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Vibration Control in Urban Drill and Blast Tunneling

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Tiivistelmä

Olli Weman
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Tämä opinnäytetyö on Sandvik Constructionin tilaama työ. Työ mennee osaksi ITA:n (International Tunneling and Underground Space Association) laajempaa tutkimusta otsikossa määritetyssä aiheesta. Sandvik on ITA:n jäsen.

Työn tarkoituksena on kerätä Suomen, Norjan, Ruotsin ja Islannin tärinään liittyviä standardeja kokoelmaksi sekä esitellä ja edistää poraus-räjäytys-menetelmää. Työssä kerättiin tieto kirjallisuudesta ja kunkin maan standardikokoelmista. Työn muissa osissa on selostettu poraus-räjäytys-menetelmästä ja tärinään liittyvistä kaavoista ja mittaustavoista. Loppuun on lisätty muutamia esimerkkiprojekteja, joissa louhinta on suoritettu tärinäherkissä kohteissa menestyksekkäästi poraus-räjäytys-menetelmällä.

Työn tuloksena yllä mainittujen maiden standardit saatiin referoitua ja vertailtua esimerkkitapauksia, joihin sovellettiin kunkin maan omaa standardia. Mielenkiintoista oli, miten standardit erosivat toisistaan ja mikä standardi antoi eniten pelivaraa poraus-räjäytys-menetelmää ajatellen.

Asiasanat: Louhinta, tärinä, tunnelinrakentaminen

Abstract

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The client of this thesis is Sandvik Construction. Sandvik is a member of ITA (Internation Tunnelling and Underground Space Association) and wanted to study current practises in vibration control when using drill and blast method. Parts of this thesis may be used in a further global study which Sandvik and ITA is considering to start about the same subject. The data was collected from literature and standard collection of each country.

The main purpose of this thesis was to collect vibration standards of Iceland, Norway, Sweden and Finland. Other parts of the thesis are current practises and general findings about the drill and blast method. In the last chapter a few challenging tunnelling projects with good vibration control practises are presented.

The outcome of this thesis was to translate the standard of each country to English and to compare them with an example cases. In other chapters, the stages and general findings drill and blast method are presented.

Keywords: Rock excavation, vibration, tunneling

Contents

1. Introduction

This thesis is created for Sandvik Construction. The thesis may be used, for some parts, for ITA working group papers about tunneling and underground space excavation. Sandvik is a member of ITA and wants to study applicability of drill and blast method in challenging environments with tight vibration controls. The aim of the thesis is also to gather the standards and legislation to one place, for everyone to discover.

The outcome of this thesis will be a paper which non-Scandinavian companies or persons may find helpful if reaching to northern tunneling markets. As the standardization varies in different countries, this paper would direct and guide the users to utilize correct standards and legislation. And for someone not familiar with drill and blast method, this thesis gives a general vision about the method.

The most parts of this thesis are about vibrations-related formulas, and definitions of the standards of each Scandinavian country. The other parts are about vibration recording methods, technology and practices and general about drilling and blasting. Sources of this thesis are mainly in Finnish, Swedish and Norwegian literature and the internet.

1.1 General

Urbanization has created new requirements for infrastructure. Every day people need transportation to go to work, school etc. Space decreasing on surface level, engineers had to find a way to transport these big masses of people. This is why engineers went underground. Everything can be built underground, typically metros, railroad tunnels, parking space and road tunnels. These tunnels and underground caverns can be excavated in several different ways. One of them is the drill and blast method.

Drill and blast method is a widely used method in tunneling. The other method is mechanical tunneling which can be separated in full profile excavation and partial face excavation. The main factors in choosing method are the hardness of the rock and rockmass properties.The harder the rock is, the more force is needed to detach the rockmass. This is why the drill and blast method is the most used method for tunneling in Scandinavia.

Drill and blast method is a cyclical method which involves several different stages. In excavation, -the main stages are drilling, charging and blasting, ventilating, mucking and measuring. Support methods will add some stages more.

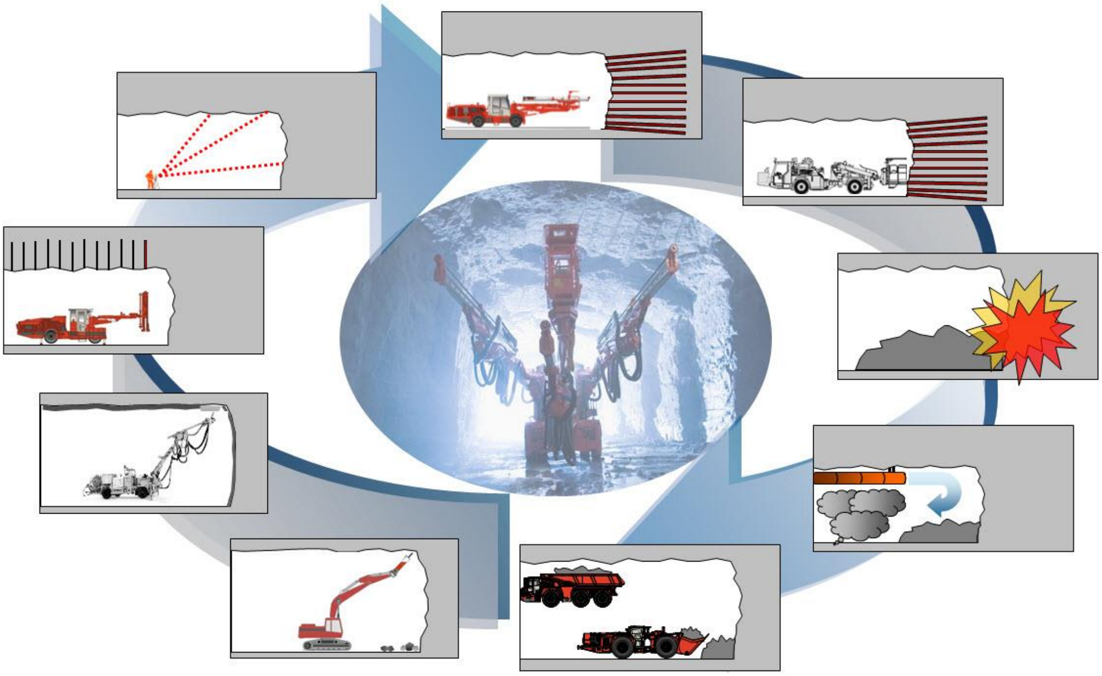

Figure 1. Cycle of drill and blast tunneling (1)

Blasting has to be very precise and well designed for optimal fragmentation and good release of the designed round. Precision and design are in higher value when tunneling in urban environment and when tunnel quality requirements are high. High quality means good water proofing, reinforcing and good shape of the tunnel. Urban environment is considered to be more difficult for the use of drill and blast method (d&b) since the structures above will also be a factor in blast designing. Blasting generates ground borne vibrations and vibration can cause damage to the existing structures. Stages of drilling and blasting might also be harmful for people living close by the site. Environment must also be considered when tunneling. These are reasons why norms and legislation are needed.

Monitoring of vibrations, blasting and other, is a vital element in tunneling (and other construction) in urban environment. Risk analysis of the existing structures will chart the risks and will prevent damage done by vibrations so that tunneling is safe for everyone. Such damages can be cracks in pad footings for instance.

