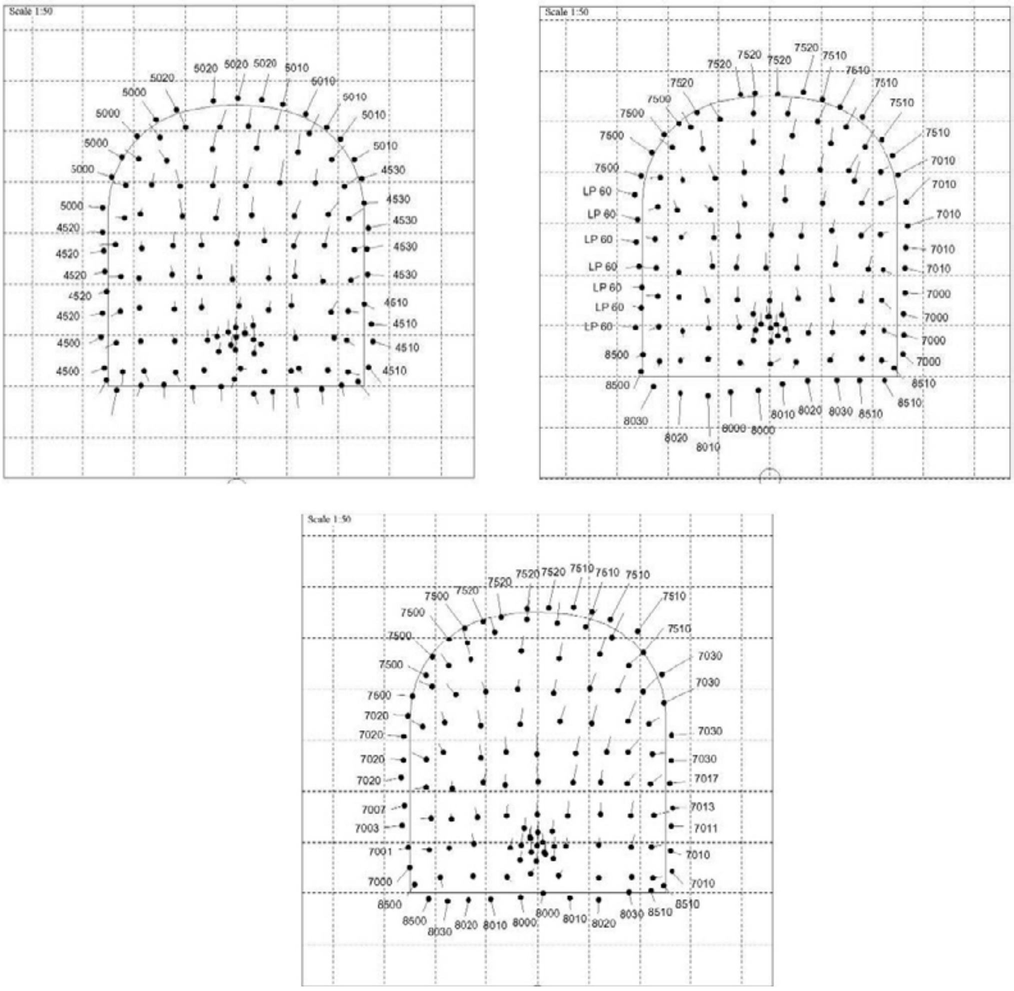

Figure 4-14. *Round logs for the 3 test rounds. Round 32 at the upper left, round 33 at the upper right and round 34 at the bottom. The lines from the collaring show approximately the lookout angles in the contour. For the opening, the helpers, and the stop holes the lines indicates a deviation in the drilling.*

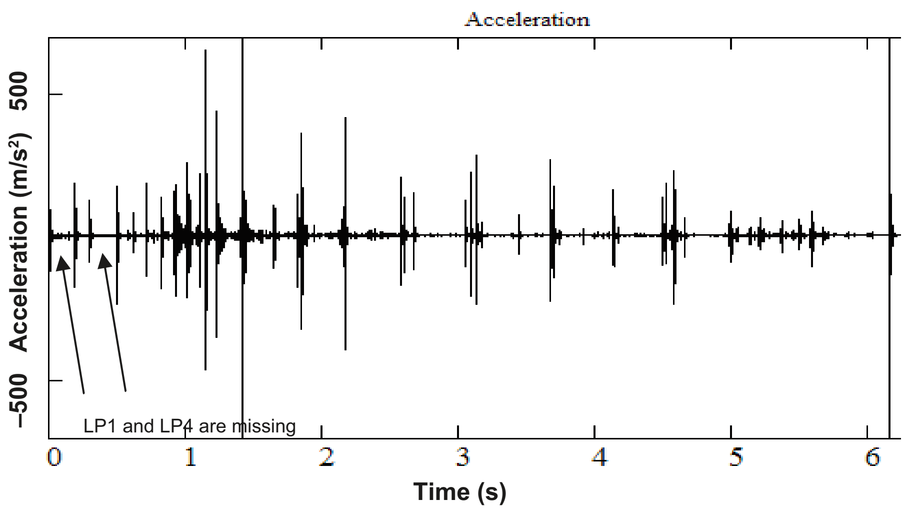

Figure 4-15. *Recordings from round 32.*

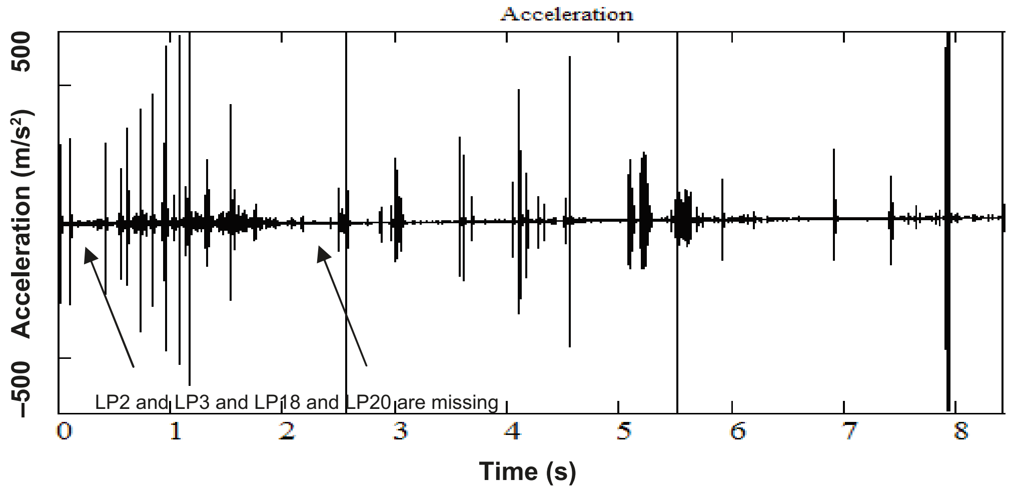

Figure 4-16. *Recordings from round 33.*

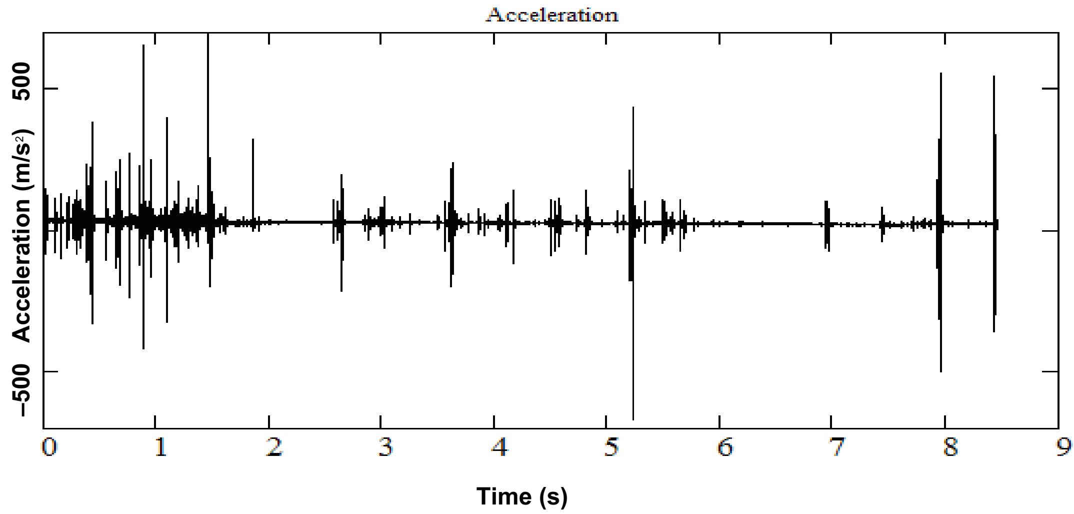

Figure 4-17. *Recordings from top heading round 34.*

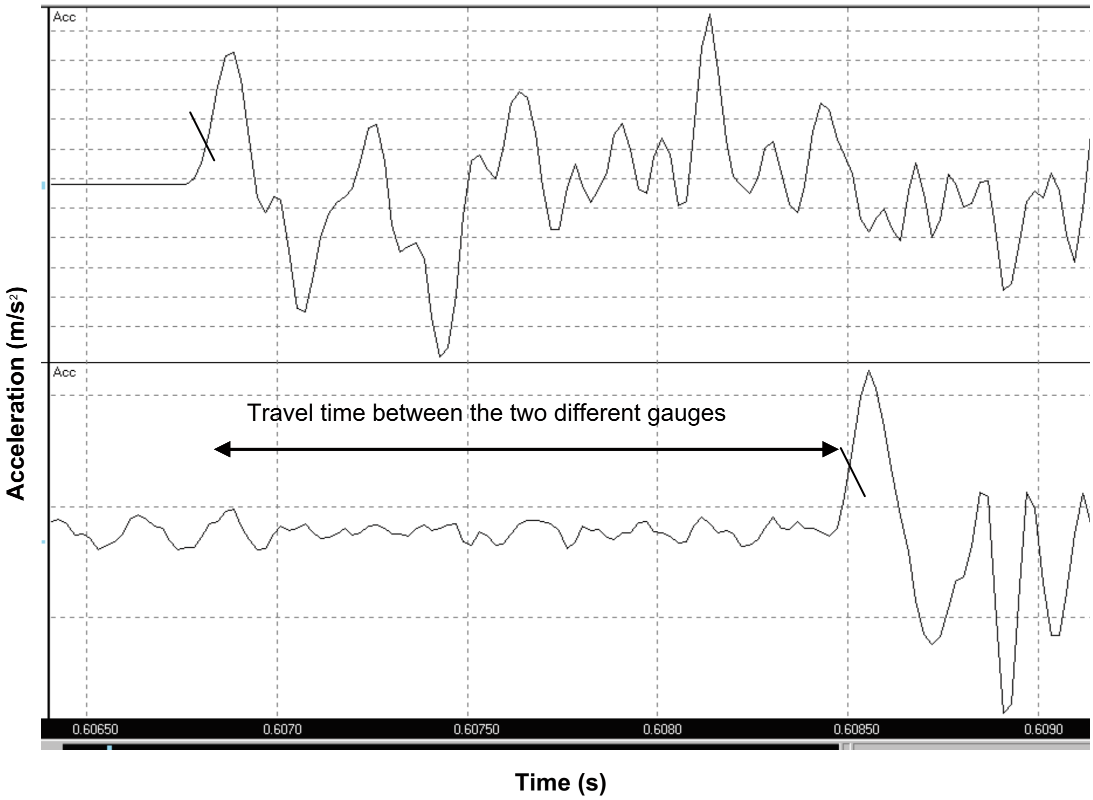

Figure 4-18. *Acceleration (m/s²) time data along the tunnel wall. The time for the wave to travel between the two different gauges is about 1.69 ms.*

/Pettitt et al. 2003/ measured velocities V_p across the TASQ tunnel at the positions of the future location of the pillar stability experiment. These velocities varied depending on the depth from the tunnel floor. In the range 0–20 cm the velocity increased gradually depending on the damaged zone. Other factors as stress and lithology were believed to affect the velocity. At 6 m depths the average V_p value was 6,050 m/s.

Large variations in velocities have been measured in other rock masses. In LKAB's iron ore mine in Kiruna, Sweden, the velocity could differ by 20% between two perpendicular wave propagation directions at the 765 m level /Nyberg and Fjellborg 2002/.

A laboratory test /Lama and Vutukuri 1978/ using the ultrasonic method has shown that V_p for a Barre granite increases by 23% if the saturation changes from 0 to 100%. For a laboratory test /Nyberg et al. 2001/ on a very competent block of Bohus granite with less porosity than 1%, the changes in P-wave velocity (m/s), rise time (s) and amplitude (μm) are significant. Specifically the increase in P-wave velocity after wetting was about 20% with a source-receiver distance of 300 mm and 1-gram explosive sources.

Our measurements in the TASQ tunnel shows, for top heading round 33, a mean velocity of Vp_{33} = 6,094 m/s with a standard deviation of σ_{33} = 238 m/s calculated from 24 measurements. For top heading round 34 V_{p34} = 5,962 m/s with σ_{34} = 131 m/s was calculated from 17 measurements.

Considering the larger standard deviation of σ_{33}, the two means V_{p33} and V_{p34} are not significantly different. Statistically, for a 68% confidence interval 1σ wide, the measured mean value/Pettitt et al. 2003/ 6 m below the tunnel floor is within the standard deviation limits for V_{p33} and V_{p34}.

4.2.3 Near field attenuation along the tunnel

In order to estimate the attenuation in the near wave field at the two gauge holes along the tunnel wall, an exponential Equation 4-4 was fitted to the data rather than the scaling law of Equation 4-1. The ratio of the amplitudes Ar_2 and Ar_1 measured at the two gauge positions r_1 and r_2 m away from the source, then becomes,

$$Ar_2/Ar_1 = r_1/r_2 \cdot \exp\,[-\lambda_1(r_2-r_1)] \qquad \text{(Eq. 4-4)}$$

where λ_1 is the rock attenuation constant. The exponential equation is written in a form often used for calculation of rock attenuation and is basically the same as the one used in Section 4.3 for calculation of the rock attenuation between the rounds and the Orion stations above ground. However, the rock attenuation can as well be calculated by using the scaling law 4-3 and the relation 4-5 between the attenuation λ_1 and the site constant β estimated between the two gauge positions,

$$\lambda_1 = (\beta-1) \cdot (\ln r_1/r_2)/(r_1-r_2) \qquad \text{(Eq. 4-5)}$$

Figure 4-19 shows an example of the vibrations at the three components accelerometer positions r_1 (14 m) and r_2 (24 m) along the wall from the nominal blast interval no 4 in round 33. The accelerometer orientations at r_1 were horizontal for ch 1 and ch 2 and vertical for ch 3. The same orientations were used for the more distant accelerometer ch 4, 5 and 6 at r_2.

The 3 components at r_1 and r_2 were summed and integrated and the first peak values were used for attenuation estimations. The values were picked in the way shown in Figure 4-20 below.

Accelerations signals from round 33 were selected and integrated. The attenuations were estimated to λ_1 = 0.040, 0.036, 0.054, 0.047, 0.062, 0.055, 0.013, 0.048, 0.042, and 0.045 with the mean 0.044.

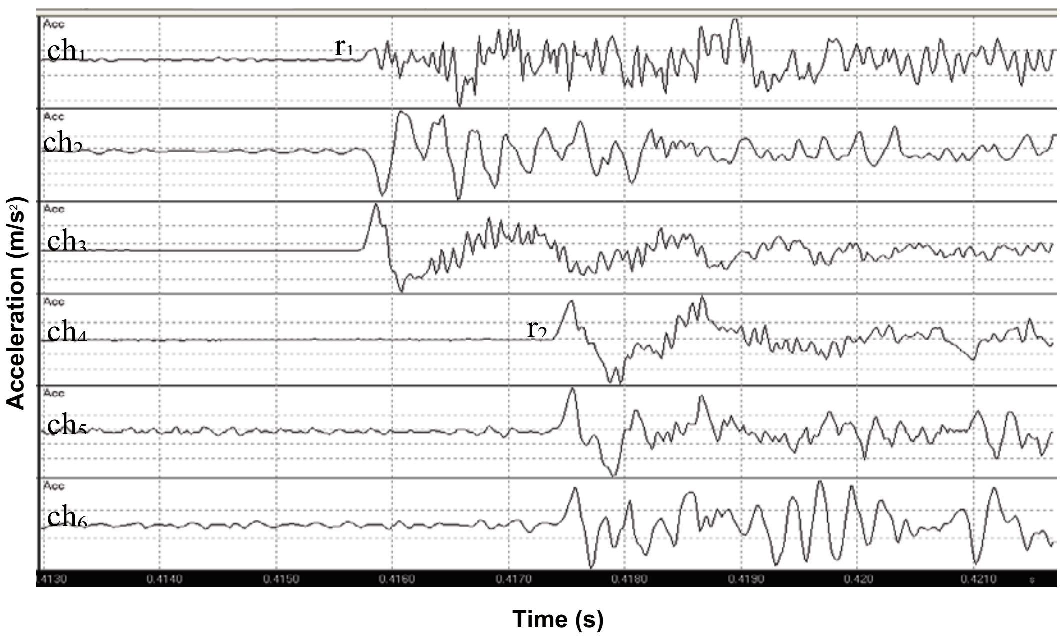

Figure 4-19. *All signals at two positions from one interval.*

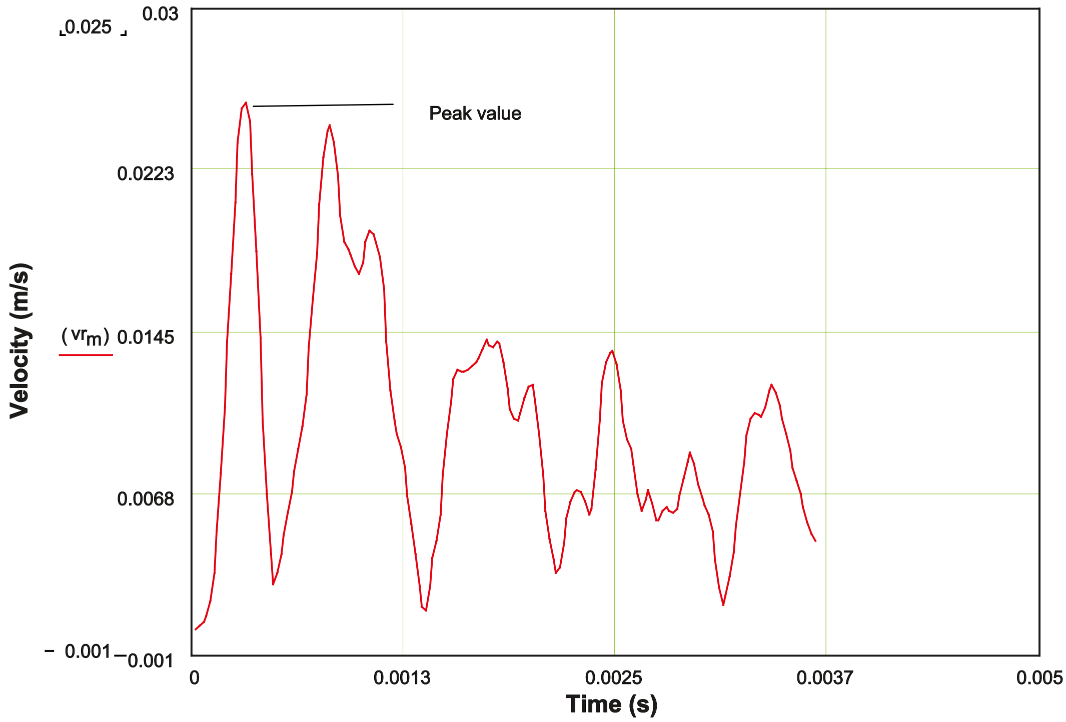

Figure 4-20. *Integrated acceleration signal for one gauge position.*

4.3 Seismographs

Two sets of data were recorded. Firstly, signals from top heading rounds 32 were recorded with all three stations positioned next to Orion 1 (Figure 3-10). Secondly, signals from top heading round 33 were recorded with the three stations distributed more widely (Figure 3-10). The recording of top heading round 32 was aimed at comparing the individual stations and to make a table of corrections to the same amplitude responses. The recording from top heading round 33 was then used to calculate the actual amplitude attenuation of the signals.