1.2 Defining vibrations

Blasting vibrations can be calculated and estimated with different formulas. The vibration specialists have found with several different researches that particle velocity is the best way to calculate vibration limits and to prevent damage done to the existing structures. (4, p.126) There are three dimensions of shock waves: horizontal, longitude and vertical. Of these three, vertical component is the most significant and most monitored dimension in Norway, Sweden and Finland. (14, p. 320) The vibration limits are set with the following equations:

Particle velocity limits can be calculated with the following formula:

$$v = 2\pi f A \quad (1)$$

In which v= particle velocity (mm/s), f= frequency (Hz), A= amplitude or anomaly (mm or µm)

For sensitive structures (for example computers and hospital equipment) controlling component of vibrations is a= acceleration (mm/s^2) caused by wave movement.

$$a = 2\pi f v \quad (2)$$

When blasting in an urban area existing structures and sensitive equipment will result an extra factor when calculating accelerations and particle velocities with an equation. This equation varies in different countries. Here is an example from Finland:

$$v = F_k * v_1 \quad (3)$$

In which v= particle velocity, F_k= building factor, v_1= peak particle velocity on different distances.

In table 1 a Finnish structural coefficient factor is defined.

Structure	Building type coefficient F_k aa-competence class	Building type coefficient F_k a-competence class
1. Heavy structures, bridges, piers etc.	2,00	1,75
2. Indrustrial structures and storages of reinforced concrete, steel or wood, shotcreted rock vaults non habituated static structures in common	1,50	1,25
3. Structures laid on pole foundations made by reinforced concrete elements, offices, residential and other buildings of steel and wood, cables and wires	1,20	1,00
4. Massive walls of brick, lightweight block, industrial, office and residential buildings with reinforced concrete frame, glasswall-steelframe buildings and brick covered wooden frame buildings, non-shotcreted rock vaults	1,00	0,85

5. Buildings with lightweight block, limestonesand-brick or other easily damaging material, old buildings sensitive to vibration and oscillia-tion like churches and structures with high arches	0,65	0,55

Table 1. Example of Finnish structural coefficient factor (6)

A qualified consultant in Finland may provide higher construction coefficients (F_k) and a- and aa-class competences are official vibration expert classifications issued by FISE (Qualification of Professionals in Building Sector in Finland). (6)

Particle velocity by the maximum instantaneous charge (or MIC) can be estimated with the following formula:

$$v = k\sqrt{\frac{Q_m}{R^{1,5}}} \quad (4)$$

In which v= peak particle velocity, k= A specific constant (known from previous blasts or test blasts estimated by distance and rock/soil type), Qm= charge (kg), R= distance (m)

Another method to calculate vibrations is scaled distance. For scaled distance the formula is:

$$S = \frac{R}{\sqrt{Q_m}} \quad (5)$$

In which S=scaled distance, R=distance, Q_m= maximum instaenous charge. The maximum instantaneous charge can be calculated with:

$$Q_m = (\frac{R}{S})^2 \quad (6)$$

In which Q_m= charge (kg), R= distance (m), S= scaled distance.

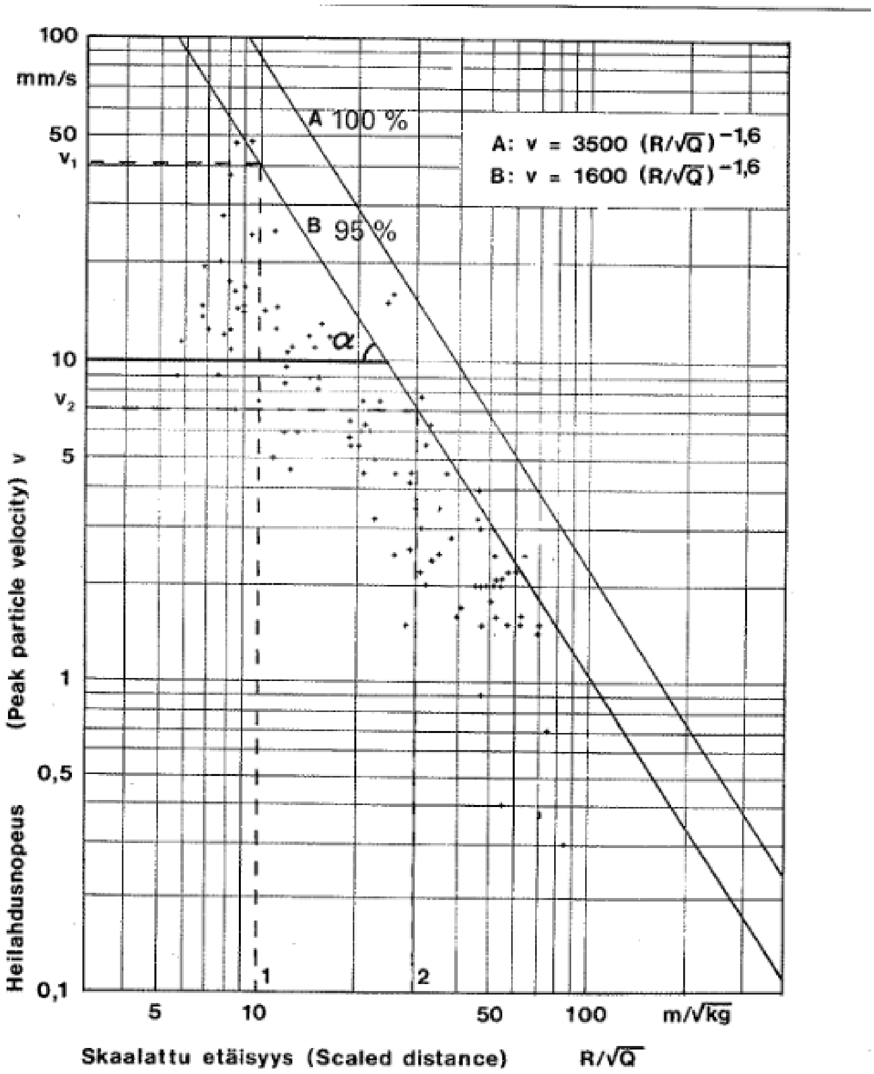

Diagram 1. The scaled distance relation to PPV. (14, p.331)

In diagram 1, the A line is a limit calculated with the formula written in the up right corner. A line is the estimate of vibration specialists when structure damage can occur. B is the maximum vibration allowed. A is 100% limit and B is 90% limit.

Formulas 3-6 work in Iceland, Sweden and Finland. These formulas used to work in Norway, but after the newest standards were published, Norwegians published new formulas to calculate the amount of charge. These formulas are presented in chapter 3.3.

2. The effects of blasting vibrations

2.1 Tunnel quality

Tunnel quality is often defined as water proofing, crack zone and shape of profile. When tunneling with d&b method, small charge rates prevent micro cracks in rock (when tunneling in hard rock). If high charges are used in the whole profile, the tunnel profile shape will be ripped and micro cracks in rock will result in water flowing in. Tunnel quality is often defined in project description.

Tunnel quality correlates with charge rates used on contour line and spacing of the contour row. The other rows are to be considered so that none of the shot holes will blast through the defined micro crack zone. The client sets quality requirements which the designer uses to create a project description. In project description, there is a part describing tunnel quality. In this section, the designer tells the requirements for profile intactness. The designer describes this intactness by a micro crack zone. To excavate a high quality tunnel, the micro crack zone has to be small and the tunnel has to be in a good shape. To reach this quality, smaller charge rates are to be used. For instance for most parts of the west metro project in Finland the micro crack zone was defined to be 400 mm. Some explosives producers have catalogs which describe details of each explosive and micro crack zone. For example, for a 400 mm micro crack zone, Forcit’s F- pipe charge is an optimal explosive. In single F-pipe, there is 100 g of dynamite – type explosive which means 0,2 kg/m charge rate. Since the charge in the contour is small, the profile will not be ripped. When the charge is smaller, spacing and burden are to be decreased for a proper release.

Depending on the charge on the contour line, the first aid row after the contour has to have a smaller charge rate. If the contour line is calculated to have a burden of 80 cm with 48-51 mm hole diameter, the first aid row will blast through the micro crack zone with almost every explosive, if the maximum charge per hole is used. For instance, kemix-a pipe charge with diameter of 32mm from Forcit has a micro crack zone of 1,5m, which in this case will hurt the shape of the profile and will crack over the defined micro crack zone (1,5 m–

0,8 m-0,4 m=0,3 m). In this case, the blast designer has to find optimal charges for each row.

Charge rates correlate with the amount of vibration. When burden, spacing and charge are small and rock release is easy, blasting will not cause much vibration. When using a smaller charge rate, the costs are always higher. Much more drill meters, detonators, explosives etc. are needed. On the other hand, the tunnel shape and water proofing (due to small micro crack and contour explosives will not rip the shape of the profile) will be better. If the tunnel is excavated with high quality requirements, for instance 400 mm micro crack zone, tunneling will not cause damage to the rock structure and the natural rock cracking will be the bigger factor in water proofing. These quality requirements are done to prevent the damage caused by blasting to the rock structure. With pre-grouting, a fan of concrete is pumped into the rock ahead.

The shape of the profile will also have other effects on costs. When a round has good release with not much under breaks or over breaks, shotcreting and rock cleansing costs will be lower as the consumption of concrete lowers. When tunnel shape is bad, much more shotcrete and water is needed to cover bigger square meter areas. With not much over breaking, pre-grouts will not be blasted off either which is good for water proofing. Good shaping means also a safer tunnel, since there will not be as much loose rocks due to cracking.

With good designing and good working methods, also under and over breaking can be prevented. When an under break is small (x<5 cm) and the tolerance for under breaks set by the designer or the client is also small, the under breaks which cannot be scaled off, has to be blasted off. When drilling in a small under break, the drilling is difficult and therefore drill rig operator has to drill with more angle. This will result in over breaking as this hole is blasted off.

All this can be prevented with good drill and blast design and accurate drilling. If drilling is done according to the plan and the drill holes are in line at the bottom of the hole, the design works. Drill rods tend to bend in drilling and drill rig operator is the one trying to prevent this bending. When rods bend, it will result in lower accuracy of the drilling which might result in bigger or smaller burden or spacing and therefore worse release of the cut. If the rod bends outwards of the round, the tunnel loses its shape as an over break or if the burden is too big, an under break may occur when the explosive does not have enough power for a proper release. Rod bending is bigger and happens more often when drilling in poor rock conditions. If the rod bends outwards, it will also create more vibrations as the power of the blast will not release in free space (under break- burden at the bottom of the hole is increased). If rods bend inwards, there will be under breaks which are to be blasted off.

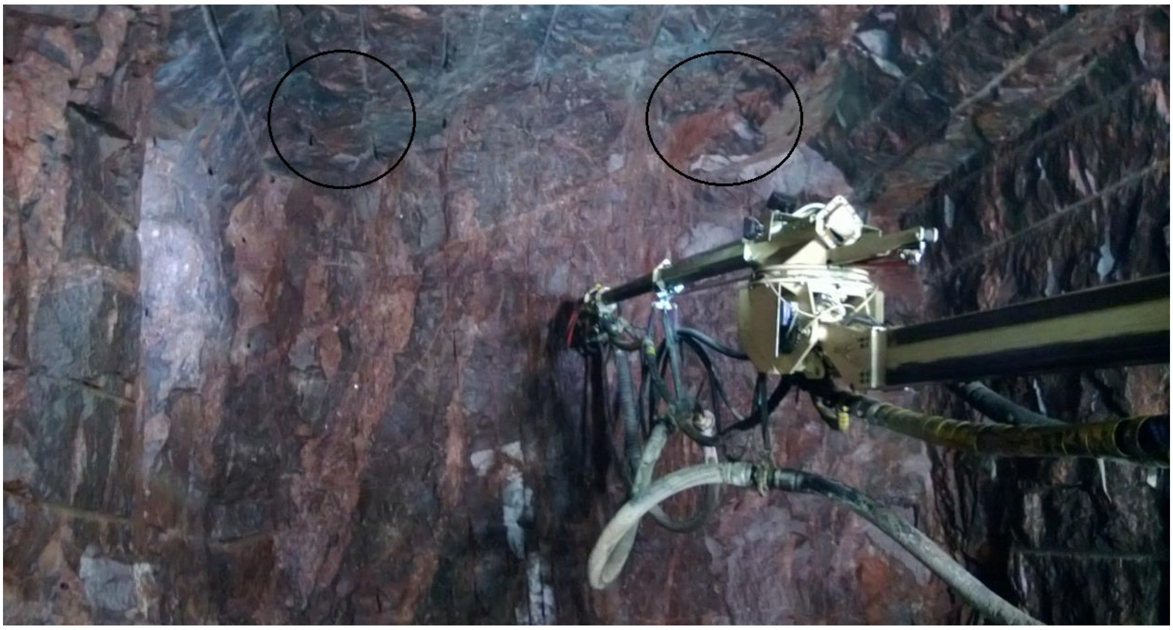

Figure 2. Under breaks at the face due to inaccurate drilling (photo by Olli Weman)

Under breaks will break the cycle if these need to be blasted off to get to drill the next round. Breaking the cycle will affect the time table and in addition bigger consumption of explosives, detonators, machinery, ventilating and working hours will higher the costs. Blasting under breaks off causes over excavation since the shot hole needs a proper burden to release the whole under break. If the burden is small, the blast will only blast the hole off.

When the interval of the detonator delays between holes is small, the release is better and the tunnel shape will be better. The ignition order is to be designed for a good release also. The ignition order has to be designed so that a shot hole will blast to free space and the angle of the release to free space is as high as possible. As the release angle is high, the vibrations are lower. The contour line can be blasted first, but this requires much tighter spacing (20-30 cm) which will affect costs. This method of blasting results in a good shape tunnel, but the vibrations are high and since cannot be done in an urban environment with small particle velocity limits.

The cut design is also a factor for a good release and vibrations. The better release, the better quality. If using a parallel cut, the shot holes have to be designed so that each hole blasts to around 90 degrees of free space when considering vibrations. Using a wedge cut is easier for vibrations since if the release is proper, the shot holes blast to bigger space and will not cause as much vibrations as parallel cut.