4.3.1 Data transformation

Figures 4-21 and 4-22 show that the raw data (bits) from the rounds lie well above the background noise. The data needs to be transformed from recorded bits to ground velocity (m/s) before further analysis (Eq. 3-1). We apply the transfer function in Equation 3-1 to get the ground motion in Figures 4-23 and 4-24.

4.3.2 Far field amplitude attenuation

The peak amplitude of the particle velocity has to be determined in all recordings. We used all 3 components for this. Since only the first signals from the opening in the blasting sequence are uncontaminated with noise, this peak was used. This procedure is typically used in the determination of earthquake magnitudes /Aki and Richards 1980/. The recordings from top heading round 32 were used to calibrate the three recordings in Figure 4-25. The middle station of the determined amplitudes was used to calculate the correction factors for the two other stations. The recorded amplitudes and the correction factors are expressed in Table 4-2.

The correction factors have been multiplied with the total particle velocity recorded from top heading round 33 in Figure 4-26. From the corrected records we determined the amplitudes and the attenuation for the data in Figure 4-27.

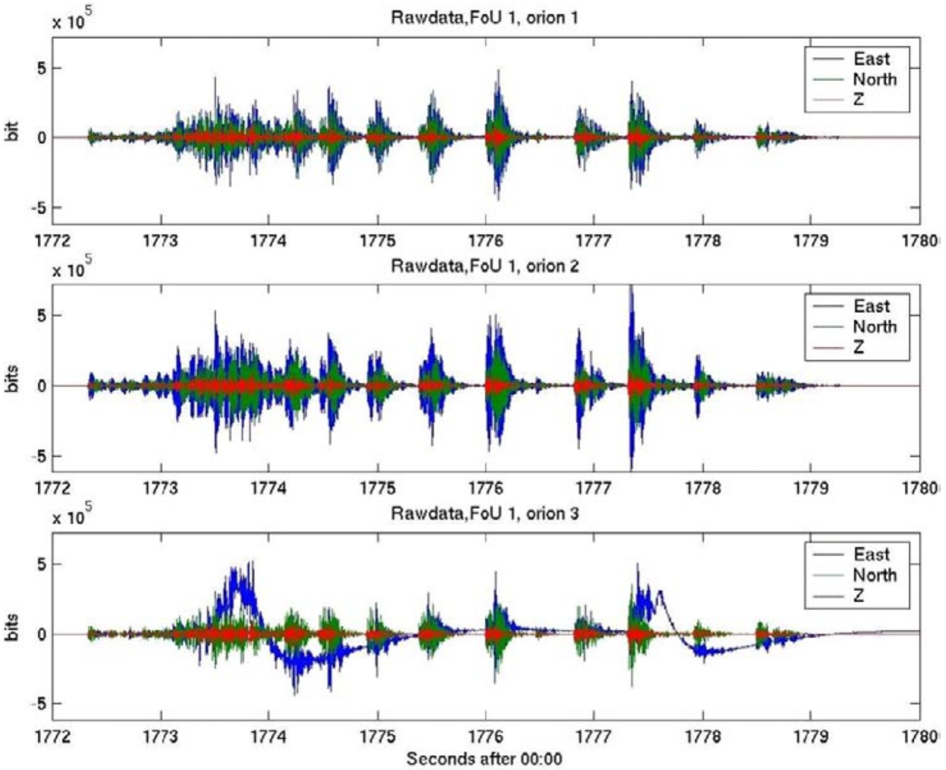

Figure 4-21. *Raw particle velocity data from top heading round 32.*

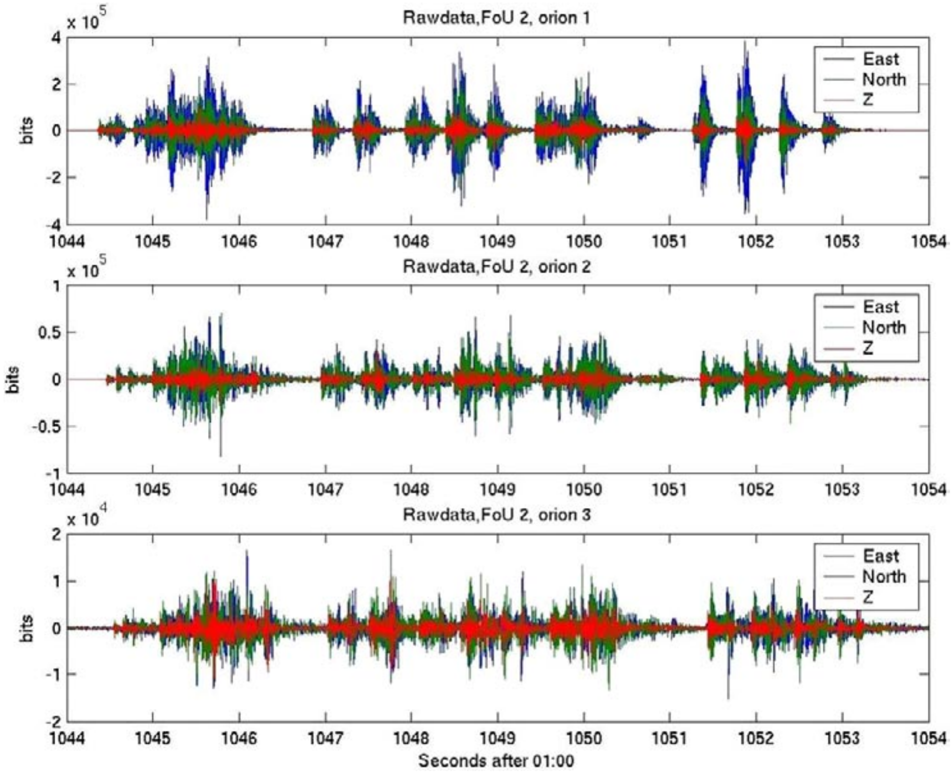

Figure 4-22. *Raw particle velocity data from top heading round 33.*

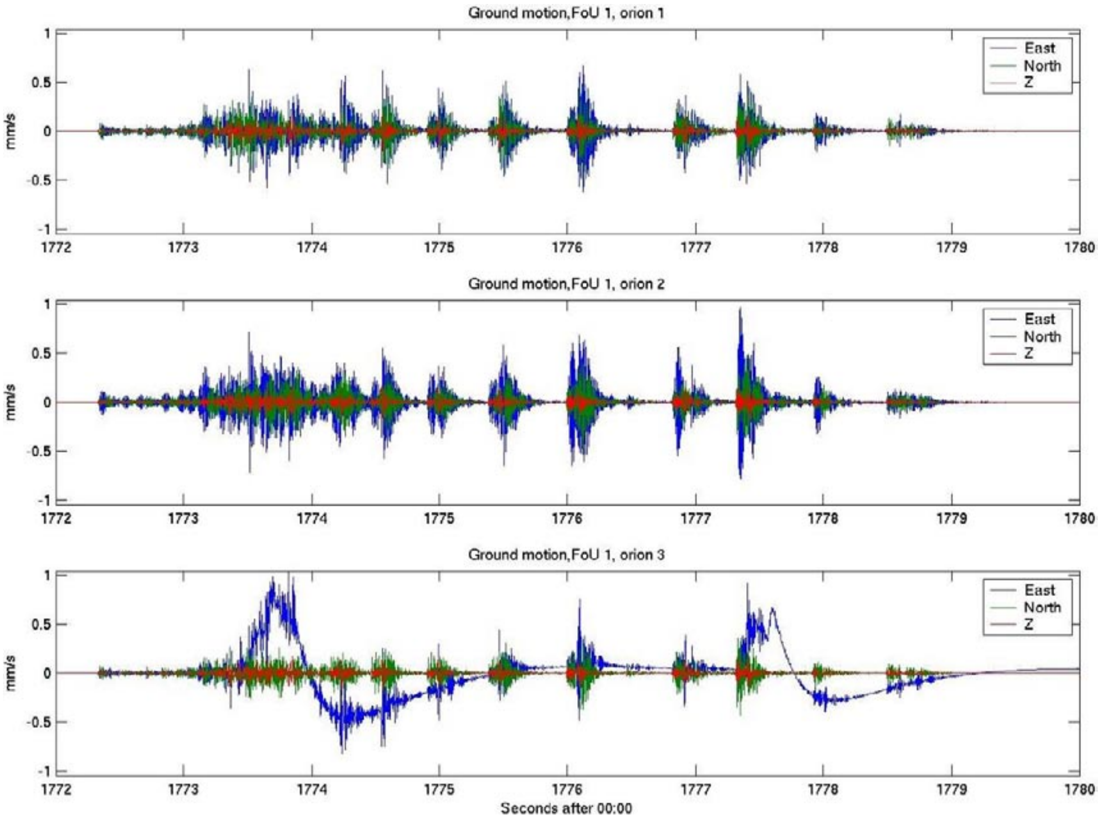

Figure 4-23. *Ground particle velocity data from top heading round 32.*

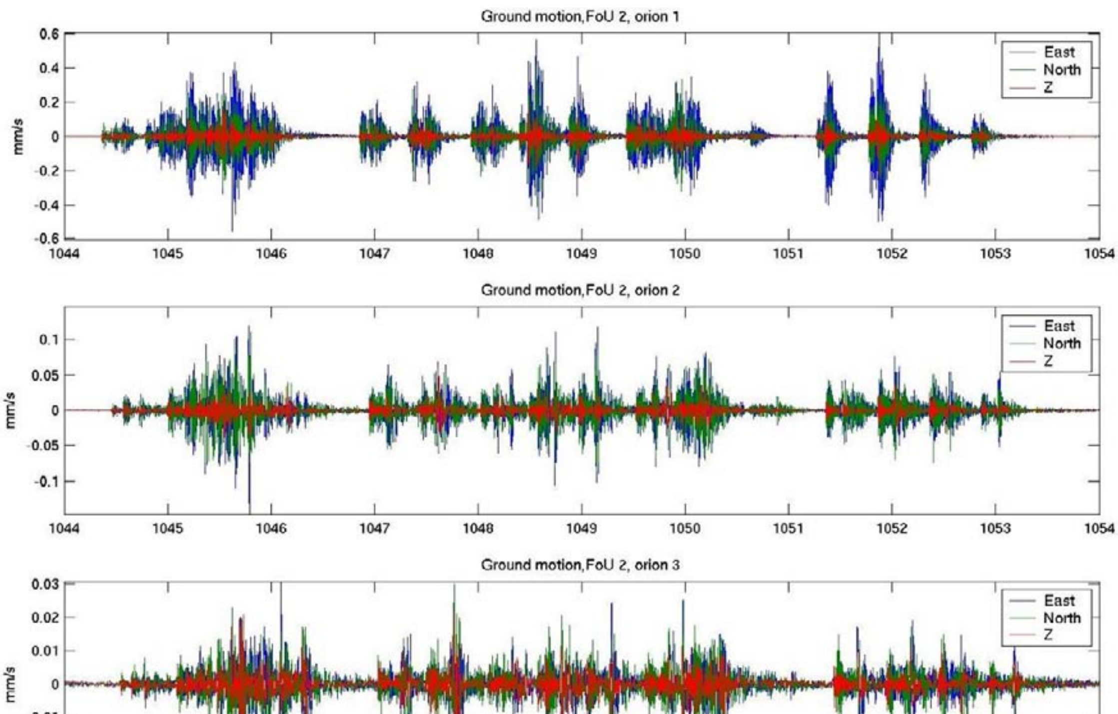

Figure 4-24. *Ground particle velocity data from top heading round 33.*

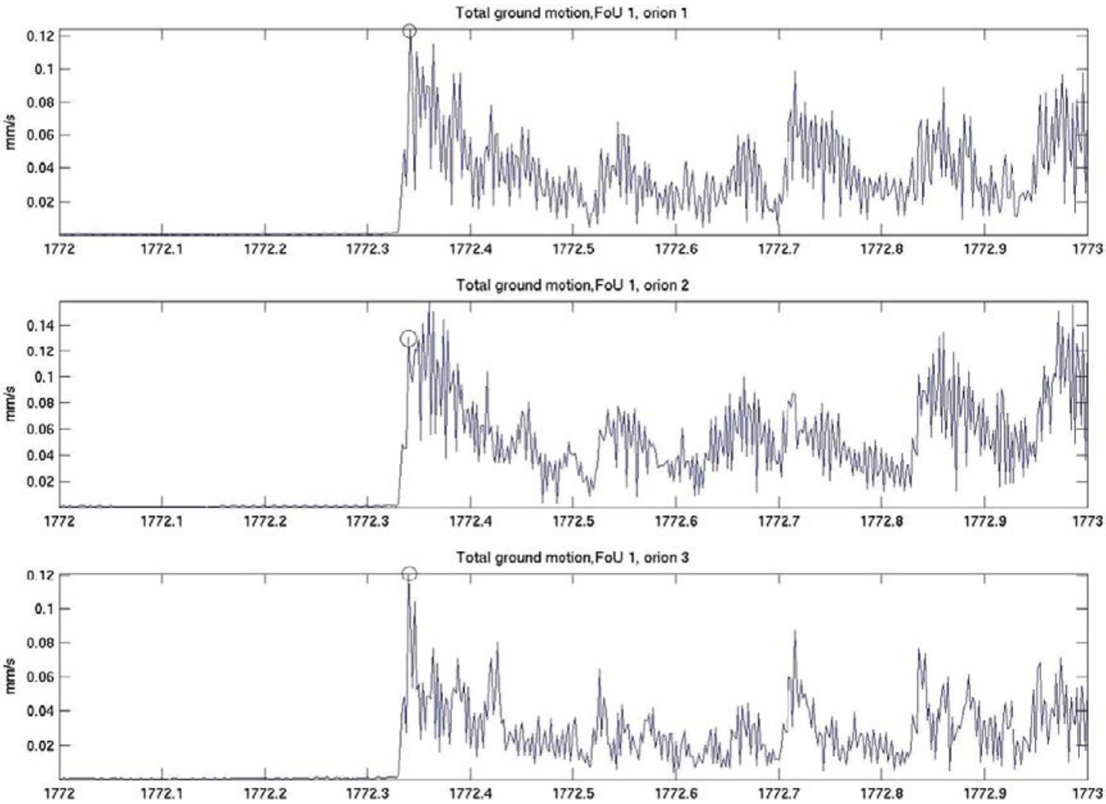

Figure 4-25. *Total particle velocity for top heading round 32. The circles enclose picked amplitude.*

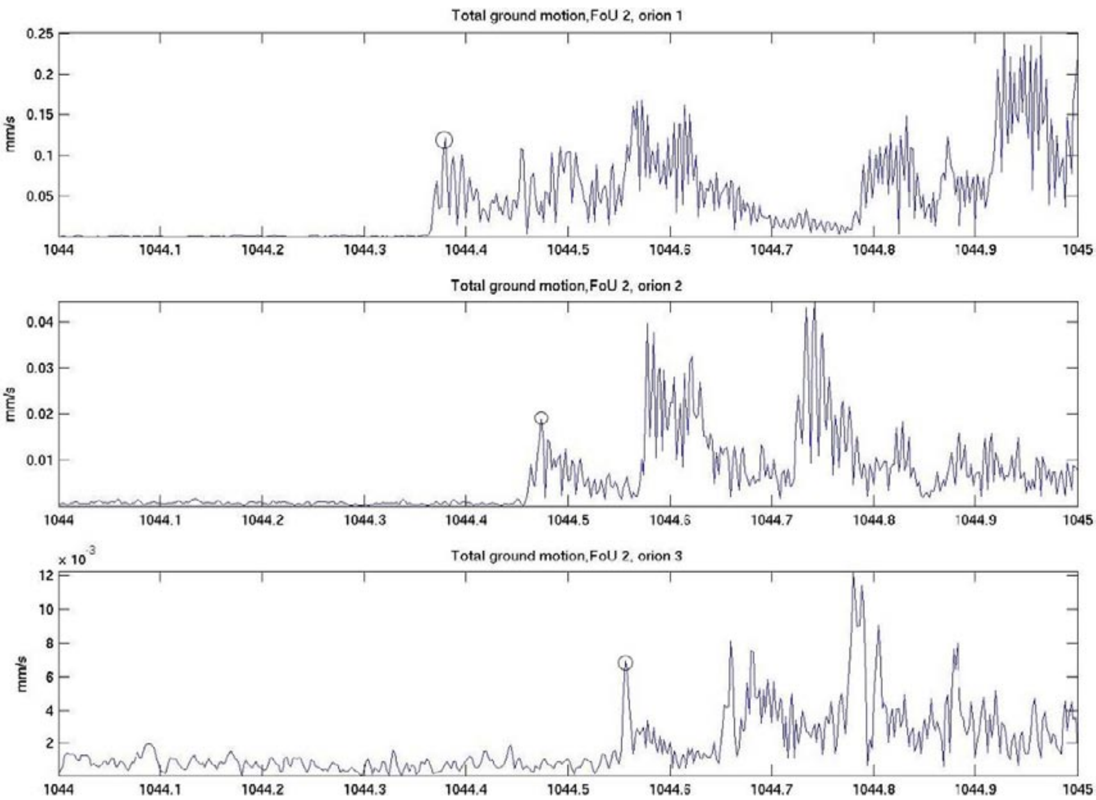

Figure 4-26. *Total particle velocity for the top heading round 33. Picked amplitudes are enclosed by a circle.*

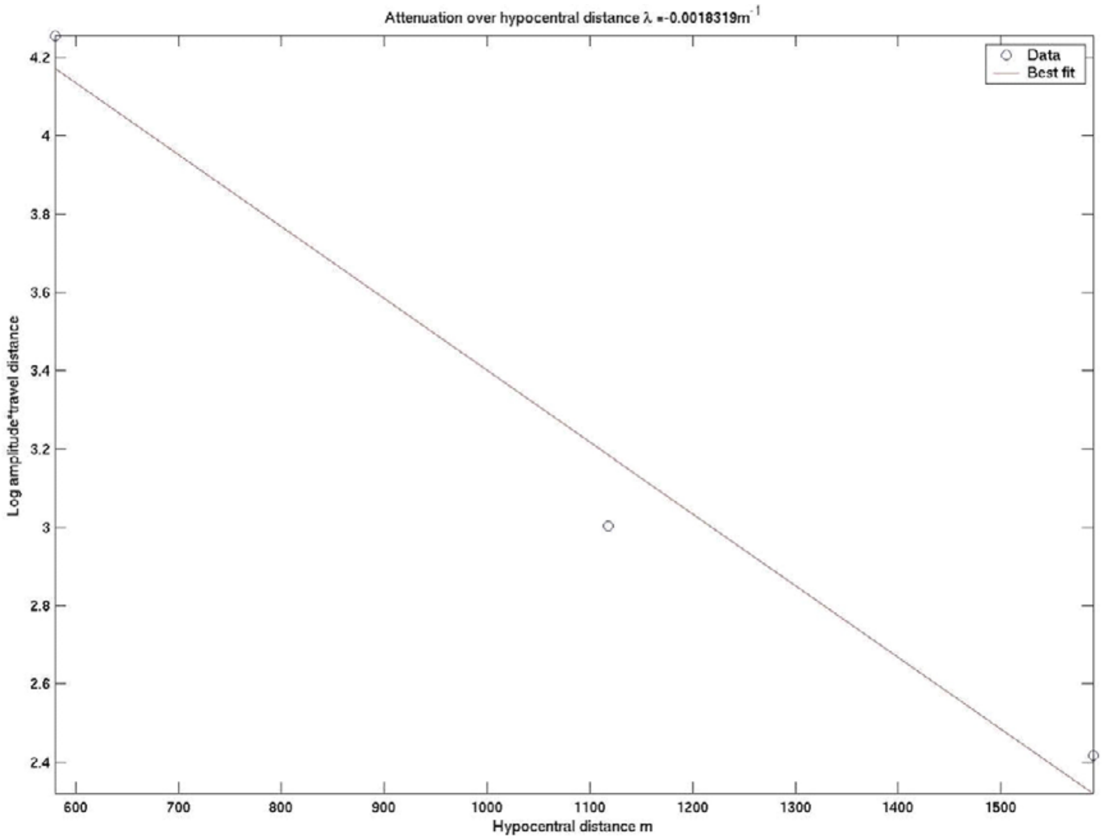

Figure 4-27. *Estimation of the attenuation as a function of distance.*

Table 4-4. Amplitude and correction factor for top heading round 32 recordings.

Station	Amplitude (mm/s)	Correction factor
Orion 1	0.1239	1
Orion 2	0.1306	0.9487
Orion 3	0.1211	1.0233

Assuming a simple homogenous model with an elastic media we can express the amplitude decay of the ground motion of the signal as the product of the geometrical spreading of the wave front and attenuation due to the in-elasticity of rock. The amplitude, A, in Equation 4-6 is described as,

$$A = A_0/r \cdot e^{-\lambda \cdot r} \qquad \text{(Eq. 4-6)}$$

with A_0 as the initial amplitude, r as the wave travel distance and λ as the attenuation coefficient. Rearranging Equation 4-6 yields an expression for the attenuation, Equation 4-7.

$$\lambda = ln(A_r / A_0)/r \qquad \text{(Eq. 4-7)}$$

Table 4-5. Corrected peak amplitude for top heading round 33 recordings.

Station	Corrected amplitude (mm/s)	Hypo centric distance [m]
Orion 1	0.1217	579.5
Orion 2	0.0180	1,118.1
Orion 3	0.0071	1,589.5

The calculated attenuation (Eq. 4-7) from the measurements of this experiment is $\lambda \approx 0.0018 m^{-1}$. Every c. 550 m the shock wave travels it will have lost half its amplitude due to attenuation. However, the signal will also loose amplitude due to geometrical spreading of the wave front.

4.3.3 Wave velocity

The wave velocity was calculated for the rock mass between the rounds and the seismic stations Orion 1, 2 and 3 above ground. The velocity was calculated to 5,715.4 ± 3.7 m/s from a least square solution for the seismic velocity and blast. The small data scatter indicates that the geological zones between Orion 1 and 2 in Figure 3-10 have no effect on the measured velocity.

5 Discussions and conclusions

In this project, 34 top heading rounds and 12 bench rounds were blasted. The top headings rounds were blasted first with short (1.5 m) blast hole length. After 10 rounds the blast holes were drilled about 4 m long, which became normal for the driving. Exceptions were rounds 25, 26 and 27 with 2.3–2.4 m hole length. Rounds 15, 16 and 21 were partly misfired. The bench rounds were made with 4.4–4.6 m blast holes with 3 exceptions namely bench round no 39, 45 and 46. During the blasting, data were collected through:

– Accelerometers at distances 14–28 m for rounds 32–34.
– Standard geophones in the range 10–600 m for all rounds.
– Seismograph in the range 600–1,600 m for round 32 and 33.

5.1 Restrictions on vibrations

5.1.1 Installations

The maximum measured vibration level at the firewall was 49 mm/s meanwhile the maximum allowed velocity was 50 mm/s. The upper limit at the transformer was reached only once during the hole blasting operation and no damage was found afterwards.

The blast vibrations were noisy or disturbed at the elevator –340 m, at tunnel Section 2/790.4 and at the transformer –450 m due to a bad gauge or to a bad transformer foundation coupling to the ground. Moisture in the electronic equipment may also have had some negative influences on the measurements.

5.1.2 Environmental impact of blasting

According to the Swedish standard SS 460 48 61 particle velocities in the range 0.4–1.0 mm/s will give moderate environmental disturbances and velocities over 1.0 mm/s will probably cause disturbance. The vibrations from the rounds had decayed to about 1 mm/s at 300 m away. Thus, moderate disturbances will very unlikely occur above ground.

Over a distance of 350 m, the mean PPV will decrease about 100 times or vibrations of 30 mm/s will drop to about 0.3 mm/s.

At distances of 600–1,600 m the vibration amplitudes are almost constant 0.18–0.16 mm/s or about a factor of 5 below the level for moderate disturbance.

There is a large amount of scatter in these data and in practice some maximum allowed vibration amplitude must be determined, for example using an upper 95% (≈+2 σ) confidence line instead of a least square fit line. The statistics say that a 95% prediction interval spans a given mean PPV times a factor of 1/5 to 5. Thus a predicted value of 3 mm/s will span from 0.6 to 15 mm/s. The conclusions are:

– Small impact from blasting above ground 450 m away from the blasting.
– Due to the scatter in PPV, a confidence factor of 5 should be added to the mean.

Note that blasting with heavier charges will increase the average PPV.

5.2 Standard geophone measurements

5.2.1 Vibrations due to blasting- and recording techniqe

The amplitude-distance dependence has been estimated in terms of the site constants A and β in the standard scaling law. The law assumes that the PPV is dependent on the maximum co-operating charge weight q_m (kg/hole). But the law does not account for pyrotechnic detonators scattering about the nominal time, nor for the total number of blast holes in the rounds or for the overlapping waveforms. This biases the results to some extent.

Conclusions of least square fitting of the standard scaling law are:

– A representative set of scaling parameters for the blasting operation are A=813 mm/s and slope or damping parameters β=1.53. Se reference data in Table 4-1.

– Rounds with maximum 92 blast holes generate lower PPV than the full blast rounds with 100–138 blast holes, especially close to the blast. Se Figure 4-6.

– Rounds with 100–138 blast holes generate significantly higher intercept A and steeper slope -β compared to the reference. Se full blast rounds in Table 4-1.

– A correction of the q_m value slightly increased the coefficient of determination r^2.

– Test rounds and misfire rounds (12% of the total data set) seem to have no effect on the PPV. Se regular rounds in Table 4-1.

– The comparison of the parameters for the bench rounds with the parameters for the top heading rounds shows no difference. Se top heading and bench 25–181 m in Table 4-1.This may indicate that the damaged zone from the top heading rounds did not affect the PPV from the bench rounds.

– Not that the coefficient of determination r^2 are typically 0.84 for the top heading rounds and 0.63 for the bench rounds.

5.2.2 Effect of water in rock structures on vibrations

A selected data set from the bench blasting round was used to evaluate if rock structures had some effect on the PPV. It is known that decoupled charges (in this case Ø17 and Ø22 mm explosives in Ø48 mm holes) has a lower blast hole pressure than if the charges are fully coupled to the rock /Nie 1999/ and that water in the blast hole free volumes acts as a strong coupling medium (Svenneby granite quarry /Ouchterlony et al. 1999/). We have found that:

– The increasing PPV for the bench rounds 36–38 (43–52 m) may be related to an increasing charge coupling due to the inflow of water from natural fractures.

– The PPV-drop at the bench rounds 39–45 correlates well with the decreasing amount of explosive in the production and with the decreasing water inflow at 52–57 m for bench round 39.

– The conclusion should be that the increasing PPV for round 36–38 can be related to the increasing inflow of water but the drop at round 39–45 can be related both to the decreasing inflow and the decreased amount of explosives for the production holes.

5.3 Velocities and attenuation in the Äspö rock mass

The wave velocities were measured along the tunnel over a 10 m distance and at long distances 0–1,600 m from the rounds.

5.3.1 Velocity in the vicinity of the tunnel

The wave velocity V_p and standard deviation σ along the tunnel wall for round 33 and 34 were calculated to:

V_{p33} =6,094 m/s with σ_{33} = 238 m/s and to

V_{p34} =5,962 m/s with σ_{34} = 131 m/s.

These values agree well with the:

- Measurements across and 6 m below the TASQ tunnel (V_p= 6,050 m/s) /Pettitt et al. 2003/ which indicate that the rock mass may be isotropic.
- The average velocity from tomography in the ZEDEX-project between the D&B tunnel and the TBM tunnel (6,060 m/s ± 100 m/s).
- Downhole measurements in the ZEDEX-project (5,800–6,300 m/s).

5.3.2 Velocity on the site scale

The velocities between the rounds and the seismic stations Orion 1, 2 and 3 above ground is slightly lower (5,715.4 ± 3.7 m/s) than the velocities in the vicinity of the tunnel. No velocity anomaly was found due to geological zones between Orion 1 and 2

5.3.3 Attenuation

The rock attenuations λ_l in the near field and λ in the far field were calculated with help of the standard exponential Equations 4-4 and 4-6.

In the near field three components acceleration data were recorded along the tunnel wall 14–28 m from the blasts. The data at the two stations were integrated to obtain peak velocities. The rock mean attenuation is relatively high, λ_l= 0.044 m^{-1}. This may be explained by the relatively high wave frequencies in the near field.

The far field three components data were recorded above ground at three seismic stations. The distances to the blast varied at the range 600–1,600 m. The attenuation was calculated to $\lambda \approx 0.0018\ m^{-1}$ i.e. a factor of 25 lower than for the near field measurements.

5.4 Blast function control

A function control of the blasting sequences for rounds 32–34 was made along the tunnel wall at distances of 14–28 m. Electronic detonators with an "exact initiation time" were used in combination with standard pyrotechnic caps.

The conclusion is that the programmed initiation time intervals for the electronic caps agree well with the monitored time intervals along the tunnel wall. This shows that:

- The electronic caps in general worked well. However, two caps were found without having detonated after blast for rounds 32 and 33.

5.5 Vibration control as an indicator of the EDZ

This section will point out some of the limitations of calculations of an "Excavated Damage Zone EDZ" from PPV values.

In general when a body of rock is stressed, grains are displaced and the rock is deformed. Hookes law relates stress to strain for elastic deformation. If the stress increases above elastic limit the rock will yield or fracture, i.e crack.

A simple vibration scaling law like the one in Equation 4-1 is sometimes used for estimation of rock damage from PPV data. The law is combined with a criterion saying that the cracks around a blast holes is related to a critical value PPV_c i.e. if the $PPV \geq PPV_c$ the rock will be damaged within the critical radius $R_c \geq R$ from the blast hole. Some limitations of this metod are:

– Strain can be related to PPV only under 1 D conditions i.e. only if PPV is measured in the same direction as the wave propagates and for less than 1/3 wave period if the rock is in rest just before the vibrations arrive /Barnhart and Skalare 1981/. Our measurements fail in this respect.

– The scaling law approach assumes that the amount of explosives that generates the vibrations is the maximum co-operating charge.

– In our test, the PPV seems to be dependent on the total number of blast holes in the top heading rounds and therefore the simple law can't be used.

– /Blair and Minchinton 1997/ has shown by using analytical modelling and Dynamic Finite Element Modelling (DFEM) that it is "invalid to assume any simple relation between vibration and strain for waves radiating from blast holes…"

– The law doesn't account for water in blast holes, instantaneous initiation of charges in adjacent holes and rock conditions.

– In the three last top heading rounds the contour holes aimed for testing of the damage zone model were initiated instantaneously. This has been proven to generate less damage compared to the standard contour initiation /Olsson and Bergqvist 1997/.

– /Ouchterlony et al. 2002/ give an overview of the limitations in calculating the damage zone around blast holes and suggest recommendations for cautious perimeter blasting.

This section clearly shows that the PPV monitored in this test should be used with great caution when trying to predict the extent of the EDZ.

6 References

Aki K, Richards P G, 1980. Quantitative seismology, theory and methods, W. H. Freeman, San Francisco, USA.

Andersson A, 2003. Aspö Pillar Stability Experiment. Summary of preparatory work and predictive modelling. SKB R-03-02, Svensk Kärnbränslehantering AB.

Barton N, 2003. Äspö HRL. Äspö pillar stability experiment. Q-logging of the TASQ tunnel at Äspö. SKB IPR-04-07, 148–, Svensk Kärnbränslehantering AB.

Bjarnholt G, Skalare H, 1981. Instrumenterad bergsprängning – inledande försök i betongblock. SveDeFo-rapport DS 1981:16, Stockholm.

Blair D P, 1990. Some Problems Associated with Standard Charge Weight Vibrations Scaling Laws, The Third Int. Sym. On Rock Fragmentation by Blasting, Brisbane.

Blair D P, Minchinton A, 1997. On the damage zone surrounding a single blasthole, Int. Journal for Blasting and Fragmentation, Vol. 1 No. 1, pp 59–72.

Bödvarsson R, Rögnvaldsson S. Th, Slunga R, Kjartansson E, 1999. Physics of The Earth and Planetary Interiors, Volume 113, Issue 1–4, Pages 89–101.

Emmelin A, Eriksson M, Fransson Å, 2004. Characterisation, design and execution of two grouting fans at 450 m level, Äspö HRL. SKB R-04-58, Svensk Kärnbränslehantering AB.

Hansen L M, Hermanson J, 2002. Äspö HRL. Local model of Geological Structure close to the F-tunnel. SKB IPR-02-48, Svensk Kärnsbränslehantering AB.

Jansson T, Stigsson M, 2002. Test with different stress measurement methods in two orthogonal bore holes in Äspö HRL. SKB R-02-26, Svensk Kärnbränslehantering AB.

Lama R D, Vutukuri S, 1978. Mechanical properties of rocks, Vol. 2, Trans Tech Publications Clauthal, Germany.

Lennartz, 1990. Reliable measurements. le3d/5s documentation, rev. 1.2. Lennartz electronic GmbH.

Nie S, 1999. Borehole Pressure in Blast Holes, Measurements in granite blocks versus estimations, SveBeFo report 42, Stockholm, Sweden.

Nyberg U, Fjellborg S, 2000. Controlled drifting and estimation of blast damage, 1st World Conference on Explosives & Blasting Technique, 207–216, Balkema, Rotterdam.

Nyberg U, Nilsson B, Tenum A, Carlsson T, 2001. Stötvågsprovning av granitblock, Försöksrapport, Mätteknik och Optik, Institutionen för Industriell Produktion, KTH, Stockholm, Sweden.

Olsson M, Reidarman L, 1995. Crack test from blasting at Äspö. Äspö Hard Rock Laboratory technical note. TN-96-01z.

Olsson O, Emsley S, Bauer C, Falls F, Stenberg L, 1996–03. ZEDEX – A study of the zone of excavation disturbance for blasted and bored tunnels, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Olsson M, Bergqvist I, 1997. Sprickutbredning vid flerhålssprängning. Sammanfattande rapport av försöksperioden 1993–96, SveBeFo Rapport 32, Stockholm.

Olsson M, Ouchterlony F, 2003. New formula for blast induced damage in the remaining rock. SvBeFo report No. 65 (In Swedish).