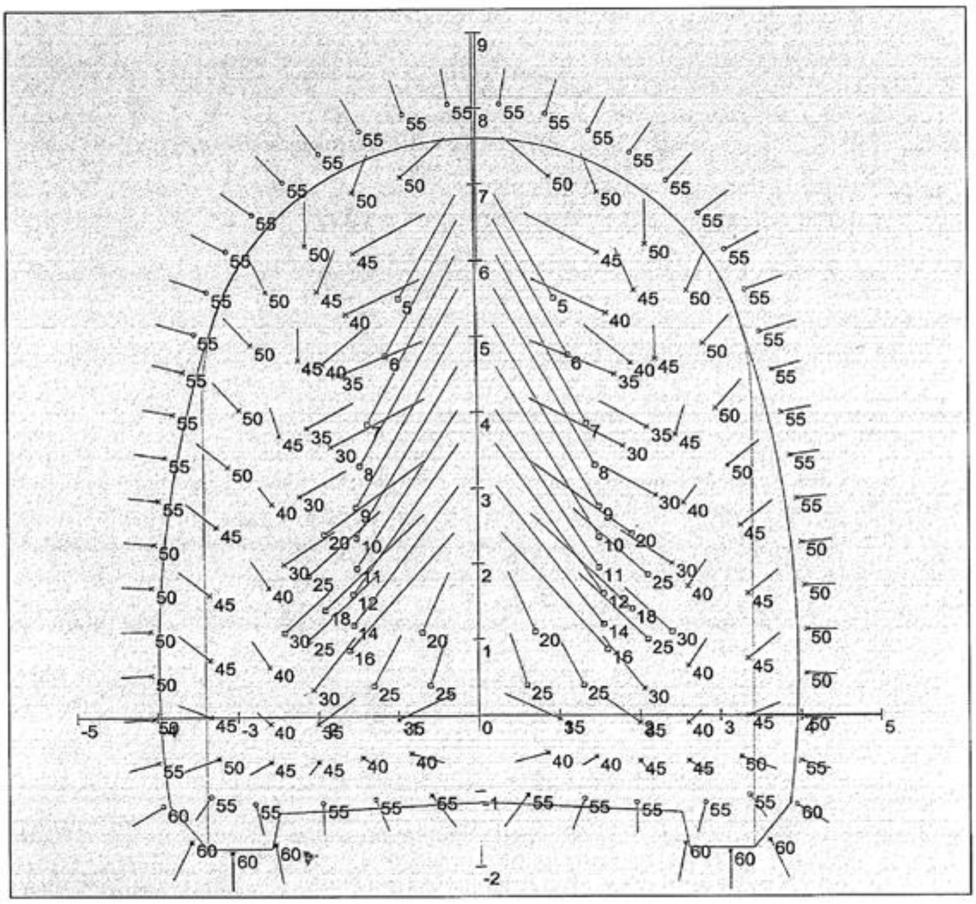

Figure 3. Vertical wedge cut with Nonel LP (Exel) series ignition (picture and design by Mr. Martti Keskinen, R&D director of Lemminkäinen Infra Ltd) (3)

If vibrations allow the tunneler to blast bigger charges, several holes can be ignited at the same time. In urban environment blasting several holes per interval is often limited to the contour line because of its small charges. In the future when the usage of electronic detonator expands, the interval of the shot holes can be set to as small as desired. This will result in an even better quality tunnel. Nowadays electronic detonators are expensive compared to impulse detonators.

2.2 Environment and structures

In blast designing, there are several things which have to be taken care of. Blasting always causes vibrations, air shock waves and throw of stones. These factors are to be analyzed before starting blasting. Damage can be prevented with experience and strong knowledge of blasting.

There are various studies of blasting vibrations and the tolerance that structures and people have for it. An international summary indicated that the particle velocity (mm/s) is the best and most practical description for defining in potential structure damage. (4, p.126)

In most of the cases, when tunneling in urban environment, a risk analysis is done. The risk analysis is done to prevent damages caused to the existing structures so that the contractor has limits and the contractor can forecast the MIC in different places. Risk analysis is done usually by a vibration and blasting consultant or someone with as strong experience and knowledge. Risk analysis typically involves:

- Type of structure (bridges, offices, residential etc.)
- Condition of structures
- Type of foundations (slab, pad footing etc.)
- Materials of foundations (soft moraine, moraine, granite etc.)
- Distance to the structures
- Frequency
- Sensitive materials and equipment

The heavier the structure is, the bigger peak particle velocity (or PPV) is allowed. For instance, in Finland bridges have structural coefficient (F_k) of 2.00 which means that PPV allowed can be multiplied with this factor when designing a blast but only when blasting or vibration specialist is present. The structures are to be in good condition to use these factors. In the other end, old historical buildings or ruins have F_k factor of 0.50. (3, p.138)

To prevent damage in sensitive equipment, the equipment manufacturer gives estimated acceleration limits. For instance, a computer has a limit of 0.25 g which is 2-4 mm/s in particle velocity when f>100Hz (3, p.140-141). This limit is low which means high costs or good design if tunneled under (to read more, see section 4).

To tunnel in a low PPV limit area, the following methods can be used to prevent crossing the PPV limit:

- Using vibration-wise best cut method, for instance the wedge cut
- Attenuation of the sensitive equipment
- Decreasing charge which means either shortening the round or decreasing burden and spacing
- Using right ignition system and blasting one hole at the time
- Blasting the profile in several sections to generate more interval in ignition

2.3 People

People living close by the tunneling area will hear and feel blasting. When rock cover is small people might also hear drilling and scaling. Air shock waves will radiate in the air from detonating charges even underground and this will shake windows etc. When project values are examined from the people view, the people will not feel or hear much of the project (depends on the project). People have to be safe and assured of their safety so people can keep on living their normal life. Discomfort and disruption has to be minimal. When everything goes according to the plan the contractors are able to keep working on their optimal productivity and the project is finished on schedule safely and with no damages. When tunneling contracts are done with high environmental and human values and no harm is done, people will tolerate much more and tunneling in future is pleasant for everyone. (3, p 123), (5) People have to be concerned when blasting through to open or when blasting first blasts. Safe area and throw of stones are to be planned and estimated properly. The blasting is usually small, blasting few holes per blast and blasting the profile in several sections. The covering of the blasts is also to be planned properly to prevent the throw of stones. The covering is usually done with tire mats, soil/rock or timber. Access to the danger zone is prevented during the blasting and this is being supervised by the worksite personnel. When excavating further into the tunnel and blasting in section is no longer necessary and throw of stones is minimal, the round length can be increased.

When tunneling in urban area, people will hear blasts and might wake up during night time. This is why sometimes in urban tunnel or underground space projects there is a time table for blasts when excavating in urban area. In some cases, people are to be informed before blasts. Informing residents is vital.

3. Regional blast vibration norms and legislation

3.1 General

Scandinavian countries have similarities in many areas. One similarity is also in construction and blasting legislation. The legislation of blasting in Scandinavian countries is similar with European Union standardization (10). Each country sets own set of rules and norms with specialists and each country has its own legislation. The thing that separates the countries is mainly in standardization. The standards are done by experts of the subject to have common rules to follow. The safety in all aspects is the priority in standardization. The legislation in a country is typically informative about safety aspects but leaves the technical design and limits to standards which are done by specialists.

Legislation concerning blasting in Scandinavian countries is widely similar. Similarities involve human related laws to increase safety. The main similarities in blasting safety of the Scandinavian countries are:

- Blast design (each country has its own forms)

In blast design the content is very similar in Iceland, Norway, Sweden and Finland. The main parts of the blast design are: drill plan, amount of explosives used, usage of explosives, ignition planning and covering. This is usually done by a blasting supervisor or a blast design engineer. These plans are to be documented for authorities.

- Safety plan

The main parts of the safety plan are: risks, an exit plan, prevention of risks, site info and working methods.

- Blasting supervisor (or foreman) (each country has its own classification)

Blasting supervision sets a person to be responsible for the site's blasting. This supervisor has different classes in different countries but the job is very similar. For instance, Norway has classes A- B- and C-class of charger. Blasting supervisor job involves approving blast designs and approving safety aspects. For instance, in the Finnish legislation the blasting supervisor must visit the blasting area once a day.

- Usage of explosives

Usage is the same in all countries. Usage involves handling and storing the explosives (safety distances etc.) Storage units are similar. The danger zone and the safety distances vary.

Each country has specifications for different explosives and job descriptions. Explosive CE- approving is compulsory for explosive manufacturers. For example in Finland the range between a drilling hole and a charging hole has to be 5 meters which is in Norway 2 meters.

- Electrical detonator safety (thunderstorms, ship underwater radars etc.)

The main parts are: work personnel escaping the blast site before thunderstorms and different types of echo sounders in ships may ignite electrical detonators.

- Explosives quality certificates (CE)

All Scandinavian countries follow the CE- quality standard in explosives.

(4, 7, 8, 9, 10)

The standardization and vibration and blasting related science are similar in Scandinavian countries since Scandinavian rock is typically hard, good and homogenious. Blasting and vibrations related equations (1-5) work in Finland, Sweden and Iceland. The differences are the building type coefficient factors, distance related coefficients, structure material coefficients and the equities how the vibration limits are to be calculated. Each country has its own set of standards, which defines the calculation of the vibrations. The v_0 or the PPV factor (see chapter 1.2) is also defined a little different. The PPV factor (v_0) is defined by the ground material between the blast and the structure. The heavier and the better condition the structure is, the higher PPV is allowed with building type coefficient factor (F_k). When structures are old and arches are long, the PPV is smaller since F_k is smaller. F_k is defined from each country's standardization collection. In Iceland the tunneling contracts are mostly in countryside (energy, road tunnel and railroad tunnel projects) so the vibrations are not really a big factor.

3.2 Iceland

Legislation concerning blasting safety can be found in chapter 9, references (7).

In Iceland, there are not much tunneling or underground projects in urban area. The projects are typically energy or road projects. The Icelandic standardization in determining vibration limits is simpler if compared to other Scandinavian countries. In table 2, Icelandic PPV allowed values are presented.

Structure	Maximum particle velocity (V=mm/s)
Construction of reinforced concrete which is footed on solid rock.	150

Buildings that stand on concrete foundations of hard consolidated rock types. Concrete floors and walls.	130
Construction on hard rock (usually the maximum velocity allowed by the government and insurance companies in the event of explosions)	70
Construction including hard rock. Repeated explosions in towns where more than state buildings prevail.	50
Construction on soft rock. Repeated explosions.	30
Construction on soft base (sand and clay). Repeated explosions	20
Human factors decisive – 10Hz	15
Human factors decisive- 25Hz	5

Table 2. Defining the PPV limit in Iceland (12)

3.3 Norway

Legislation concerning blasting safety can be found in chapter 9, referencecs (9)

Norwegian vibration guideline values are defined in the Norwegian standard collection. The new standard is NS8141-1:2012+A1:2013 Vibration and shock, guideline limit values from construction work, open-pit and underground mining and traffic.

The vibration limits are calculated with the following formula:

$$v_f = v_0 * F_b * F_m * F_t * F_v \quad (7)$$

In which v_f= guideline limit for vibrations, v_0= a basic vertical particle velocity, 35 mm/s, F_b= building factor, F_m= structure factor, F_t= structure condition factor, F_v= length of the blasting factor (1 in tunneling and construction projects). (13, p 6) All factors but v_0 are defined in tables 3-6.

Type of building	Building factor F_b
Heavy structures, such as bridges, piers, etc	1,7
Industrial and commercial buildings	1,2
Normal buildings, residential etc.	1,0
Special buildings, such as long span arches, marble staircases etc.	0,7

Table 3. Defining building factor F_b (13, p.7)

Type of structure	Structure factor F_m
Reinforced concrete, steel and wood	1,2
Plain concrete, brick, concrete hollow blocks, lightweight-aggregate con-crete	1,0
Autoclaved aerated concrete etc.	0,8

Table 4. Definition of structure factor F_m (13, p 7)

Building condition	Building condition factor F_t

Normal	1,0
Fragile	0,8

Table 5. Defining building condition factor F_t (13, p. 7)

Type of work	Work factor F_v
Construction	1,0
Mining and quarry	0,7

Table 6. Definition of blasting time factor, F_v (13, p. 8)

The Norwegian standards describe their own calculation method to calculate the amount of charge:

$$Q = K_Q * F_H * d^2 \quad (11)$$

In which, Q=amount of charge, K_Q= a charge coefficient which is defined in table 7, F_H=factor read from diagram 3 and d= distance between measuring point and blast.

Type of rock construction	Charge coefficient K_Q for zone A	Charge coefficient K_Q for zone B
Surface	0,049	0,020
Tunnel	0,191	-

Table 7. Charge coefficient factor (24)

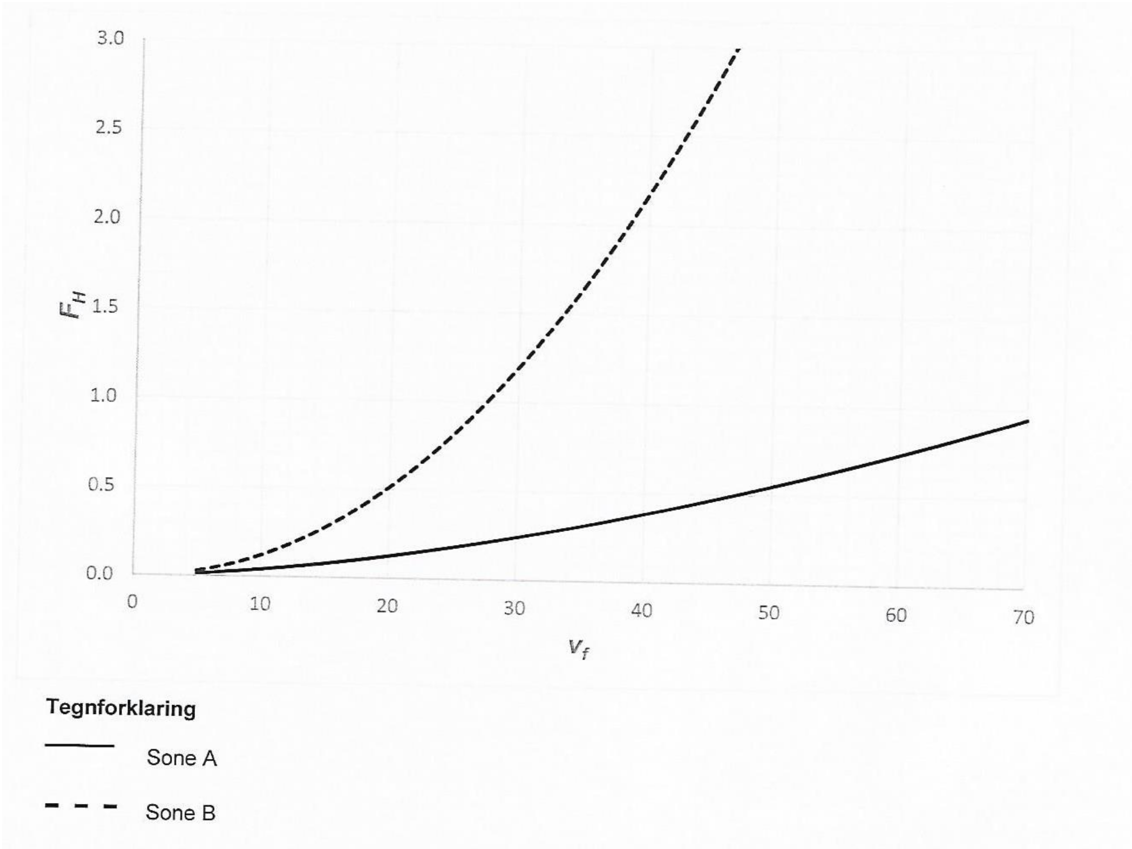

Diagram 3. F_H definition: A= solid line, B= the dotted line (25)