Olsson M, Niklasson B, Wilson L, Andersson C, Christiansson R, 2004. Experiences of blasting of the TASQ tunnel. SKB R-04-73, Svensk Kärnbränslehantering AB.

Ouchterlony F, 1992. Some Recent Research and Developments in Swedish Tunnel Blasting, SveDeFo Report DS 1992:1, Stockholm, Sweden.

Ouchterlony F, Olsson M, Båvik S-O, 1999. Bench blasting round in Granite With Axial Notches and Radial Bottom Slots In: Proc. Sixth Int. Sym. For Rock Fragmentation and Blasting, South African Inst. Min. and Metallurgy, Johannesburg, pp. 229–239.

Ouchterlony F, Olsson M, Bergqvist I, 2002. Towards New Swedish Recommendations for Cautious Perimeter Blasting, Int. Journal for Blasting and Fragmentation, Vol. 6, No. 2, pp. 235–261.

Ouchterlony F, Nyberg U, Olsson M, Bergqvist I, Granlund L, Grind H, 2003. The energy balance of production blasts at Nordkalk's Klinthagen quarry. *Proc. 2nd World Conf. on Explosives & Blasting:* 193–203. Rotterdam: Balkema.

Pettitt W S, Collins D S, Haycox J, Young R P, 2003. Borehole Velocity Profile Survey in the APSE Tunnel between boreholes KQ0064G03 and KQ0064G02. SKB APSE02, Svensk Kärnbränslehantering AB.

Reidarman L, Nyberg U, 2000. Vibrationer bakom front vid tunneldrivning i södra länken – betydelse för nysprutad betong? SveBeFo-rapport 51, Stockholm, Sweden.

Rhén I, Gustavsson G, Stanfors R, Wikberg P, 1997. Äspö HRl – Geoscientific evaluation 1997/5. Models based on site characterisation 1986–1995. SKB TR 97-06, Svensk Kärnbränslehantering AB.

SKB, 2004. Preliminary site description. Simpevarp area version 1.1 SKB R-04-25, Svensk Kärnbränslehantering AB.

Staub I, Andersson C, Magnor B, 2004. Äspö Pillar Stability Experiment. Geology and mechanical properties. Of the rock in the TASQ. SKB R-04-01, Svensk Kärnbränslehantering AB.

Wikman H, Kornfält K-A, 1995. Updating of a lithological model of the bedrock of the Äspö area. SKB PR-25-95-04, Svensk Kärnbränslehantering AB.

Winberg A, Andersson P, Byegård J, Poteri A, Chetkovic V, Dershovittz W, Doe T, Hermanson J, Gomez-Hernandez JJ, Hautojärvi A, Billaux D, Tullborg EL, Holton D, Meier P, Medina A, 2002. Final report of the TRUE Block Scale project. SKB TR-02-16, Svensk Kärnbränslehantering AB.

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Appendix 1

Technical specifications

Geophone measurements Ava 95

Data storage: Unlimited when the measuring unit is connected to Bergsäker AB's AvaNet or AvaNet XT by GSM, Modem, Radio or Wire (Directly connected by modem cable)

Reporting: To AvaNet/AvaNet XT software on Internet

User interface: Keyboard whit 4 buttons and at two rows LCD display

Sampling rate: 3,000 Hz on each channel

Frequency range: 0.3–350 Hz (–3 db)

Self test: Once a day

Temperature range: –20 to + 40 ºC

Measuring tolerance: + –1%

Geophones

Standard geophones (used underground in the tunnel systems)

Range: 0–273 mm/s (normal range), 0–27.3 (low range = x 10)

Resolution: 0.135 mm/s (normal range), 0.0135 (low range = x 10)

Frequency range: 5–1,000 Hz

Low frequency geophones (used on the surface)

Range: 0–273 mm/s (normal range), 0–27.3 (low range = x 10)

Resolution: 0.135 mm/s (normal range), 0.0135 (low range = x 10)

Frequency range: 1–1,000 Hz

Measuring tolerance for both types of geophones: + –3%

Acceleration measurements

Recorder

Type: High-speed digital data recorder SIR 1000 from SONY

Bandwidth: DC-20 KHz

Dynamic range: 80 dB

Sampling rate: 48,000 Hz

Sampling frequency: 2.4 times the bandwidth

Accelerometers

Type: 8704B5000

Acceleration Range: g ±5,000

Acceleration Limit: $g$pk ±10,000

Sensitivity (±5%): mV/g 1

Resonant Frequency nom., mounted: kHz 54

Frequency Response ± 5%: Hz 1 ...10,000

Transverse Sensitivity typ. (max.) %: 1.5 (3)

Appendix 2

Blasting positions and charge weights

The vibrations were generated at positions shown in Table A2-1 and Table A2-2 for top heading rounds (blast 1–34) and bench rounds (blast 34–46).

Table A2-1. Top heading rounds with position and cooperating charge.

Name	Time	Section	Pos. X	Pos. Y	Pos. Z	co. charge
Blast 01	2003-04-15 22:38	10.3 m	7282.21194	2088.03217	-449.45105	0.39 kg
Blast 02	2003-04-15 23:46	10.3 m	7282.21194	2088.03217	-449.45105	0.75 kg
Blast 03	2003-04-22 22:44	10.3 m	7282.21194	2088.03217	-449.45105	1.11 kg
Blast 04	2003-04-24 00:44	10.3 m	7282.21194	2088.03217	-449.45105	1.11 kg
Blast 05	2003-04-27 18:35	12 m	7283.39286	2089.25505	-449.40997	1.31 kg
Blast 06	2003-04-29 00:01	12 m	7283.39286	2089.25505	-449.40997	0.82 kg
Blast 07	2003-04-29 23:22	12 m	7283.39286	2089.25505	-449.40997	1.19 kg
Blast 08	2003-05-05 22:09	12 m	7283.39286	2089.25505	-449.40997	2.11 kg
Blast 09	2003-05-07 00:26	14 m	7284.78217	2090.69372	-449.36163	2.57 kg
Blast 10	2003-05-07 23:47	14 m	7284.78217	2090.69372	-449.36163	2.8 kg
Blast 11	2003-05-08 22:41	14 m	7284.78217	2090.69372	-449.36163	2.05 kg
Blast 12	2003-05-10 18:48	16 m	7286.17148	2092.13240	-449.31329	2.94 kg
Blast 13	2003-05-11 22:29	16 m	7286.17148	2092.13240	-449.31329	2.94 kg
Blast 14	2003-05-13 02:02	20 m	7288.95010	2095.00975	-449.21661	2.8 kg
Blast 15	2003-05-14 01:42	23 m	7291.03407	2097.16776	-449.14411	3.3 kg
Blast 16	2003-05-14 21:33	23 m	7291.03407	2097.16776	-449.14411	3.3 kg
Blast 17	2003-05-19 22:46	23 m	7291.03407	2097.16776	-449.14411	2.9 kg
Blast 18	2003-05-21 00:37	27 m	7293.81269	2100.04512	-449.04743	2.9 kg
Blast 19	2003-05-22 01:23	30 m	7295.89665	2102.20313	-448.97492	1.29 kg
Blast 20	2003-05-23 19:13	34 m	7298.67527	2105.08048	-448.87825	2.94 kg
Blast 21	2003-05-24 19:28	37 m	7300.75924	2107.23849	-448.80574	3.3 kg
Blast 22	2003-05-25 11:40	37 m	7300.75924	2107.23849	-448.80574	4 kg
Blast 23	2003-05-25 23:55	41 m	7303.53786	2110.11584	-448.70906	3.7 kg
Blast 24	2003-05-27 01:56	46 m	7307.01114	2113.71253	-448.58822	3.7 kg
Blast 25	2003-06-15 23:56	50 m	7309.78976	2116.58988	-448.49154	1.84 kg
Blast 26	2003-06-16 22:57	52 m	7311.17907	2118.02856	-448.44320	1.84 kg
Blast 27	2003-06-17 21:59	54 m	7312.56838	2119.46724	-448.39486	1.84 kg
Blast 28	2003-06-24 02:20	54 m	7312.56838	2119.46724	-448.39486	1.84 kg
Blast 29	2003-06-24 02:52	56 m	7313.95769	2120.90591	-448.34652	1.84 kg
Blast 30	2003-06-28 21:14	60 m	7316.73631	2123.78326	-448.24985	1.84 kg
Blast 31	2003-06-29 22:23	64 m	7319.51493	2126.66061	-448.15317	3.63 kg
Blast 32	2003-07-01 00:29	69 m	7322.98821	2130.25730	-448.03233	4.1 kg
Blast 33	2003-07-02 01:17	74 m	7326.46148	2133.85399	-447.91148	4.34 kg
Blast 34	2003-07-02 20:37	78 m	7329.24010	2136.73134	-447.81480	4.34 kg

Table A2-2. Bench rounds with position and cooperating charge.

Name	Time	Section	Pos. X	Pos. Y	Pos. Z	co. charge
Blast 35	2003-07-11 20:00	37 m	7300.75924	2107.2384	-448.8057	1.47 kg
Blast 36	2003-07-12 10:24	41 m	7303.53786	2110.1158	-448.7090	1.81 kg
Blast 37	2003-07-12 16:07	45 m	7306.31648	2112.9932	-448.6123	1.81 kg
Blast 38	2003-07-13 11:08	50 m	7309.78976	2116.5898	-448.4915	1.81 kg
Blast 39	2003-07-13 20:02	55 m	7313.26303	2120.1865	-448.3706	1.62 kg
Blast 40	2003-07-14 16:10	59 m	7316.04165	2123.0639	-448.2740	1.81 kg
Blast 41	2003-07-14 21:27	64 m	7319.51493	2126.6606	-448.1531	1.81 kg
Blast 42	2003-07-15 11:45	64 m	7319.51493	2126.6606	-448.1531	1.81 kg
Blast 43	2003-07-15 16:29	68 m	7322.29355	2129.5379	-448.0565	1.81 kg
Blast 44	2003-07-15 21:42	73 m	7325.76683	2133.1346	-447.9356	1.81 kg
Blast 45	2003-07-16 15:13	77 m	7328.54545	2136.0120	-447.8389	1.62 kg
Blast 46	2003-07-17 07:22	77 m	7328.54545	2136.0120	-447.843	0.44 kg

Results from vibration measurements

Test blasts no 1–4

Blasts no 1 to 4 were testing rounds with 1.5 metres drill depth with really small charges (0.39–1.11 kg). According to the risk assessment, “Riskbedömning samt rekommendationer för sprängarbeten vid utbyggnad av nya tunnlar inom –450 m nivån, Äspö HRL, Metron Mätteknik AB”, the recommendation was to use maximum 1 kg of explosives in the test blasts. Figures A3-1 and A3-2 show the test blast design.

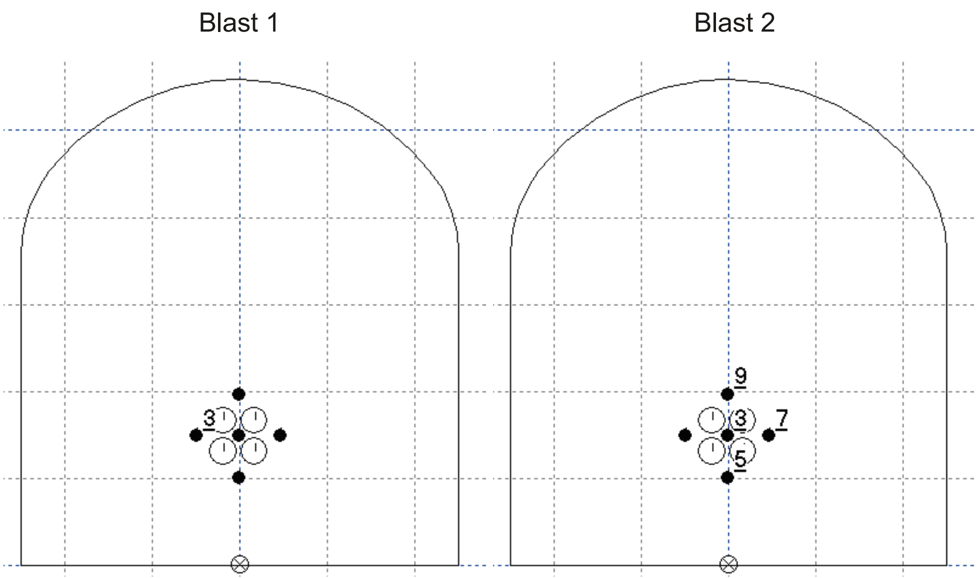

Figure A3-1. *Test blast layout.*

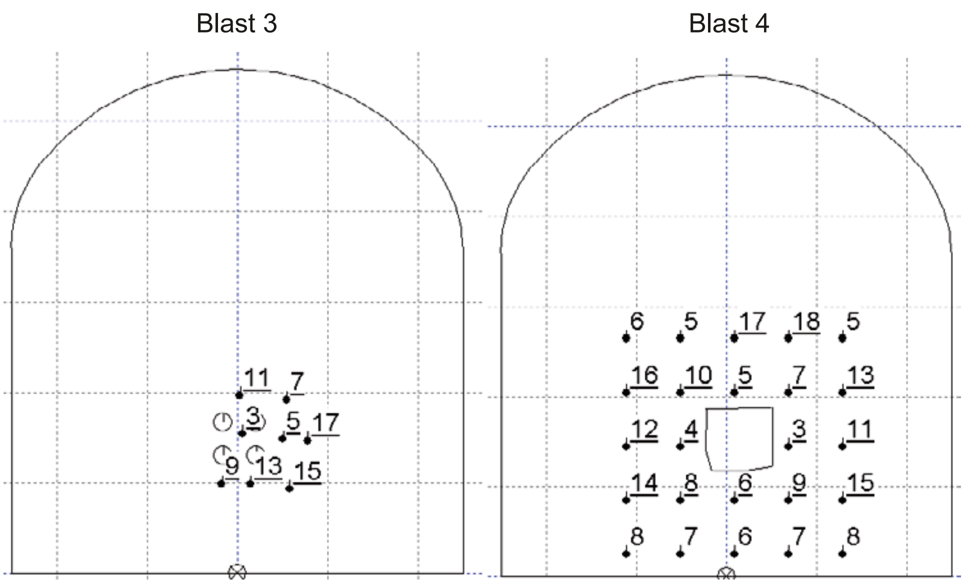

Figure A3-2. *Test blast layout.*

Table A3-1. PPV-values for top heading rounds 1–4.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 01	2003-04-15 22:38	PA2201A01	Tunnel A 2/201,5	280 m	0.03 mm/s	
Blast 01	2003-04-15 22:38	PA3064A01	Tunnel A 3/064,1 LTDE	306 m	0.04 mm/s	
Blast 01	2003-04-15 22:38	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	8.3 mm/s	
Blast 01	2003-04-15 22:38	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	4.3 m/s2	30 m/s2
Blast 01	2003-04-15 22:38	PA3390B01	Tunnel A 3/390,8 Elevator -450	16 m	0.1 mm/s	50 mm/s
Blast 02	2003-04-15 23:46	PA2201A01	Tunnel A 2/201,5	280 m	0.04 mm/s	
Blast 02	2003-04-15 23:46	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	16.4 mm/s	
Blast 02	2003-04-15 23:46	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	8.3 m/s2	30 m/s2
Blast 02	2003-04-15 23:46	PA3390B01	Tunnel A 3/390,8 Elevator -450	16 m	0.4 mm/s	50 mm/s
Blast 03	2003-04-22 22:44	PA1685B01	Tunnel A 1/685,2 Elevator - 220 KBS Bl.c.	226 m	0.08 mm/s	
Blast 03	2003-04-22 22:44	PA2201A01	Tunnel A 2/201,5	280 m	0.05 mm/s	
Blast 03	2003-04-22 22:44	PA3064A01	Tunnel A 3/064,1 LTDE	306 m	0.07 mm/s	
Blast 03	2003-04-22 22:44	PA3064A01	Tunnel A 3/064,1 LTDE	306 m	0.07 mm/s	
Blast 03	2003-04-22 22:44	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	15.6 mm/s	
Blast 03	2003-04-22 22:44	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	7.9 m/s2	30 m/s2
Blast 03	2003-04-22 22:44	PA3390B01	Tunnel A 3/390,8 Elevator -450	16 m	1.6 mm/s	50 mm/s
Blast 04	2003-04-24 00:44	PA1685B01	Tunnel A 1/685,2 Elevator - 220 KBS Bl.c.	226 m	0.15 mm/s	
Blast 04	2003-04-24 00:44	PA2201A01	Tunnel A 2/201,5	280 m	0.09 mm/s	
Blast 04	2003-04-24 00:44	PA3064A01	Tunnel A 3/064,1 LTDE	306 m	0.08 mm/s	
Blast 04	2003-04-24 00:44	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	35.0 mm/s	
Blast 04	2003-04-24 00:44	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	15.0 m/s2	30 m/s2
Blast 04	2003-04-24 00:44	PA3390B01	Tunnel A 3/390,8 Elevator -450	16 m	3.3 mm/s	50 mm/s

Tunnelling blasts no 5–34

Table A3-2. PPV-values for top heading rounds 5–10.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 05	2003-04-27 18:35	PA2201A01	Tunnel A 2/201,5	280 m	0.04 mm/s	
Blast 05	2003-04-27 18:35	PA3064A01	Tunnel A 3/064,1 LTDE	304 m	0.04 mm/s	
Blast 05	2003-04-27 18:35	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	5.4 mm/s	
Blast 05	2003-04-27 18:35	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	3.3 m/s2	30 m/s2
Blast 05	2003-04-27 18:35	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	12.1 mm/s	50 mm/s
Blast 05	2003-04-27 18:35	PA3390B01	Tunnel A 3/390,8 Elevator -450	17 m	2.8 mm/s	50 mm/s
Blast 06	2003-04-29 00:01	PA2201A01	Tunnel A 2/201,5	280 m	0.09 mm/s	
Blast 06	2003-04-29 00:01	PA3064A01	Tunnel A 3/064,1 LTDE	304 m	0.04 mm/s	
Blast 06	2003-04-29 00:01	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	8.8 mm/s	
Blast 06	2003-04-29 00:01	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	3.1 m/s2	30 m/s2
Blast 06	2003-04-29 00:01	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	11.4 mm/s	50 mm/s
Blast 06	2003-04-29 00:01	PA3390B01	Tunnel A 3/390,8 Elevator -450	17 m	1.9 mm/s	50 mm/s
Blast 07	2003-04-29 23:22	PA2201A01	Tunnel A 2/201,5	280 m	0.16 mm/s	
Blast 07	2003-04-29 23:22	PA3064A01	Tunnel A 3/064,1 LTDE	304 m	0.05 mm/s	
Blast 07	2003-04-29 23:22	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	25.0 mm/s	
Blast 07	2003-04-29 23:22	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	9.2 m/s2	30 m/s2
Blast 07	2003-04-29 23:22	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	18.3 mm/s	50 mm/s
Blast 07	2003-04-29 23:22	PA3390B01	Tunnel A 3/390,8 Elevator -450	17 m	4.5 mm/s	50 mm/s
Blast 08	2003-05-05 22:09	PA2201A01	Tunnel A 2/201,5	280 m	0.18 mm/s	
Blast 08	2003-05-05 22:09	PA3270B01	Tunnel A 3/270 Fullface	101 m	1.5 mm/s	
Blast 08	2003-05-05 22:09	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	23.9 mm/s	
Blast 08	2003-05-05 22:09	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	10.1 m/s2	30 m/s2
Blast 08	2003-05-05 22:09	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	31.7 mm/s	50 mm/s
Blast 08	2003-05-05 22:09	PA3390B01	Tunnel A 3/390,8 Elevator -450	17 m	3.9 mm/s	50 mm/s
Blast 08	2003-05-05 22:09	PD0016B01	Tunnel D 0/016,8	199 m	0.9 mm/s	
Blast 09	2003-05-07 00:26	PA2201A01	Tunnel A 2/201,5	279 m	0.15 mm/s	
Blast 09	2003-05-07 00:26	PA3064A01	Tunnel A 3/064,1 LTDE	303 m	0.07 mm/s	
Blast 09	2003-05-07 00:26	PA3270B01	Tunnel A 3/270 Fullface	99 m	0.7 mm/s	
Blast 09	2003-05-07 00:26	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	9.2 mm/s	
Blast 09	2003-05-07 00:26	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	3.7 m/s2	30 m/s2
Blast 09	2003-05-07 00:26	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	25.6 mm/s	50 mm/s
Blast 09	2003-05-07 00:26	PA3390B01	Tunnel A 3/390,8 Elevator -450	18 m	3.3 mm/s	50 mm/s
Blast 09	2003-05-07 00:26	PD0016B01	Tunnel D 0/016,8	197 m	0.6 mm/s	
Blast 10	2003-05-07 23:47	PA2201A01	Tunnel A 2/201,5	279 m	0.20 mm/s	
Blast 10	2003-05-07 23:47	PA3064A01	Tunnel A 3/064,1 LTDE	303 m	0.11 mm/s	
Blast 10	2003-05-07 23:47	PA3270B01	Tunnel A 3/270 Fullface	99 m	1.6 mm/s	
Blast 10	2003-05-07 23:47	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	15.1 mm/s	
Blast 10	2003-05-07 23:47	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	6.7 m/s2	30 m/s2
Blast 10	2003-05-07 23:47	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	30.8 mm/s	50 mm/s
Blast 10	2003-05-07 23:47	PA3390B01	Tunnel A 3/390,8 Elevator -450	18 m	9.2 mm/s	50 mm/s
Blast 10	2003-05-07 23:47	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	139 m	0.8 mm/s	30 mm/s
Blast 10	2003-05-07 23:47	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	139 m	0.7 mm/s	30 mm/s
Blast 10	2003-05-07 23:47	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	139 m	0.3 mm/s	30 mm/s
Blast 10	2003-05-07 23:47	PD0016B01	Tunnel D 0/016,8	197 m	0.7 mm/s	
Blast 10	2003-05-07 23:47	PG0007B01	Tunnel G 0/007 Measuringcont.	133 m	0.6 mm/s	30 mm/s

Table A3-3. PPV-values for top heading rounds 11–14.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 11	2003-05-08 22:41	PA2201A01	Tunnel A 2/201,5	279 m	0.19 mm/s	
Blast 11	2003-05-08 22:41	PA3270B01	Tunnel A 3/270 Fullface	99 m	1.0 mm/s	
Blast 11	2003-05-08 22:41	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	26.6 mm/s	
Blast 11	2003-05-08 22:41	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	13.1 m/s2	30 m/s2
Blast 11	2003-05-08 22:41	PA3378B01	Tunnel A 3/378,2 Firewall	9 m	20.1 mm/s	50 mm/s
Blast 11	2003-05-08 22:41	PA3390B01	Tunnel A 3/390,8 Elevator -450	18 m	3.3 mm/s	50 mm/s
Blast 11	2003-05-08 22:41	PD0016B01	Tunnel D 0/016,8	197 m	0.9 mm/s	
Blast 12	2003-05-10 18:48	PA2201A01	Tunnel A 2/201,5	279 m	0.19 mm/s	
Blast 12	2003-05-10 18:48	PA2609B01	Tunnel A 2/609,7 Elevator -340	111 m	0.08 mm/s	
Blast 12	2003-05-10 18:48	PA2790B01	Tunnel A 2/790,4	175 m	0.87 mm/s	
Blast 12	2003-05-10 18:48	PA2790B01	Tunnel A 2/790,4	175 m	0.05 mm/s	
Blast 12	2003-05-10 18:48	PA3064A01	Tunnel A 3/064,1 LTDE	301 m	0.09 mm/s	
Blast 12	2003-05-10 18:48	PA3270B01	Tunnel A 3/270 Fullface	97 m	2.4 mm/s	
Blast 12	2003-05-10 18:48	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	13.2 mm/s	
Blast 12	2003-05-10 18:48	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	5.5 m/s2	30 m/s2
Blast 12	2003-05-10 18:48	PA3378B01	Tunnel A 3/378,2 Firewall	10 m	38.3 mm/s	50 mm/s
Blast 12	2003-05-10 18:48	PA3390B01	Tunnel A 3/390,8 Elevator -450	20 m	10.3 mm/s	50 mm/s
Blast 12	2003-05-10 18:48	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	141 m	0.7 mm/s	30 mm/s
Blast 12	2003-05-10 18:48	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	141 m	0.9 mm/s	30 mm/s
Blast 12	2003-05-10 18:48	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	141 m	0.6 mm/s	30 mm/s
Blast 12	2003-05-10 18:48	PD0016B01	Tunnel D 0/016,8	196 m	1.1 mm/s	
Blast 12	2003-05-10 18:48	PG0007B01	Tunnel G 0/007 Measuringcont.	134 m	0.7 mm/s	30 mm/s
Blast 13	2003-05-11 22:29	PA2201A01	Tunnel A 2/201,5	279 m	0.23 mm/s	
Blast 13	2003-05-11 22:29	PA2609B01	Tunnel A 2/609,7 Elevator -340	111 m	1.25 mm/s	
Blast 13	2003-05-11 22:29	PA2790B01	Tunnel A 2/790,4	175 m	0.64 mm/s	
Blast 13	2003-05-11 22:29	PA2790B01	Tunnel A 2/790,4	175 m	0.05 mm/s	
Blast 13	2003-05-11 22:29	PA3270B01	Tunnel A 3/270 Fullface	97 m	1.2 mm/s	
Blast 13	2003-05-11 22:29	PA3364A01	Tunnel A 3/364,2 Tranformerr	14 m	50.1 mm/s	
Blast 13	2003-05-11 22:29	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	14 m	22.2 m/s2	30 m/s2
Blast 13	2003-05-11 22:29	PA3378B01	Tunnel A 3/378,2 Firewall	10 m	38.8 mm/s	50 mm/s
Blast 13	2003-05-11 22:29	PA3390B01	Tunnel A 3/390,8 Elevator -450	20 m	3.4 mm/s	50 mm/s
Blast 13	2003-05-11 22:29	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	141 m	0.6 mm/s	30 mm/s
Blast 13	2003-05-11 22:29	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	141 m	0.8 mm/s	30 mm/s
Blast 13	2003-05-11 22:29	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	141 m	0.4 mm/s	30 mm/s
Blast 13	2003-05-11 22:29	PD0016B01	Tunnel D 0/016,8	196 m	0.8 mm/s	
Blast 13	2003-05-11 22:29	PG0007B01	Tunnel G 0/007 Measuringcont.	134 m	0.5 mm/s	30 mm/s
Blast 14	2003-05-13 02:02	PA2201A01	Tunnel A 2/201,5	278 m	0.23 mm/s	
Blast 14	2003-05-13 02:02	PA2609B01	Tunnel A 2/609,7 Elevator -340	111 m	1.55 mm/s	
Blast 14	2003-05-13 02:02	PA2790B01	Tunnel A 2/790,4	172 m	0.05 mm/s	
Blast 14	2003-05-13 02:02	PA3064A01	Tunnel A 3/064,1 LTDE	298 m	0.12 mm/s	
Blast 14	2003-05-13 02:02	PA3270B01	Tunnel A 3/270 Fullface	94 m	2.2 mm/s	
Blast 14	2003-05-13 02:02	PA3364A01	Tunnel A 3/364,2 Tranformerr	16 m	25.6 mm/s	
Blast 14	2003-05-13 02:02	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	16 m	7.8 m/s2	30 m/s2
Blast 14	2003-05-13 02:02	PA3378B01	Tunnel A 3/378,2 Firewall	11 m	43.7 mm/s	50 mm/s
Blast 14	2003-05-13 02:02	PA3390B01	Tunnel A 3/390,8 Elevator -450	23 m	5.6 mm/s	50 mm/s
Blast 14	2003-05-13 02:02	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	144 m	0.5 mm/s	30 mm/s
Blast 14	2003-05-13 02:02	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	144 m	0.7 mm/s	30 mm/s
Blast 14	2003-05-13 02:02	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	144 m	0.4 mm/s	30 mm/s
Blast 14	2003-05-13 02:02	PD0016B01	Tunnel D 0/016,8	193 m	1.1 mm/s	
Blast 14	2003-05-13 02:02	PG0007B01	Tunnel G 0/007 Measuringcont.	137 m	0.5 mm/s	30 mm/s

Blast 14 was done due to the limited space in the beginning of the first full face rounds.

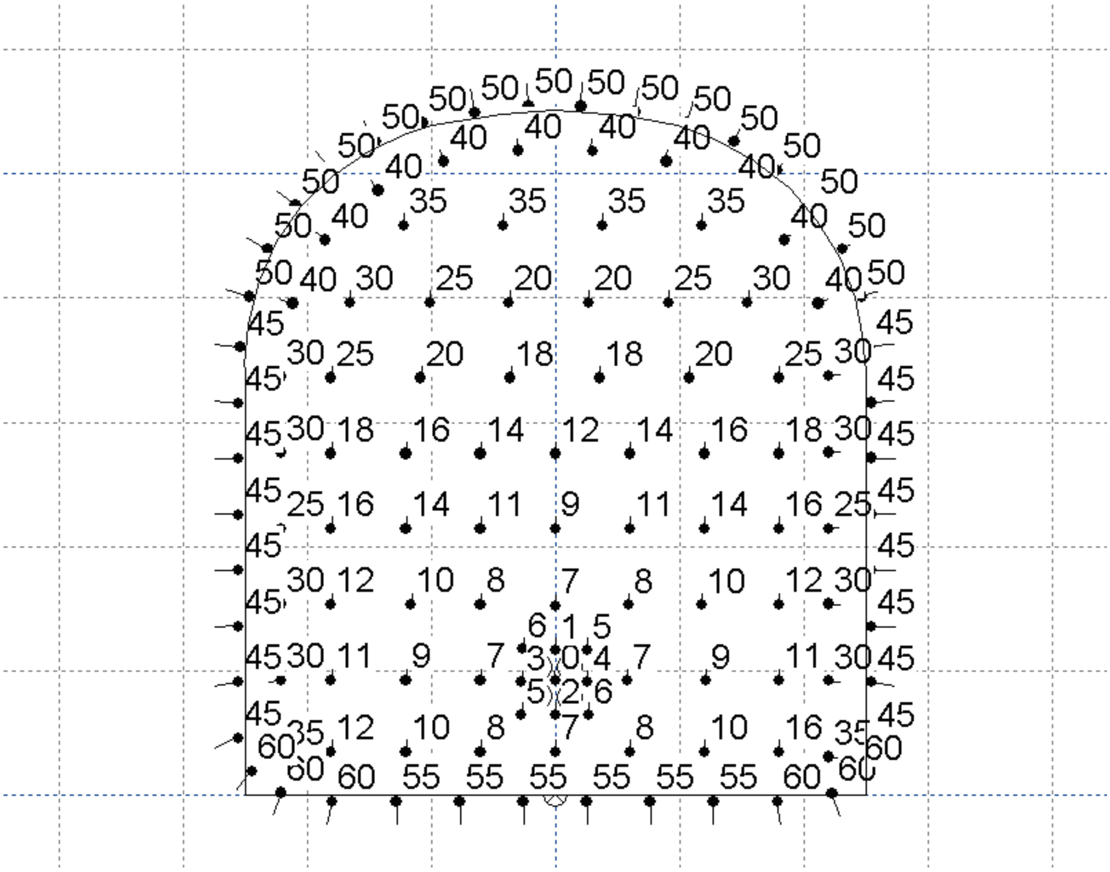

Figure A3-3. *First full face blast with drill- and firing pattern (Blast 14).*

Table A3-4. PPV-values for top heading rounds 15–18.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 15	2003-05-14 01:42	PA2201A01	Tunnel A 2/201,5	277 m	0.23 mm/s	
Blast 15	2003-05-14 01:42	PA2609B01	Tunnel A 2/609,7 Elevator -340	111 m	0.99 mm/s	
Blast 15	2003-05-14 01:42	PA2790B01	Tunnel A 2/790,4	169 m	1.00 mm/s	
Blast 15	2003-05-14 01:42	PA3064A01	Tunnel A 3/064,1 LTDE	295 m	0.12 mm/s	
Blast 15	2003-05-14 01:42	PA3270B01	Tunnel A 3/270 Fullface	92 m	1.5 mm/s	
Blast 15	2003-05-14 01:42	PA3364A01	Tunnel A 3/364,2 Tranformerr	17 m	31.3 mm/s	
Blast 15	2003-05-14 01:42	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	17 m	11.8 m/s2	30 m/s2
Blast 15	2003-05-14 01:42	PA3378B01	Tunnel A 3/378,2 Firewall	13 m	38.9 mm/s	50 mm/s
Blast 15	2003-05-14 01:42	PA3390B01	Tunnel A 3/390,8 Elevator -450	25 m	3.8 mm/s	50 mm/s
Blast 15	2003-05-14 01:42	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	147 m	0.6 mm/s	30 mm/s
Blast 15	2003-05-14 01:42	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	147 m	0.7 mm/s	30 mm/s
Blast 15	2003-05-14 01:42	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	147 m	0.3 mm/s	30 mm/s
Blast 15	2003-05-14 01:42	PD0016B01	Tunnel D 0/016,8	191 m	0.8 mm/s	
Blast 15	2003-05-14 01:42	PG0007B01	Tunnel G 0/007 Measuringcont.	139 m	0.5 mm/s	30 mm/s
Blast 16	2003-05-14 21:33	PA3270B01	Tunnel A 3/270 Fullface	92 m	0.9 mm/s	
Blast 16	2003-05-14 21:33	PA3364A01	Tunnel A 3/364,2 Tranformerr	17 m	75.6 mm/s	
Blast 16	2003-05-14 21:33	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	17 m	37.0 m/s2	30 m/s2
Blast 16	2003-05-14 21:33	PA3378B01	Tunnel A 3/378,2 Firewall	13 m	27.7 mm/s	50 mm/s
Blast 16	2003-05-14 21:33	PA3390B01	Tunnel A 3/390,8 Elevator -450	25 m	2.5 mm/s	50 mm/s
Blast 16	2003-05-14 21:33	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	147 m	0.3 mm/s	30 mm/s
Blast 16	2003-05-14 21:33	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	147 m	0.5 mm/s	30 mm/s
Blast 16	2003-05-14 21:33	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	147 m	0.2 mm/s	30 mm/s
Blast 16	2003-05-14 21:33	PD0016B01	Tunnel D 0/016,8	191 m	0.8 mm/s	
Blast 16	2003-05-14 21:33	PG0007B01	Tunnel G 0/007 Measuringcont.	139 m	0.4 mm/s	30 mm/s
Blast 17	2003-05-19 22:46	PA2201A01	Tunnel A 2/201,5	277 m	0.30 mm/s	
Blast 17	2003-05-19 22:46	PA2609B01	Tunnel A 2/609,7 Elevator -340	111 m	1.49 mm/s	
Blast 17	2003-05-19 22:46	PA2790B01	Tunnel A 2/790,4	169 m	0.96 mm/s	
Blast 17	2003-05-19 22:46	PA3270B01	Tunnel A 3/270 Fullface	92 m	1.8 mm/s	
Blast 17	2003-05-19 22:46	PA3364A01	Tunnel A 3/364,2 Tranformerr	17 m	40.2 mm/s	
Blast 17	2003-05-19 22:46	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	17 m	14.0 m/s2	30 m/s2
Blast 17	2003-05-19 22:46	PA3378B01	Tunnel A 3/378,2 Firewall	13 m	49.1 mm/s	50 mm/s
Blast 17	2003-05-19 22:46	PA3390B01	Tunnel A 3/390,8 Elevator -450	25 m	2.8 mm/s	50 mm/s
Blast 17	2003-05-19 22:46	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	147 m	0.5 mm/s	30 mm/s
Blast 17	2003-05-19 22:46	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	147 m	0.6 mm/s	30 mm/s
Blast 17	2003-05-19 22:46	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	147 m	0.4 mm/s	30 mm/s
Blast 17	2003-05-19 22:46	PD0016B01	Tunnel D 0/016,8	191 m	1.5 mm/s	
Blast 17	2003-05-19 22:46	PG0007B01	Tunnel G 0/007 Measuringcont.	139 m	0.4 mm/s	30 mm/s
Blast 18	2003-05-21 00:37	PA2201A01	Tunnel A 2/201,5	276 m	0.47 mm/s	
Blast 18	2003-05-21 00:37	PA2609B01	Tunnel A 2/609,7 Elevator -340	111 m	1.19 mm/s	
Blast 18	2003-05-21 00:37	PA2790B01	Tunnel A 2/790,4	166 m	0.87 mm/s	
Blast 18	2003-05-21 00:37	PA3064A01	Tunnel A 3/064,1 LTDE	292 m	0.16 mm/s	
Blast 18	2003-05-21 00:37	PA3270B01	Tunnel A 3/270 Fullface	89 m	1.9 mm/s	
Blast 18	2003-05-21 00:37	PA3364A01	Tunnel A 3/364,2 Tranformerr	20 m	15.9 mm/s	
Blast 18	2003-05-21 00:37	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	20 m	6.3 m/s2	30 m/s2
Blast 18	2003-05-21 00:37	PA3378B01	Tunnel A 3/378,2 Firewall	16 m	34.2 mm/s	50 mm/s
Blast 18	2003-05-21 00:37	PA3390B01	Tunnel A 3/390,8 Elevator -450	29 m	4.0 mm/s	50 mm/s
Blast 18	2003-05-21 00:37	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	150 m	0.7 mm/s	30 mm/s
Blast 18	2003-05-21 00:37	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	150 m	0.9 mm/s	30 mm/s
Blast 18	2003-05-21 00:37	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	150 m	0.5 mm/s	30 mm/s
Blast 18	2003-05-21 00:37	PD0016B01	Tunnel D 0/016,8	188 m	1.4 mm/s	
Blast 18	2003-05-21 00:37	PG0007B01	Tunnel G 0/007 Measuringcont.	142 m	0.7 mm/s	30 mm/s