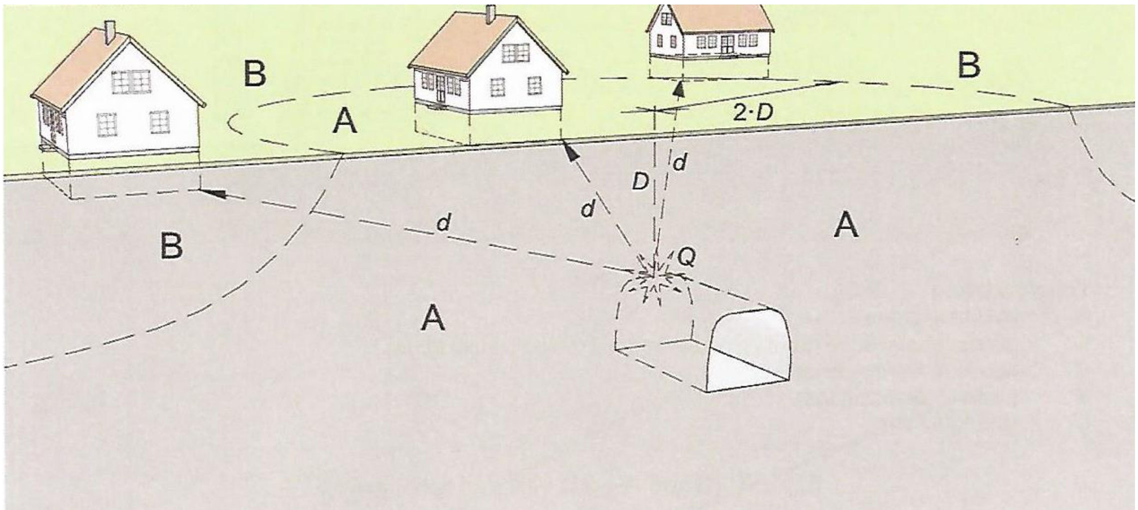

Figure 4. Defining shock zones used in diagram 3 and table 7 (24)

Figure 4 presents: A=shock wave pressure zone, B=surface shock wave pressure zone (horizontal separation 2*D, but at least 30 meters), D=depth to nearest charge, d=slant range distance and Q=charge.

When tunneling in an urban environment, it can be assumed that the shock zone is A. Definition for shock zone B coefficient can be found from a book called Veiledning til NS 8141-1 og 8141-2, Vibrasjoner fra sprengning og annen anleggsvirksomhet – Veiledning til NS 8141-1:2012+A1 og NS8141-2:2013. P-741.

When blasting near the existing tunnels, table 8 is used for V_f:

Description of the tunnel quality	$V_{f,tunnel}$ (mm/s)
Poor rock quality, scattered bolting or no reinforcement or no reinforced shotcrete	15
Poor rock quality, reinforced shot-crete together with bolts	25
Poor rock quality, cast concrete pro-file	45
Good rock quality, scattered bolting or no reinforcement or no reinforced concrete	25
Good rock quality, reinforced shot-crete with bolts	45
*If the tunnel is not in use, the speci-fied limits can be multiplied with the factor of 1,25. *If measured on standalone vault in the tunnel, the specified limit should be reduced with factor of 0,5 *Certain technical installations may	

govern the limit	

Table 8, V_0 for different rock structures. (13, p. 10)

3.4 Sweden

Legislation concerning blasting safety can be found in chapter 9, references (9)

Swedish vibration guideline values are defined in SS4604866: Vibration and shock – guidance levels for blasting included vibrations in buildings and other structures. This value is PPV (mm/s) and it concerns the vertical direction. (5)

The standard directs the user to calculate PPV values (v) at building foundation level according to the formula:

$$v = v_0 * F_b * F_m * F_d * F_t \quad (12)$$

In which v_0=Uncorrected PPV in the vertical axis, depending on substrata (table 9), F_b=Building factor based on the type of building and its sensitivity to vibration, F_m=Material factor based on the vibration sensitivity of the weakest material in building, F_d= Distance factor based on the distance between the blast and the measuring point, F_t=Blasting-work duration factor, which concerns for how long the project carries on. (5) Factors to define PPV allowed limit are presented in tables 9-12.

Substrata	Substratum	Vertical PPV, v_0, mm/s
Loosely layered moraine, sand gravel, clay	Clay	18
Compactly layered moraine, schist, soft lime-	Moraine	35

stone		
Granite, gneiss, hard limestone, quartzitic sandstone, diabase	Rock	70

Table 9. Guideline limits for vertical PPV (v_0) in different substrata (5)

Class	Building	Building factor, F_b
1	Heavy constructions such as bridges, quays, defense installations, etc.	1,70
2	Industrial and office buildings consisting mainly of prefabricated elements	1,20
3	Normal residential buildings	1,00
4	Especially sensitive buildings and buildings with high vaults or constructions with large spans	0,65
5	Guideline values for especially sensitive heritage buildings, installations or environments identified in the investigation shall be determined separately. (per special investigation.)	$F_b \leq 0{,}5$

Table 10. Vibration sensitivity factors for different buildings (5)

Material factor concerns the material of the structure. Material factor is defined in table 11

Class	Material	Material factor, F_m
1	Reinforced concrete, steel, wood	1,20

2	Plain concrete, brick, concrete hollow blocks, lightweight-aggregate concrete	1,00
3	Autoclaved aerated concrete, plaster, lath- and-plaster, stucco, render, etc.	0,75
4	Sand-lime brick, tiled oven with sensitive joints	0,65

Table 11. Defining material factor (5)

The distance factor F_d can be estimated with the diagram below. In distances under 10 meters, special problems can arise such as unfavorable ground conditions like occurrence of horizontal joints can cause large displacement. The equation for distances between 0 and 10 meters is calculated with formula 13. Formulas 14-16 are for different materials between the blast and the measuring point. Formula 14 is for clay, 15 is for moraine and 16 is for rock.

In greater distances than 350 meters, the F_d factors are the same. F_d for clay is 0,5, for moraine 0,35 and for rock it is 0,22. (5)

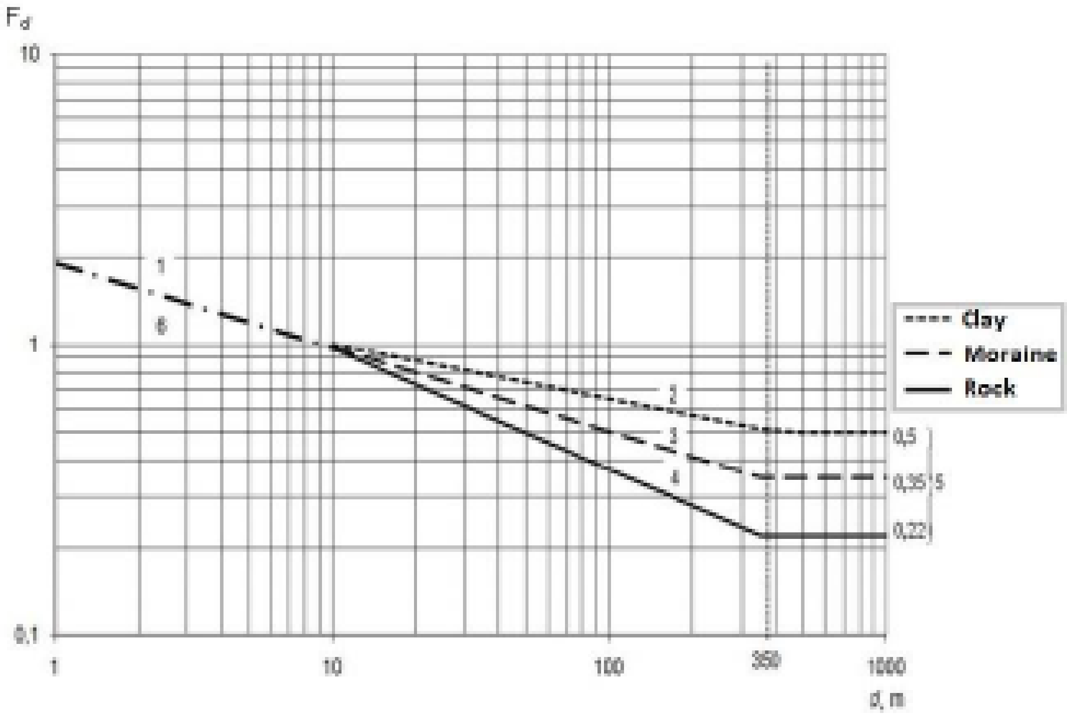

Diagram 4. F_d factor as a function of distance (5)