Table A3-5. PPV-values for top heading rounds 19–22.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 19	2003-05-22 01:23	PA2201A01	Tunnel A 2/201,5	275 m	0.54 mm/s	
Blast 19	2003-05-22 01:23	PA2609B01	Tunnel A 2/609,7 Elevator -340	112 m	1.09 mm/s	
Blast 19	2003-05-22 01:23	PA2790B01	Tunnel A 2/790,4	164 m	1.14 mm/s	
Blast 19	2003-05-22 01:23	PA3064A01	Tunnel A 3/064,1 LTDE	289 m	0.18 mm/s	
Blast 19	2003-05-22 01:23	PA3270B01	Tunnel A 3/270 Fullface	87 m	2.1 mm/s	
Blast 19	2003-05-22 01:23	PA3364A01	Tunnel A 3/364,2 Tranformerr	22 m	16.6 mm/s	
Blast 19	2003-05-22 01:23	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	22 m	6.0 m/s2	30 m/s2
Blast 19	2003-05-22 01:23	PA3378B01	Tunnel A 3/378,2 Firewall	19 m	17.4 mm/s	50 mm/s
Blast 19	2003-05-22 01:23	PA3390B01	Tunnel A 3/390,8 Elevator -450	31 m	7.3 mm/s	50 mm/s
Blast 19	2003-05-22 01:23	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	152 m	0.7 mm/s	30 mm/s
Blast 19	2003-05-22 01:23	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	152 m	1.1 mm/s	30 mm/s
Blast 19	2003-05-22 01:23	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	152 m	0.6 mm/s	30 mm/s
Blast 19	2003-05-22 01:23	PD0016B01	Tunnel D 0/016,8	186 m	1.2 mm/s	
Blast 19	2003-05-22 01:23	PG0007B01	Tunnel G 0/007 Measuringcont.	144 m	0.7 mm/s	30 mm/s
Blast 20	2003-05-23 19:13	PA2201A01	Tunnel A 2/201,5	274 m	0.68 mm/s	
Blast 20	2003-05-23 19:13	PA2609B01	Tunnel A 2/609,7 Elevator -340	112 m	0.73 mm/s	
Blast 20	2003-05-23 19:13	PA2790B01	Tunnel A 2/790,4	160 m	1.06 mm/s	
Blast 20	2003-05-23 19:13	PA3270B01	Tunnel A 3/270 Fullface	84 m	2.6 mm/s	
Blast 20	2003-05-23 19:13	PA3364A01	Tunnel A 3/364,2 Tranformerr	25 m	22.9 mm/s	
Blast 20	2003-05-23 19:13	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	25 m	7.4 m/s2	30 m/s2
Blast 20	2003-05-23 19:13	PA3378B01	Tunnel A 3/378,2 Firewall	22 m	18.0 mm/s	50 mm/s
Blast 20	2003-05-23 19:13	PA3390B01	Tunnel A 3/390,8 Elevator -450	35 m	3.6 mm/s	50 mm/s
Blast 20	2003-05-23 19:13	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	156 m	0.8 mm/s	30 mm/s
Blast 20	2003-05-23 19:13	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	156 m	0.8 mm/s	30 mm/s
Blast 20	2003-05-23 19:13	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	156 m	0.6 mm/s	30 mm/s
Blast 20	2003-05-23 19:13	PD0016B01	Tunnel D 0/016,8	183 m	1.9 mm/s	
Blast 20	2003-05-23 19:13	PG0007B01	Tunnel G 0/007 Measuringcont.	147 m	0.7 mm/s	30 mm/s
Blast 21	2003-05-24 19:28	PA2201A01	Tunnel A 2/201,5	274 m	0.61 mm/s	
Blast 21	2003-05-24 19:28	PA2609B01	Tunnel A 2/609,7 Elevator -340	113 m	0.04 mm/s	
Blast 21	2003-05-24 19:28	PA2790B01	Tunnel A 2/790,4	158 m	1.21 mm/s	
Blast 21	2003-05-24 19:28	PA3270B01	Tunnel A 3/270 Fullface	82 m	2.1 mm/s	
Blast 21	2003-05-24 19:28	PA3364A01	Tunnel A 3/364,2 Tranformerr	28 m	17.5 mm/s	
Blast 21	2003-05-24 19:28	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	28 m	9.1 m/s2	30 m/s2
Blast 21	2003-05-24 19:28	PA3378B01	Tunnel A 3/378,2 Firewall	25 m	15.9 mm/s	50 mm/s
Blast 21	2003-05-24 19:28	PA3390B01	Tunnel A 3/390,8 Elevator -450	38 m	2.8 mm/s	50 mm/s
Blast 21	2003-05-24 19:28	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	158 m	0.7 mm/s	30 mm/s
Blast 21	2003-05-24 19:28	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	158 m	0.9 mm/s	30 mm/s
Blast 21	2003-05-24 19:28	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	158 m	0.7 mm/s	30 mm/s
Blast 21	2003-05-24 19:28	PD0016B01	Tunnel D 0/016,8	181 m	1.2 mm/s	
Blast 21	2003-05-24 19:28	PG0007B01	Tunnel G 0/007 Measuringcont.	149 m	0.5 mm/s	30 mm/s
Blast 22	2003-05-25 11:40	PA2201A01	Tunnel A 2/201,5	274 m	0.66 mm/s	
Blast 22	2003-05-25 11:40	PA2609B01	Tunnel A 2/609,7 Elevator -340	113 m	0.04 mm/s	
Blast 22	2003-05-25 11:40	PA2790B01	Tunnel A 2/790,4	158 m	1.29 mm/s	
Blast 22	2003-05-25 11:40	PA3064A01	Tunnel A 3/064,1 LTDE	284 m	0.15 mm/s	
Blast 22	2003-05-25 11:40	PA3270B01	Tunnel A 3/270 Fullface	82 m	2.7 mm/s	
Blast 22	2003-05-25 11:40	PA3364A01	Tunnel A 3/364,2 Tranformerr	28 m	31.2 mm/s	
Blast 22	2003-05-25 11:40	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	28 m	8.9 m/s2	30 m/s2
Blast 22	2003-05-25 11:40	PA3378B01	Tunnel A 3/378,2 Firewall	25 m	12.3 mm/s	50 mm/s
Blast 22	2003-05-25 11:40	PA3390B01	Tunnel A 3/390,8 Elevator -450	38 m	2.5 mm/s	50 mm/s
Blast 22	2003-05-25 11:40	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	158 m	0.5 mm/s	30 mm/s
Blast 22	2003-05-25 11:40	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	158 m	0.8 mm/s	30 mm/s
Blast 22	2003-05-25 11:40	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	158 m	0.2 mm/s	30 mm/s
Blast 22	2003-05-25 11:40	PD0016B01	Tunnel D 0/016,8	181 m	1.5 mm/s	
Blast 22	2003-05-25 11:40	PG0007B01	Tunnel G 0/007 Measuringcont.	149 m	0.4 mm/s	30 mm/s

Table A3-6. PPV-values for top heading rounds 23–25.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 23	2003-05-25 23:55	PA2201A01	Tunnel A 2/201,5	273 m	0.95 mm/s	
Blast 23	2003-05-25 23:55	PA2609B01	Tunnel A 2/609,7 Elevator -340	114 m	0.04 mm/s	
Blast 23	2003-05-25 23:55	PA2790B01	Tunnel A 2/790,4	155 m	1.21 mm/s	
Blast 23	2003-05-25 23:55	PA3064A01	Tunnel A 3/064,1 LTDE	280 m	0.16 mm/s	
Blast 23	2003-05-25 23:55	PA3270B01	Tunnel A 3/270 Fullface	80 m	4.1 mm/s	
Blast 23	2003-05-25 23:55	PA3364A01	Tunnel A 3/364,2 Tranformerr	31 m	12.1 mm/s	
Blast 23	2003-05-25 23:55	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	31 m	5.0 m/s2	30 m/s2
Blast 23	2003-05-25 23:55	PA3378B01	Tunnel A 3/378,2 Firewall	29 m	18.7 mm/s	50 mm/s
Blast 23	2003-05-25 23:55	PA3390B01	Tunnel A 3/390,8 Elevator -450	41 m	4.2 mm/s	50 mm/s
Blast 23	2003-05-25 23:55	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	162 m	0.9 mm/s	30 mm/s
Blast 23	2003-05-25 23:55	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	162 m	1.4 mm/s	30 mm/s
Blast 23	2003-05-25 23:55	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	162 m	0.8 mm/s	30 mm/s
Blast 23	2003-05-25 23:55	PD0016B01	Tunnel D 0/016,8	178 m	2.5 mm/s	
Blast 23	2003-05-25 23:55	PG0007B01	Tunnel G 0/007 Measuringcont.	152 m	0.7 mm/s	30 mm/s
Blast 24	2003-05-27 01:56	PA2201A01	Tunnel A 2/201,5	272 m	0.75 mm/s	
Blast 24	2003-05-27 01:56	PA2609B01	Tunnel A 2/609,7 Elevator -340	115 m	0.12 mm/s	
Blast 24	2003-05-27 01:56	PA2790B01	Tunnel A 2/790,4	151 m	1.38 mm/s	
Blast 24	2003-05-27 01:56	PA3064A01	Tunnel A 3/064,1 LTDE	276 m	0.15 mm/s	
Blast 24	2003-05-27 01:56	PA3270B01	Tunnel A 3/270 Fullface	77 m	2.5 mm/s	
Blast 24	2003-05-27 01:56	PA3364A01	Tunnel A 3/364,2 Tranformerr	36 m	32.4 mm/s	
Blast 24	2003-05-27 01:56	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	36 m	15.9 m/s2	30 m/s2
Blast 24	2003-05-27 01:56	PA3378B01	Tunnel A 3/378,2 Firewall	34 m	22.2 mm/s	50 mm/s
Blast 24	2003-05-27 01:56	PA3390B01	Tunnel A 3/390,8 Elevator -450	46 m	3.4 mm/s	50 mm/s
Blast 24	2003-05-27 01:56	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	166 m	0.8 mm/s	30 mm/s
Blast 24	2003-05-27 01:56	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	166 m	1.4 mm/s	30 mm/s
Blast 24	2003-05-27 01:56	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	166 m	0.6 mm/s	30 mm/s
Blast 24	2003-05-27 01:56	PD0016B01	Tunnel D 0/016,8	175 m	1.5 mm/s	
Blast 24	2003-05-27 01:56	PG0007B01	Tunnel G 0/007 Measuringcont.	156 m	0.5 mm/s	30 mm/s
Blast 25	2003-06-15 23:56	PA2201A01	Tunnel A 2/201,5	271 m	0.42 mm/s	
Blast 25	2003-06-15 23:56	PA3064A01	Tunnel A 3/064,1 LTDE	273 m	0.122 mm/s	
Blast 25	2003-06-15 23:56	PA3270B01	Tunnel A 3/270 Fullface	74 m	1.6 mm/s	
Blast 25	2003-06-15 23:56	PA3364A01	Tunnel A 3/364,2 Tranformerr	40 m	21.7 mm/s	
Blast 25	2003-06-15 23:56	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	40 m	9.8 m/s2	30 m/s2
Blast 25	2003-06-15 23:56	PA3378B01	Tunnel A 3/378,2 Firewall	37 m	6.8 mm/s	50 mm/s
Blast 25	2003-06-15 23:56	PA3390B01	Tunnel A 3/390,8 Elevator -450	50 m	1.4 mm/s	50 mm/s
Blast 25	2003-06-15 23:56	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	170 m	0.3 mm/s	30 mm/s
Blast 25	2003-06-15 23:56	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	170 m	0.5 mm/s	30 mm/s
Blast 25	2003-06-15 23:56	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	170 m	0.2 mm/s	30 mm/s
Blast 25	2003-06-15 23:56	PD0016B01	Tunnel D 0/016,8	172 m	0.9 mm/s	
Blast 25	2003-06-15 23:56	PG0007B01	Tunnel G 0/007 Measuringcont.	159 m	0.3 mm/s	30 mm/s
Blast 25	2003-06-15 23:56	PKT OJ 14	West KAS02 Lillbåten Vertical	572 m	0.027 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 14 NS	West KAS02 Lillbåten North/South	572 m	0.054 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	572 m	0.054 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 15	West Office Vertical	472 m	0.054 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 15 NS	West Office North/South	472 m	0.054 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 15 ÖV	West Office East/West	472 m	0.081 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 16	West KAS04 Äspöstigen Vertical	599 m	0.054 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	599 m	0.027 mm/s	
Blast 25	2003-06-15 23:56	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	599 m	0.095 mm/s	

Table A3-7. PPV-values for top heading rounds 26–28.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 26	2003-06-16 22:57	PA2201A01	Tunnel A 2/201,5	271 m	0.43 mm/s	
Blast 26	2003-06-16 22:57	PA3064A01	Tunnel A 3/064,1 LTDE	271 m	0.149 mm/s	
Blast 26	2003-06-16 22:57	PA3270B01	Tunnel A 3/270 Fullface	73 m	2.3 mm/s	
Blast 26	2003-06-16 22:57	PA3364A01	Tunnel A 3/364,2 Tranformerr	42 m	23.2 mm/s	
Blast 26	2003-06-16 22:57	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	42 m	13.3 m/s2	30 m/s2
Blast 26	2003-06-16 22:57	PA3378B01	Tunnel A 3/378,2 Firewall	39 m	6.6 mm/s	50 mm/s
Blast 26	2003-06-16 22:57	PA3390B01	Tunnel A 3/390,8 Elevator -450	52 m	1.1 mm/s	50 mm/s
Blast 26	2003-06-16 22:57	PD0016B01	Tunnel D 0/016,8	171 m	1.3 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 14	West KAS02 Lillbåten Vertical	573 m	0.041 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 14 NS	West KAS02 Lillbåten North/South	573 m	0.068 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	573 m	0.068 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 15	West Office Vertical	473 m	0.054 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 15 NS	West Office North/South	473 m	0.081 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 15 ÖV	West Office East/West	473 m	0.109 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 16	West KAS04 Äspöstigen Vertical	599 m	0.068 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	599 m	0.041 mm/s	
Blast 26	2003-06-16 22:57	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	599 m	0.109 mm/s	
Blast 27	2003-06-17 21:59	PA2201A01	Tunnel A 2/201,5	271 m	0.50 mm/s	
Blast 27	2003-06-17 21:59	PA3064A01	Tunnel A 3/064,1 LTDE	270 m	0.095 mm/s	
Blast 27	2003-06-17 21:59	PA3270B01	Tunnel A 3/270 Fullface	72 m	1.8 mm/s	
Blast 27	2003-06-17 21:59	PA3364A01	Tunnel A 3/364,2 Tranformerr	44 m	36.8 mm/s	
Blast 27	2003-06-17 21:59	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	44 m	16.0 m/s2	30 m/s2
Blast 27	2003-06-17 21:59	PA3378B01	Tunnel A 3/378,2 Firewall	41 m	5.6 mm/s	50 mm/s
Blast 27	2003-06-17 21:59	PA3390B01	Tunnel A 3/390,8 Elevator -450	54 m	1.2 mm/s	50 mm/s
Blast 27	2003-06-17 21:59	PD0016B01	Tunnel D 0/016,8	170 m	1.3 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 14	West KAS02 Lillbåten Vertical	574 m	0.041 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 14 NS	West KAS02 Lillbåten North/South	574 m	0.054 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	574 m	0.095 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 15	West Office Vertical	473 m	0.081 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 15 NS	West Office North/South	473 m	0.109 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 15 ÖV	West Office East/West	473 m	0.122 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 16	West KAS04 Äspöstigen Vertical	598 m	0.081 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	598 m	0.054 mm/s	
Blast 27	2003-06-17 21:59	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	598 m	0.136 mm/s	
Blast 28	2003-06-24 02:20	PA2201A01	Tunnel A 2/201,5	271 m	1.00 mm/s	
Blast 28	2003-06-24 02:20	PA3064A01	Tunnel A 3/064,1 LTDE	270 m	0.244 mm/s	
Blast 28	2003-06-24 02:20	PA3270B01	Tunnel A 3/270 Fullface	72 m	1.5 mm/s	
Blast 28	2003-06-24 02:20	PA3364A01	Tunnel A 3/364,2 Tranformerr	44 m	5.0 mm/s	
Blast 28	2003-06-24 02:20	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	44 m	3.7 m/s2	30 m/s2
Blast 28	2003-06-24 02:20	PA3378B01	Tunnel A 3/378,2 Firewall	41 m	20.4 mm/s	50 mm/s
Blast 28	2003-06-24 02:20	PA3390B01	Tunnel A 3/390,8 Elevator -450	54 m	9.4 mm/s	50 mm/s
Blast 28	2003-06-24 02:20	PD0016B01	Tunnel D 0/016,8	170 m	0.9 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 14	West KAS02 Lillbåten Vertical	574 m	0.041 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 14 NS	West KAS02 Lillbåten North/South	574 m	0.041 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	574 m	0.054 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 15	West Office Vertical	473 m	0.041 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 15 NS	West Office North/South	473 m	0.054 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 15 ÖV	West Office East/West	473 m	0.054 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 16	West KAS04 Äspöstigen Vertical	598 m	0.027 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	598 m	0.027 mm/s	
Blast 28	2003-06-24 02:20	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	598 m	0.054 mm/s	

Table A3-8. PPV-values for top heading rounds 28–30.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 29	2003-06-24 02:52	PA3270B01	Tunnel A 3/270 Fullface	71 m	3.5 mm/s	
Blast 29	2003-06-24 02:52	PA3364A01	Tunnel A 3/364,2 Tranformerr	45 m	11.1 mm/s	
Blast 29	2003-06-24 02:52	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	45 m	5.0 m/s2	30 m/s2
Blast 29	2003-06-24 02:52	PA3378B01	Tunnel A 3/378,2 Firewall	43 m	14.0 mm/s	50 mm/s
Blast 29	2003-06-24 02:52	PA3390B01	Tunnel A 3/390,8 Elevator -450	56 m	3.6 mm/s	50 mm/s
Blast 29	2003-06-24 02:52	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	175 m	0.8 mm/s	30 mm/s
Blast 29	2003-06-24 02:52	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	175 m	1.0 mm/s	30 mm/s
Blast 29	2003-06-24 02:52	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	175 m	0.9 mm/s	30 mm/s
Blast 29	2003-06-24 02:52	PD0016B01	Tunnel D 0/016,8	168 m	1.8 mm/s	
Blast 29	2003-06-24 02:52	PG0007B01	Tunnel G 0/007 Measuringcont.	164 m	0.7 mm/s	30 mm/s
Blast 29	2003-06-24 02:52	PKT OJ 14	West KAS02 Lillbåten Vertical	575 m	0.705 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 14 NS	West KAS02 Lillbåten North/South	575 m	0.407 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	575 m	0.190 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 15	West Office Vertical	473 m	0.122 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 15 NS	West Office North/South	473 m	0.204 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 15 ÖV	West Office East/West	473 m	0.244 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 16	West KAS04 Äspöstigen Vertical	598 m	0.136 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	598 m	0.081 mm/s	
Blast 29	2003-06-24 02:52	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	598 m	0.190 mm/s	
Blast 30	2003-06-28 21:14	PA2201A01	Tunnel A 2/201,5	270 m	0.733 mm/s	
Blast 30	2003-06-28 21:14	PA2609B01	Tunnel A 2/609,7 Elevator -340	120 m	2.510 mm/s	
Blast 30	2003-06-28 21:14	PA2790B01	Tunnel A 2/790,4	140 m	1.859 mm/s	
Blast 30	2003-06-28 21:14	PA3064A01	Tunnel A 3/064,1 LTDE	265 m	0.217 mm/s	
Blast 30	2003-06-28 21:14	PA3270B01	Tunnel A 3/270 Fullface	69 m	4.3 mm/s	
Blast 30	2003-06-28 21:14	PA3364A01	Tunnel A 3/364,2 Tranformerr	49 m	11.0 mm/s	
Blast 30	2003-06-28 21:14	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	49 m	4.6 m/s2	30 m/s2
Blast 30	2003-06-28 21:14	PA3378B01	Tunnel A 3/378,2 Firewall	47 m	8.7 mm/s	50 mm/s
Blast 30	2003-06-28 21:14	PA3390B01	Tunnel A 3/390,8 Elevator -450	60 m	2.1 mm/s	50 mm/s
Blast 30	2003-06-28 21:14	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	178 m	0.7 mm/s	30 mm/s
Blast 30	2003-06-28 21:14	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	178 m	1.1 mm/s	30 mm/s
Blast 30	2003-06-28 21:14	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	178 m	0.6 mm/s	30 mm/s
Blast 30	2003-06-28 21:14	PD0016B01	Tunnel D 0/016,8	166 m	1.9 mm/s	
Blast 30	2003-06-28 21:14	PG0007B01	Tunnel G 0/007 Measuringcont.	167 m	0.9 mm/s	30 mm/s
Blast 30	2003-06-28 21:14	PKT OJ 14	West KAS02 Lillbåten Vertical	577 m	0.136 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 14 NS	West KAS02 Lillbåten North/South	577 m	0.163 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	577 m	0.136 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 15	West Office Vertical	474 m	0.136 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 15 NS	West Office North/South	474 m	0.204 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 15 ÖV	West Office East/West	474 m	0.231 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 16	West KAS04 Äspöstigen Vertical	597 m	0.149 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	597 m	0.095 mm/s	
Blast 30	2003-06-28 21:14	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	597 m	0.176 mm/s	

Table A3-9. PPV-values for top heading rounds 31–32.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 31	2003-06-29 22:23	PA2201A01	Tunnel A 2/201,5	269 m	0.828 mm/s	
Blast 31	2003-06-29 22:23	PA2609B01	Tunnel A 2/609,7 Elevator -340	121 m	2.401 mm/s	
Blast 31	2003-06-29 22:23	PA2790B01	Tunnel A 2/790,4	137 m	1.248 mm/s	
Blast 31	2003-06-29 22:23	PA3064A01	Tunnel A 3/064,1 LTDE	262 m	0.244 mm/s	
Blast 31	2003-06-29 22:23	PA3270B01	Tunnel A 3/270 Fullface	67 m	3.8 mm/s	
Blast 31	2003-06-29 22:23	PA3364A01	Tunnel A 3/364,2 Tranformerr	53 m	23.9 mm/s	
Blast 31	2003-06-29 22:23	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	53 m	10.9 m/s2	30 m/s2
Blast 31	2003-06-29 22:23	PA3378B01	Tunnel A 3/378,2 Firewall	51 m	7.6 mm/s	50 mm/s
Blast 31	2003-06-29 22:23	PA3390B01	Tunnel A 3/390,8 Elevator -450	64 m	2.0 mm/s	50 mm/s
Blast 31	2003-06-29 22:23	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	182 m	0.7 mm/s	30 mm/s
Blast 31	2003-06-29 22:23	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	182 m	0.9 mm/s	30 mm/s
Blast 31	2003-06-29 22:23	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	182 m	0.5 mm/s	30 mm/s
Blast 31	2003-06-29 22:23	PD0016B01	Tunnel D 0/016,8	163 m	2.0 mm/s	
Blast 31	2003-06-29 22:23	PG0007B01	Tunnel G 0/007 Measuringcont.	170 m	0.7 mm/s	30 mm/s
Blast 31	2003-06-29 22:23	PKT OJ 14	West KAS02 Lillbåten Vertical	579 m	0.109 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 14 NS	West KAS02 Lillbåten North/South	579 m	0.136 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	579 m	0.149 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 15	West Office Vertical	475 m	0.149 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 15 NS	West Office North/South	475 m	0.204 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 15 ÖV	West Office East/West	475 m	0.258 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 16	West KAS04 Äspöstigen Vertical	597 m	0.122 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	597 m	0.095 mm/s	
Blast 31	2003-06-29 22:23	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	597 m	0.217 mm/s	
Blast 32	2003-07-01 00:29	PA2201A01	Tunnel A 2/201,5	269 m	1.058 mm/s	
Blast 32	2003-07-01 00:29	PA2609B01	Tunnel A 2/609,7 Elevator -340	123 m	2.998 mm/s	
Blast 32	2003-07-01 00:29	PA2790B01	Tunnel A 2/790,4	134 m	1.479 mm/s	
Blast 32	2003-07-01 00:29	PA3064A01	Tunnel A 3/064,1 LTDE	258 m	0.285 mm/s	
Blast 32	2003-07-01 00:29	PA3270B01	Tunnel A 3/270 Fullface	65 m	5.4 mm/s	
Blast 32	2003-07-01 00:29	PA3364A01	Tunnel A 3/364,2 Tranformerr	58 m	29.4 mm/s	
Blast 32	2003-07-01 00:29	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	58 m	12.2 m/s2	30 m/s2
Blast 32	2003-07-01 00:29	PA3378B01	Tunnel A 3/378,2 Firewall	56 m	9.4 mm/s	50 mm/s
Blast 32	2003-07-01 00:29	PA3390B01	Tunnel A 3/390,8 Elevator -450	68 m	2.4 mm/s	50 mm/s
Blast 32	2003-07-01 00:29	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	187 m	1.1 mm/s	30 mm/s
Blast 32	2003-07-01 00:29	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	187 m	0.9 mm/s	30 mm/s
Blast 32	2003-07-01 00:29	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	187 m	0.9 mm/s	30 mm/s
Blast 32	2003-07-01 00:29	PD0016B01	Tunnel D 0/016,8	160 m	2.4 mm/s	
Blast 32	2003-07-01 00:29	PG0007B01	Tunnel G 0/007 Measuringcont.	174 m	1.0 mm/s	30 mm/s
Blast 32	2003-07-01 00:29	PKT OJ 14	West KAS02 Lillbåten Vertical	581 m	0.122 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 14 NS	West KAS02 Lillbåten North/South	581 m	0.176 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	581 m	0.190 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 15	West Office Vertical	476 m	0.136 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 15 NS	West Office North/South	476 m	0.231 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 15 ÖV	West Office East/West	476 m	0.231 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 16	West KAS04 Äspöstigen Vertical	596 m	0.163 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	596 m	0.109 mm/s	
Blast 32	2003-07-01 00:29	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	596 m	0.258 mm/s	

Table A3-10 PPV-values for top heading rounds 33–34.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 33	2003-07-02 01:17	PA2201A01	Tunnel A 2/201,5	268 m	0.814 mm/s	
Blast 33	2003-07-02 01:17	PA2609B01	Tunnel A 2/609,7 Elevator -340	126 m	2.116 mm/s	
Blast 33	2003-07-02 01:17	PA2790B01	Tunnel A 2/790,4	130 m	1.425 mm/s	
Blast 33	2003-07-02 01:17	PA3064A01	Tunnel A 3/064,1 LTDE	254 m	0.271 mm/s	
Blast 33	2003-07-02 01:17	PA3270B01	Tunnel A 3/270 Fullface	64 m	4.6 mm/s	
Blast 33	2003-07-02 01:17	PA3270B01	Tunnel A 3/270 Fullface	64 m	3.7 mm/s	
Blast 33	2003-07-02 01:17	PA3364A01	Tunnel A 3/364,2 Tranformerr	63 m	26.2 mm/s	
Blast 33	2003-07-02 01:17	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	63 m	9.0 m/s2	30 m/s2
Blast 33	2003-07-02 01:17	PA3378B01	Tunnel A 3/378,2 Firewall	61 m	8.3 mm/s	50 mm/s
Blast 33	2003-07-02 01:17	PA3390B01	Tunnel A 3/390,8 Elevator -450	73 m	2.2 mm/s	50 mm/s
Blast 33	2003-07-02 01:17	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	191 m	1.0 mm/s	30 mm/s
Blast 33	2003-07-02 01:17	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	191 m	1.2 mm/s	30 mm/s
Blast 33	2003-07-02 01:17	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	191 m	0.8 mm/s	30 mm/s
Blast 33	2003-07-02 01:17	PD0016B01	Tunnel D 0/016,8	158 m	2.2 mm/s	
Blast 33	2003-07-02 01:17	PG0007B01	Tunnel G 0/007 Measuringcont.	178 m	0.7 mm/s	30 mm/s
Blast 33	2003-07-02 01:17	PKT OJ 14	West KAS02 Lillbåten Vertical	584 m	0.122 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 14 NS	West KAS02 Lillbåten North/South	584 m	0.176 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	584 m	0.217 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 15	West Office Vertical	477 m	0.109 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 15 NS	West Office North/South	477 m	0.176 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 15 ÖV	West Office East/West	477 m	0.244 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 16	West KAS04 Äspöstigen Vertical	595 m	0.136 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	595 m	0.095 mm/s	
Blast 33	2003-07-02 01:17	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	595 m	0.217 mm/s	
Blast 34	2003-07-02 20:37	PA2201A01	Tunnel A 2/201,5	268 m	0.909 mm/s	
Blast 34	2003-07-02 20:37	PA2609B01	Tunnel A 2/609,7 Elevator -340	128 m	1.587 mm/s	
Blast 34	2003-07-02 20:37	PA2790B01	Tunnel A 2/790,4	127 m	1.560 mm/s	
Blast 34	2003-07-02 20:37	PA3064A01	Tunnel A 3/064,1 LTDE	251 m	0.285 mm/s	
Blast 34	2003-07-02 20:37	PA3270B01	Tunnel A 3/270 Fullface	63 m	5.1 mm/s	
Blast 34	2003-07-02 20:37	PA3270B01	Tunnel A 3/270 Fullface	63 m	4.4 mm/s	
Blast 34	2003-07-02 20:37	PA3364A01	Tunnel A 3/364,2 Tranformerr	67 m	25.2 mm/s	
Blast 34	2003-07-02 20:37	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	67 m	9.5 m/s2	30 m/s2
Blast 34	2003-07-02 20:37	PA3378B01	Tunnel A 3/378,2 Firewall	65 m	7.9 mm/s	50 mm/s
Blast 34	2003-07-02 20:37	PA3390B01	Tunnel A 3/390,8 Elevator -450	77 m	1.9 mm/s	50 mm/s
Blast 34	2003-07-02 20:37	PA3514B01 L	Tunnel A 3/514,6 PROTOTYPE	195 m	0.7 mm/s	30 mm/s
Blast 34	2003-07-02 20:37	PA3514B01 T	Tunnel A 3/514,6 PROTOTYPE	195 m	0.9 mm/s	30 mm/s
Blast 34	2003-07-02 20:37	PA3514B01 V	Tunnel A 3/514,6 PROTOTYPE	195 m	0.8 mm/s	30 mm/s
Blast 34	2003-07-02 20:37	PD0016B01	Tunnel D 0/016,8	155 m	2.2 mm/s	
Blast 34	2003-07-02 20:37	PD0016B01	Tunnel D 0/016,8	155 m	1.9 mm/s	
Blast 34	2003-07-02 20:37	PG0007B01	Tunnel G 0/007 Measuringcont.	181 m	0.8 mm/s	30 mm/s
Blast 34	2003-07-02 20:37	PKT OJ 14	West KAS02 Lillbåten Vertical	586 m	0.014 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 14 NS	West KAS02 Lillbåten North/South	586 m	0.027 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 14 ÖV	West KAS02 Lillbåten East/West	586 m	0.054 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 15	West Office Vertical	478 m	0.041 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 15 NS	West Office North/South	478 m	0.027 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 15 ÖV	West Office East/West	478 m	0.027 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 16	West KAS04 Äspöstigen Vertical	594 m	0.027 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 16 NS	West KAS04 Äspöstigen North/South	594 m	0.014 mm/s	
Blast 34	2003-07-02 20:37	PKT OJ 16 ÖV	West KAS04 Äspöstigen East/West	594 m	0.054 mm/s	

Bench rounds no 35–46

Blast 35 to 46 were pure bench blasts for the floor section of the tunnel. All the measuring points above ground and in the main tunnel (from tunnel D and upwards was shut down 2003-07-03).

Six measuring points connected with cable to the Ava Net XT server were used for measuring on blast 35 to 46.