1. $F_d = 1{,}91 * d^{-0{,}28}$ (13) (between 0-10meters)
2. $F_d = 1{,}56 * d^{-0{,}19}$ (14)
3. $F_d = 1{,}91 * d^{-0{,}29}$ (15)
4. $F_d = 2{,}57 * d^{-0{,}42}$ (16)

Formulas 13-16 are from source 5.

The blasting duration factor depends on the project.

Class	Blasting-work duration factor, F_t
For the construction of tunnels, rock chambers, road cuttings, foundations etc.	1,0
For permanent works such as rock quarries and mines	1,0-0,75

Table 12, blasting duration factors (5)

For tunnel construction projects, the blasting-work duration factor will not matter.

3.5 Finland

Legislation concerning blasting safety can be found in chapter 9, references (4) and (12).

The vibration guideline values are defined in RIL 253-2010, Rakentamisen aiheuttamat tärinät (Vibrations caused by construction). The guideline value is set for PPV allowed (mm/s). The guideline value affects all directions of the shock wave, horizontal, vertical and longitude. A qualified consultant may use higher building coefficient factors. The consultants are defined to be FISE (Quality of Professionals in Building Sector) to AA- or A-class vibration specialist. (6)

The vibrations are calculated with the following formula:

$$v = v_1 * F_k \quad (17)$$

In which v_1 is PPV (mm/s) is defined in table 13 and F_k is defined in table 14.

1	2	3	4	5
Distance (m)	Soft clay, shear resistance <25kN/m	Tough clay, silt, loose sand	Compact sand, gravel, moraine broken or loose rock	Solid rock
1	9	18	35	140
5	9	18	35	85
10	9	18	35	70
20	8	15	28	55
30	7	14	25	45
50	6	12	21	38
100	5	10	17	28
200	4	9	14	22
500	3	7	11	15
1000	3	6	9	12
2000	3	5	7	9

Table 13. PPV (mm/s) limits for different ground materials (6)

Structure	Building type coefficient F_k aa-competence class	Building type coefficient F_k a-competence class
1. Heavy structures, bridges, piers etc.	2,00	1,75
2. Industrial structures and storages of reinforced concrete, steel or wood, shotcreted rock vaults non habituated static structures in common	1,50	1,25
3. Structures laid on pole foundations made of reinforced concrete elements, offices, residential and other buildings of steel and wood,	1,20	1,00

cables and wires		
4. Massive walls of brick, lightweight block, industrial, office and residential buildings with reinforced concrete frame, glasswall-steelframe buildings and brick covered wooden frame buildings, non-shotcreted rock vaults	1,00	0,85
5. Buildings with lightweight block, limestonesand-brick or other easily damaging material, old buildings sensitive to vibration and oscillia-tion like churches and structures with high arches	0,65	0,55

Table 14. Example of Finnish structural coefficient factor (6)

3.6 Review of the standards

Norwegian and Swedish standards are very similar. The Norwegian standard does not concern distance. The Icelandic standard limits are simple and that is because Icelandic projects are not usually close to populated or industrial areas. The Finnish standard is simpler than The Swedish and Norwegian standards since Finnish structural coefficient already includes the structural factors.

For instance, a residential building built of concrete in normal condition at the distance of 100 meters and material which residential structure is footed on is moraine, the frequency of the material between the blast and the structure is 100 Hz and the project is a tunnel project:

Country	Norway	Sweden	Iceland	Finland (aa)

PPV (mm/s)	42	22,75	30	20,4

Table 15. PPV values for an example project

The maximum instantaneous charge for these limits is calculated with the following formula (k-factor 50) (formula 11 for Norway, zone A):

$$Q_m = (\frac{v}{k})^2 * R^{1,5} \quad (18)$$

Country	Norway	Sweden	Iceland	Finland
MIC (kg)	665	207	360	166,5

Table 16. The maximum instantaneous charge for an example project

In this case, monitoring the building is not vital.

Another example: an industrial building (multi-storey building) built of reinforced concrete in normal condition at the distance of 15 meters and footing material is granite. The frequency is 250Hz and the project is a tunnel project:

Country	Norway	Sweden	Iceland	Finland (aa)
PPV (mm/s)	50,4	87,7	70	93,75

Table 17. PPV values for an example project

The maximum instantaneous charge for PPV limits are calculated with formula x (k-factor 200). Norwegian MIC is calculated with formula 11 in zone A.

Country	Norway	Sweden	Iceland	Finland
MIC (kg)	21,4	11,17	7,12	12,76

Table 18. The maximum instantaneous charge for an example project

An example case when acceleration limits are decisive: sensitive computer with 0.25 g limit defined by the manufacturer and this computer cannot be attenuated. The building is an industrial building of reinforced concrete, distance 70 meters, building is footed on moraine and the frequency between the measuring sensor and the blast is 150Hz (material between building+ building material). The building is in good condition. The project is a tunneling project. Acceleration is to be calculated with formula 2. In this case, the countries standards are not decisive since the computer manufacturer has set limits 0,25 g=2452,5mm/s^2.

$$v = \frac{2452{,}5\,{}^{mm}/_{s^2}}{2 * \pi * {}^{150}/_{s}} = 2{,}60 mm/s \quad (19)$$

As the v= 2,60 mm/s, the maximum instantaneous charge can be calculated (k-factor 100):

$$Q_m = \left(\frac{2{,}60\,{}^{mm}/_{s}}{100}\right)^2 * 70m^{1{,}5} = 0{,}400kg \quad (20)$$

This low charge per delay is difficult for blast design. This case is doable, but it will be very expensive. The cut hole can be drilled for instance, with d=400 mm drill bit and the blast design can be calculated for example for ammonia nitrate emulsion explosive for the whole round. If the project designing is running, working methods would allow around 1 kg per delay. If 1 kg was the lowest limit, in this case the distance should be 130 meters.

4. Methods, practices and technologies to measure and record vibrations

The vibrations in Scandinavian countries are recorded in the same way. The vibration meters are measuring the vertical particle velocity (mm/s) axis. The vertical particle velocity is the priority measuring parameter since the damage caused to structures is usually caused by vertical movement of the structure. If the distances are small, all the particles (vertical, horizontal and longitudinal) are to be monitored. If there is especially vibration-wise sensitive equipment or gear close by the source of the vibrations such as computers, electrical units, rail switches etc. the vibration specialists recommend using acceleration (mm/s^2) to be monitored. In some cases, the structure movement (usually measured in micro meters, µm) is the monitored particle. The particle to be monitored is recommended by the vibration specialists or consultants.