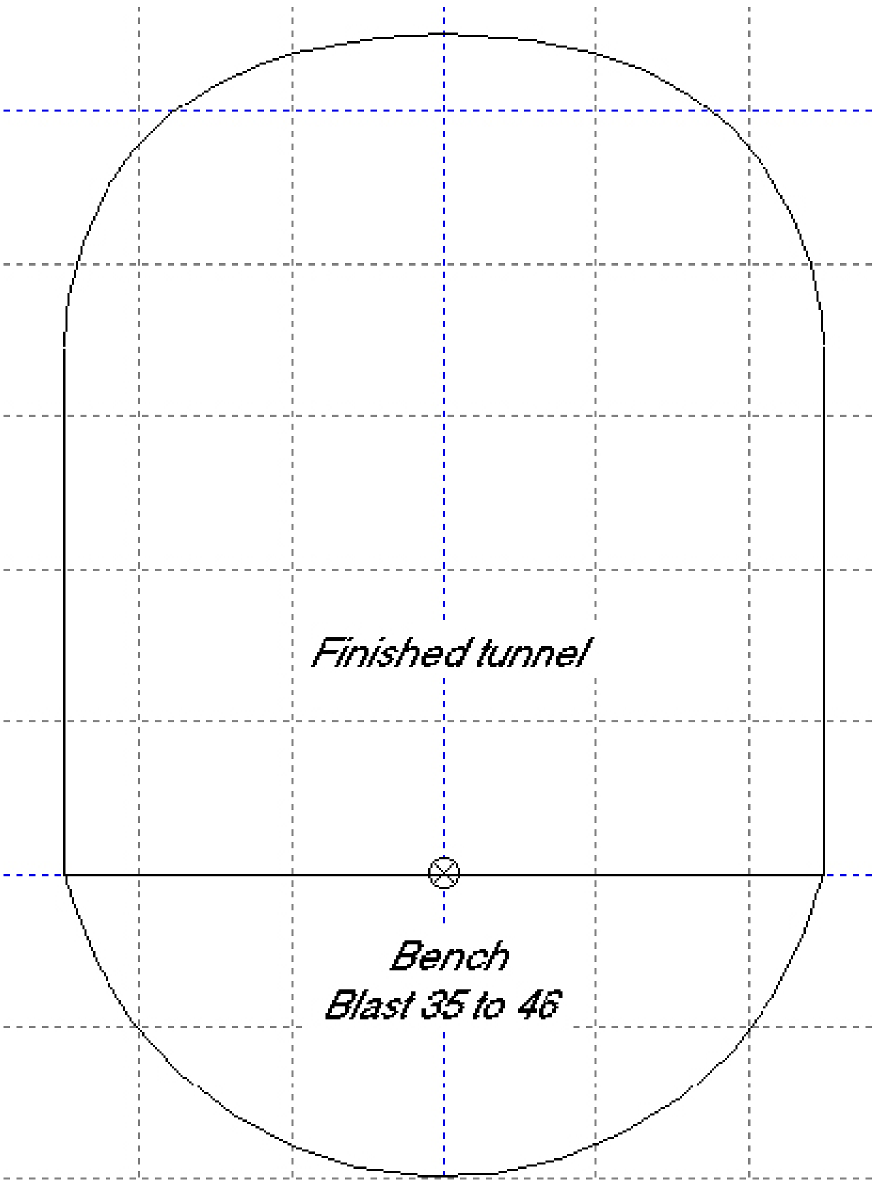

Figure A3-4. *Bench blasting round layout.*

Table A3-11. PPV-values for bench rounds 35–37.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 35	2003-07-11 20:00	PA3270B01	Tunnel A 3/270 Fullface	82 m	1.0 mm/s	
Blast 35	2003-07-11 20:00	PA3364A01	Tunnel A 3/364,2 Tranformerr	28 m	6.9 mm/s	
Blast 35	2003-07-11 20:00	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	28 m	2.7 m/s2	30 m/s2
Blast 35	2003-07-11 20:00	PA3378B01	Tunnel A 3/378,2 Firewall	25 m	9.6 mm/s	50 mm/s
Blast 35	2003-07-11 20:00	PA3390B01	Tunnel A 3/390,8 Elevator -450	38 m	2.4 mm/s	50 mm/s
Blast 35	2003-07-11 20:00	PD0016B01	Tunnel D 0/016,8	181 m	0.7 mm/s	
Blast 36	2003-07-12 10:24	PA3270B01	Tunnel A 3/270 Fullface	80 m	1.3 mm/s	
Blast 36	2003-07-12 10:24	PA3364A01	Tunnel A 3/364,2 Tranformerr	31 m	19.4 mm/s	
Blast 36	2003-07-12 10:24	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	31 m	8.3 m/s2	30 m/s2
Blast 36	2003-07-12 10:24	PA3378B01	Tunnel A 3/378,2 Firewall	29 m	15.3 mm/s	50 mm/s
Blast 36	2003-07-12 10:24	PA3390B01	Tunnel A 3/390,8 Elevator -450	41 m	2.6 mm/s	50 mm/s
Blast 36	2003-07-12 10:24	PD0016B01	Tunnel D 0/016,8	178 m	1.1 mm/s	
Blast 37	2003-07-12 16:07	PA3270B01	Tunnel A 3/270 Fullface	77 m	1.6 mm/s	
Blast 37	2003-07-12 16:07	PA3364A01	Tunnel A 3/364,2 Tranformerr	35 m	13.3 mm/s	
Blast 37	2003-07-12 16:07	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	35 m	5.3 m/s2	30 m/s2
Blast 37	2003-07-12 16:07	PA3378B01	Tunnel A 3/378,2 Firewall	33 m	13.0 mm/s	50 mm/s
Blast 37	2003-07-12 16:07	PA3390B01	Tunnel A 3/390,8 Elevator -450	45 m	3.4 mm/s	50 mm/s
Blast 37	2003-07-12 16:07	PD0016B01	Tunnel D 0/016,8	175 m	1.1 mm/s	

Table A3-12. PPV-values for bench rounds 38–46.

Blast no	Date/Time	ID Code	Location	Distance	Value	Perm Value
Blast 38	2003-07-13 11:08	PA3270B01	Tunnel A 3/270 Fullface	74 m	1.6 mm/s	
Blast 38	2003-07-13 11:08	PA3364A01	Tunnel A 3/364,2 Tranformerr	40 m	10.4 mm/s	
Blast 38	2003-07-13 11:08	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	40 m	4.3 m/s2	30 m/s2
Blast 38	2003-07-13 11:08	PA3378B01	Tunnel A 3/378,2 Firewall	37 m	19.9 mm/s	50 mm/s
Blast 38	2003-07-13 11:08	PA3390B01	Tunnel A 3/390,8 Elevator -450	50 m	3.7 mm/s	50 mm/s
Blast 38	2003-07-13 11:08	PD0016B01	Tunnel D 0/016,8	172 m	0.8 mm/s	
Blast 39	2003-07-13 20:02	PA3270B01	Tunnel A 3/270 Fullface	72 m	1.3 mm/s	
Blast 39	2003-07-13 20:02	PA3364A01	Tunnel A 3/364,2 Tranformerr	44 m	8.4 mm/s	
Blast 39	2003-07-13 20:02	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	44 m	4.6 m/s2	30 m/s2
Blast 39	2003-07-13 20:02	PA3378B01	Tunnel A 3/378,2 Firewall	42 m	8.1 mm/s	50 mm/s
Blast 39	2003-07-13 20:02	PA3390B01	Tunnel A 3/390,8 Elevator -450	55 m	1.6 mm/s	50 mm/s
Blast 39	2003-07-13 20:02	PD0016B01	Tunnel D 0/016,8	169 m	0.7 mm/s	
Blast 40	2003-07-14 16:10	PA3270B01	Tunnel A 3/270 Fullface	70 m	1.3 mm/s	
Blast 40	2003-07-14 16:10	PA3364A01	Tunnel A 3/364,2 Tranformerr	48 m	12.3 mm/s	
Blast 40	2003-07-14 16:10	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	48 m	5.5 m/s2	30 m/s2
Blast 40	2003-07-14 16:10	PA3378B01	Tunnel A 3/378,2 Firewall	46 m	8.3 mm/s	50 mm/s
Blast 40	2003-07-14 16:10	PA3390B01	Tunnel A 3/390,8 Elevator -450	59 m	2.2 mm/s	50 mm/s
Blast 40	2003-07-14 16:10	PD0016B01	Tunnel D 0/016,8	166 m	0.7 mm/s	
Blast 41	2003-07-14 21:27	PA3270B01	Tunnel A 3/270 Fullface	67 m	1.4 mm/s	
Blast 41	2003-07-14 21:27	PA3364A01	Tunnel A 3/364,2 Tranformerr	53 m	5.7 mm/s	
Blast 41	2003-07-14 21:27	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	53 m	3.8 m/s2	30 m/s2
Blast 41	2003-07-14 21:27	PA3378B01	Tunnel A 3/378,2 Firewall	51 m	5.3 mm/s	50 mm/s
Blast 41	2003-07-14 21:27	PA3390B01	Tunnel A 3/390,8 Elevator -450	64 m	1.4 mm/s	50 mm/s
Blast 41	2003-07-14 21:27	PD0016B01	Tunnel D 0/016,8	163 m	1.0 mm/s	
Blast 42	2003-07-15 11:45	PA3270B01	Tunnel A 3/270 Fullface	67 m	1.7 mm/s	
Blast 42	2003-07-15 11:45	PA3364A01	Tunnel A 3/364,2 Tranformerr	53 m	8.5 mm/s	
Blast 42	2003-07-15 11:45	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	53 m	3.8 m/s2	30 m/s2
Blast 42	2003-07-15 11:45	PA3378B01	Tunnel A 3/378,2 Firewall	51 m	9.9 mm/s	50 mm/s
Blast 42	2003-07-15 11:45	PA3390B01	Tunnel A 3/390,8 Elevator -450	64 m	2.3 mm/s	50 mm/s
Blast 42	2003-07-15 11:45	PD0016B01	Tunnel D 0/016,8	163 m	0.7 mm/s	
Blast 43	2003-07-15 16:29	PA3270B01	Tunnel A 3/270 Fullface	66 m	2.3 mm/s	
Blast 43	2003-07-15 16:29	PA3364A01	Tunnel A 3/364,2 Tranformerr	57 m	9.9 mm/s	
Blast 43	2003-07-15 16:29	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	57 m	4.4 m/s2	30 m/s2
Blast 43	2003-07-15 16:29	PA3378B01	Tunnel A 3/378,2 Firewall	55 m	6.1 mm/s	50 mm/s
Blast 43	2003-07-15 16:29	PA3390B01	Tunnel A 3/390,8 Elevator -450	68 m	2.2 mm/s	50 mm/s
Blast 43	2003-07-15 16:29	PD0016B01	Tunnel D 0/016,8	161 m	1.1 mm/s	
Blast 44	2003-07-15 21:42	PA3270B01	Tunnel A 3/270 Fullface	64 m	1.5 mm/s	
Blast 44	2003-07-15 21:42	PA3364A01	Tunnel A 3/364,2 Tranformerr	62 m	12.1 mm/s	
Blast 44	2003-07-15 21:42	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	62 m	5.8 m/s2	30 m/s2
Blast 44	2003-07-15 21:42	PA3378B01	Tunnel A 3/378,2 Firewall	60 m	5.8 mm/s	50 mm/s
Blast 44	2003-07-15 21:42	PA3390B01	Tunnel A 3/390,8 Elevator -450	72 m	1.5 mm/s	50 mm/s
Blast 44	2003-07-15 21:42	PD0016B01	Tunnel D 0/016,8	158 m	0.8 mm/s	
Blast 45	2003-07-16 15:13	PA3270B01	Tunnel A 3/270 Fullface	63 m	2.5 mm/s	
Blast 45	2003-07-16 15:13	PA3364A01	Tunnel A 3/364,2 Tranformerr	66 m	10.3 mm/s	
Blast 45	2003-07-16 15:13	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	66 m	5.0 m/s2	30 m/s2
Blast 45	2003-07-16 15:13	PA3378B01	Tunnel A 3/378,2 Firewall	64 m	4.6 mm/s	50 mm/s
Blast 45	2003-07-16 15:13	PA3390B01	Tunnel A 3/390,8 Elevator -450	76 m	1.5 mm/s	50 mm/s
Blast 45	2003-07-16 15:13	PD0016B01	Tunnel D 0/016,8	156 m	1.5 mm/s	
Blast 46	2003-07-17 07:22	PA3364A01	Tunnel A 3/364,2 Tranformerr	66 m	6.2 mm/s	
Blast 46	2003-07-17 07:22	PA3364A012	Tunnel A 3/364,2 Tranformerr acc	66 m	2.8 m/s2	30 m/s2
Blast 46	2003-07-17 07:22	PA3378B01	Tunnel A 3/378,2 Firewall	64 m	0.9 mm/s	50 mm/s
Blast 46	2003-07-17 07:22	PA3390B01	Tunnel A 3/390,8 Elevator -450	76 m	0.2 mm/s	50 mm/s

Function control of top heading rounds 32–34

Table A3-13 to Table A3-15 shows the results (marked in the Table) from the test of the i-kon detonators time accuracy. The relative measured time $\Delta\mathbf{t}$ should be compared with the nominal initiation intervals. Note that the *time corrected* values for the electronic detonators differs from nominal due to the time shift to the first recorded signal from the first pyrotechnic initiated blast hole.

Table A3-13. Delay times at blast Section 0/069 round 32.

Interval	Nominal (ms)	Measured (s)	Correction To int. 0 (s)	Relative Δt (ms)
0	25	0.005813	0.0250	
1	100			
2	200	0.19223	0.2114	186.42
3	300	0.29879	0.3180	106.56
4	400			
5	500	0.50294	0.5221	204.15
6	600	0.61698	0.6362	114.04
7	700	0.70875	0.7279	91.77
8	800	0.81633	0.8355	107.58
9	900	0.91546	0.9346	99.13
10	1,000	1.015	1.0342	99.54
11	1,110	1.1009	1.1201	85.90
12	1,235	1.2316	1.2508	130.70
14	1,400	1.4121	1.4313	180.50
16	1,600	1.6499	1.6691	237.80
18	1,800	1.8196	1.8388	169.70
20	2,075	2.1389	2.1581	319.30
25	2,500	2.5754	2.5946	436.50
30	3,000	3.0523	3.0715	476.90
35	3,500	3.669	3.6882	616.70
40	4,000	4.1359	4.1551	466.90
i-kon	*4,510*	*4.4994*	*4.5186*	*363.50*
i-kon	*4,530*	*4.5196*	*4.5388*	*20.20*
i-kon	*5,000*	*4.9889*	*5.0081*	*469.30*
i-kon	*5,010*	*4.9981*	*5.0173*	*9.20*
i-kon	*5,020*	*5.0083*	*5.0275*	*10.20*
55	5,500	5.5019	5.5211	493.60
60	6,000	6.1617	6.1809	659.80

Table A3-14. Delay times at blast Section 0/074 round 33.

Interval	Nominal (ms)	Measured (s)	Correction to int. 0 (s)	Relative Δt (ms)
1	100	0.001	0.100	
2	200	0.113	0.212	111.65
3	300			
4	400			
5	500	0.417	0.516	304.21
6	600	0.549	0.648	131.89
7	700	0.623	0.722	74.19
8	800	0.740	0.839	116.88
9	900	0.843	0.941	102.47
10	1,000	0.939	1.037	95.94
11	1,100	1.081	1.180	142.34
12	1,200	1.173	1.272	92.30
14	1,400	1.318	1.417	144.80
16	1,600	1.534	1.632	215.70
18	1,800			
20	2,000			
25	2,500	2.551	2.649	1,016.90
30	3,000	3.004	3.103	453.40
35	3,500	3.569	3.668	565.40
40	4,000	4.037	4.136	467.80
45	4,500	4.541	4.640	503.60
50	5,000	5.071	5.169	529.80
55	5,500	5.512	5.610	440.90
60	6,000	5.919	6.017	407.20
i-kon	*7,000*	*6.901*	6.999	*981.96*
i-kon	*7,010*	*6.911*	7.010	*10.39*
i-kon	*7,500*	*7.411*	7.510	*499.99*
i-kon	*7,510*	*7.421*	7.520	*10.07*
i-kon	*7,520*	*7.431*	7.530	*10.27*
i-kon	*8,000*	*7.928*	8.027	*496.59*
i-kon	*8,010*	*7.939*	8.038	*11.11*
i-kon	*8,020*	*7.948*	8.047	*9.03*
i-kon	*8,030*	*7.958*	8.057	*9.82*
i-kon	*8,500*	*8.458*	8.557	*500.01*
i-kon	*8,510*	*8.468*	8.566	*9.81*

Table A3-15. Delay times at blast Section 0/078 round34.

Interval	Nominal (ms)	Measured (s)	Correction to int. 0 (s)	Relative ∆t (ms)
3	75	0.0014	0.0750	
5	125	0.0180	0.0916	16.521
7	175	0.0981	0.1717	80.146
9	225	0.1434	0.2170	45.313
11	275	0.2078	0.2814	64.354
13	325	0.2586	0.3322	50.791
15	375	0.2879	0.3615	29.355
17	425	0.3284	0.4020	40.437
19	475	0.4117	0.4853	83.333
5	500	0.4251	0.4987	13.396
6	600	0.5501	0.6237	125.042
7	700	0.6412	0.7148	91.042
8	800	0.7571	0.8307	115.937
9	900	0.8486	0.9222	91.459
10	1,000	0.9495	1.0231	100.916
11	1,110	1.0794	1.1530	129.961
12	1,235	1.1837	1.2573	104.250
14	1,400	1.3434	1.4170	159.730
16	1,600	1.4804	1.5540	136.930
18	1,800			
20	2,075			
25	2,500	2.5673	2.6409	2,640.870
30	3,000	3.0100	3.0836	442.710
35	3,500	3.6134	3.6870	603.370
40	4,000	4.1055	4.1791	492.130
45	4,500	4.4898	4.5634	384.350
50	5,000	5.1944	5.2680	704.550
55	5,500	5.4875	5.5611	293.120
60	6,000			
i-kon	*7,000*	*6.9236*	*6.9972*	*1,436.120*
i-kon	*7,010*	*6.93298*	*7.0066*	*9.360*
i-kon	*7,030*	*6.9531*	*7.0267*	*20.120*
i-kon	*7,500*	*7.42375*	*7.4974*	*470.650*
i-kon	*7,510*	*7.43429*	*7.5079*	*10.540*
i-kon	*7,520*	*7.44396*	*7.5176*	*9.670*
i-kon	*8,000*	*7.91848*	*7.9921*	*474.520*
i-kon	*8,010*	*7.92913*	*8.0027*	*10.650*
i-kon	*8,020*	*7.93835*	*8.0120*	*9.220*
i-kon	*8,030*	*7.948*	*8.0216*	*9.650*
i-kon	*8,500*			
i-kon	*8,510*			
3	75	0.0014	0.0750	
5	125	0.0180	0.0916	16.521
7	175	0.0981	0.1717	80.146
9	225	0.1434	0.2170	45.313

Appendix 4

P-wave time/distance data along the tunnel wall

Table A4-1. P-wave velocities along 10 m of the tunnel wall at different times for round 33 (24 values, mean velocity V_{p33} = 6,094 m/s and with a standard deviation σ_{33} = 238 m/s and 34 17 values V_{p34} = 5,962 m/s and with σ_{34} = 131 m/s).

$Time_{33}$ s	Δt_{33} ms	V_{p33} m/s	$Time_{34}$ s	Δt_{34} ms	V_{p34} m/s
0.607	1.584	6.314	0.295	1.662	6.015
1.020	1.618	6.182	0.307	1.683	5.941
1.020	1.703	5.871	0.352	1.717	5.824
1.151	1.587	6.300	0.497	1.657	6.034
1.151	1.690	5.917	0.614	1.725	5.798
1.226	1.630	6.133	2.771	1.710	5.847
1.226	1.726	5.793	2.848	1.692	5.910
1.541	1.649	6.065	3.754	1.700	5.882
1.541	1.733	5.770	3.822	1.681	5.950
1.558	1.612	6.202	4.366	1.677	5.962
1.558	1.703	5.870	4.737	1.710	5.849
1.775	1.642	6.089	5.403	1.672	5.979
1.920	1.531	6.533	7.128	1.570	6.368
2.135	1.683	5.942	8.157	1.651	6.055
3.092	1.550	6.453	8.127	1.674	5.975
4.171	1.650	6.061	8.147	1.691	5.912
4.215	1.683	5.941	8.636	1.653	6.049
4.289	1.642	6.089			
4.637	1.690	5.917			
5.142	1.712	5.842			
6.125	1.707	5.858			
8.500	1.587	6.302			
9.002	1.507	6.636			
8.500	1.617	6.185			