4.1 Methods

When designing a tunnel project, the environment and the existing structures are to be examined. If the tunneling is done in an urban environment, the existing structures are to be observed before blasting. The observation is done usually by structure and/or vibration specialists and they map for instance the existing cracks on the walls and the type of footing of the building. This is called a risk analysis. This risk analysis maps the risks of the blasting vibrations and prevents the risk of damage done to the existing structures. Specialists calculate and set the maximum values to particle velocity so that the structures are safe. The specialist can do a schematic presentation of the house and an analysis of probable stressed zones so that the possible cracking is acknowledged. These analyses are a vital proof if the property owner starts complaining about cracking in walls etc. If these cracks are observed in the risk analysis, the proof is undisputed. Using specialists is also good business. A senior consultant of Finnrock Ltd (Finnish vibration consultant) calculated one case in Finland: a single throw of stone cost the contractor as much as 16, 5 years of consulting. (18)

As the limits are set, the contractor can calculate the project. As the PPV allowed is set for each structure, the contractor can calculate the maximum charge per delay with the formula used in the particular country and calculate the round length. There are several cases in which the contractor has calculated for instance, a 3 meter round for a specific area and with good drill and blast design, tunneled past this area with a 5 meter round.

If tunneling under sensitive places, such as hospitals or laboratories equipped with sensitive equipment, the specialists make a special analysis for each equipment and define the limits. Equipment producers define the amount of vibration or acceleration to the equipment so that the equipment will not be damaged.

Each country has its own road and railroad administrations which define the specifics for structures and electrical equipment. In Finland this administration has published a book of guidelines when blasting close by railroads. Since there are no specific rules for sensitive structures, this type of guidelines set rules to protect the structures, rail switches and traffic. These guidelines contain specified particle velocity limits for each sensitive equipment such as electric units, pillars, transformers and equipment attached to railroad (shaft calculator). For instance, for relay and computer based rail switches, the PPV is set to 10 mm/s. The distance does not matter (before calculating the amount of charge). This is the guideline used when tunneling nearby a railroad and not the one defined in chapter 3.5. (18)

The measuring method to monitor the vibrations caused is to install a sensor to the structure or building with a risk of damage. The order of measurement chain is: sensor→cable→programmed data record unit→transferring data→computer with a program to handle the measured data.

The amount of vibration depends on the following factors:

- Vibration conductivity in rock and soil
- Distance between measuring sensor and blast
- Charge per drill hole
- Charge per interval
- Topography between measuring sensor and blast
- Are the charges in rod like or dot like ratio to measuring sensor (14, p 325-326)

The best positions to install the sensors are parts like pad footings, basements or other structures with soil beneath or the footing of the sensitive equipment. The sensors are to be placed to the closest edge of the blasts if possible. The sensor is supposed to lay as close to the lowest structure layer as possible. With this method, the vibrations are examined in the closest particle. This definition is also in Finnish, Norwegian and Swedish vibration standards (see chapter 3). (14)

4.2 Practices

The practices of the blasting vibrations depend on the target. Sensitive structures and/or sensitive equipment are to be observed by a specialist. This specialist will get the limits from equipment producers.

If the PPV or acceleration limit is very low (for instance only 0,06 kg maximum charge per delay), the tunneling will be very expensive. In these types of situations, the footings of the equipment can be attenuated for instance with different hardness of rubber- like pads.

Figure 5. Attenuation pads. Different colors are for different amounts of masses. Photo taken by Olli Weman in Finnrock Ltd storage

These rubber pads will decrease the amount of vibration to the equipment. There is also another method used in vibration attenuation. Drilling a gap between the blast and the monitored structure/equipment. This is more expensive than attenuating the equipment in its footing with rubber pads so this method is rare. (14, p. 355) In some cases, the equipment and the foundation of the equipment can be measured separately. This will give good readings of the amount of attenuation. And this is also good evidence if the owner of the equipment blames the contractor for damages.

According to Finnrock Ltd specialists, hospital equipment such as magnetic resonance imaging units are so sensitive that vibration specialists are not allowed to lift or touch the MRI machines to attenuate the machine. Moving or lifting can only be done by the producer of the machine. This is why the acceleration limits for MRI and other sensitive hospital equipment is set to 0,1 g (0,981 mm/s^2) which means 1,95 mm/s if f=80Hz and calculated with formula (2). This means 0,134 kg/interval if the distance is 50 meters and k-factor=100. 0,134kg is so low that proper blasting cannot be done in tunneling.

Distance to gap (m)	Gap depth (m)	Attenuation (%)
<3	<0,5	>80
3-6	0,5-1,0	65-80
6-9	1,0-1,5	50-65
>9	>1,5	<50

Table 19. Attenuation measured behind the gap (14, p. 355)

When tunneling in a project that has building sites near, the curing of concrete has to be concerned. As the concrete is curing, the strength of it is not high. In this situation, the curing is to be considered when defining the particle velocity allowed. Consultants have their own recommendations for different stages of curing. Here is an example of Finnrock Ltd's guidelines:

Time (d)	Concrete strength K (MPa)	V allowed (%)	Example when Vmax when V(0)=70mm/s
2h-1d	5		always 10mm/s
1-3d	20	65	45
3-7d	25	75	50
>7d	30+	100	70

Table 20. Guideline particle velocity values for curing concrete (19)

An example of a practice of vibration control is when tunneling under or near a railroad. In Finland in such cases, quick response of the vibration recording units to the analysis program in pc is vital. Co- operation with railroad traffic control (blasting between train schedules) has to be precise. In one case, the contractor was to inform the traffic control by 15:00 about blasts in the evening (21:00-22:00) so that the traffic control could give a time for the blast and make sure that no trains would cross the tunnel. If the vibration limits would have been crossed, the railroad maintenance were to check rail switches and rail road structures before letting trains through. A strange thing in this project was that heavy cargo trains crossed the particle velocity limits but blasting did not.

Another practice is informing the property owners nearby. There was one project which involved tunneling under research facilities and research tunnels. In this project, the contractor was to inform the research laboratories and tunnels about blasts so that laboratories had time to shut down the sensitive laboratory equipment before blasting.

In another case, an old woman lived close by the tunneling project. This woman was to be informed before each blast.

4.3 Technology

Particle velocity is the main particle which is monitored during blasting. The other particles measured are acceleration, frequency and amplitude. Some vibration meters send an sms- message to users or to measuring programs installed on computers (such as NCVIB or Blastview etc.). In some cases, when recording and measuring has to be fast, such vibration measures prove to be useful. Such cases are for instance, when co-operating with rail traffic control (blasting between train schedules) when the contractor has to check that vibrations of the blasts did not cross the PPV allowed limits and no harm is done to railroad structures or rail switches. This kind of practice can be used when tunneling under railroads. If there is any delay on railroad traffic due to blasting, there will be financial sanctions. If the vibration meters are up to date, the vibration program shows the results almost instantly and there is no need for further actions.

Again, if the vibration limits are crossed, depending on tolerance, the railroads and switches are to be checked before rail traffic can continue running. This is also very expensive. This is why calibration and maintenance of the recording units and sensors are vital. If batteries are used in recording units, they are also to be checked frequently.

The sensors used are mainly geophones which are small velocity sensors. Since they are small, it is easy to install them properly. The structure of a horizontal and vertical geophone is different so the geophone type has to be chosen prior to the component measured. In geophones, there is no need for a measuring signal amplifier before transforming the signal to the measuring unit. The frequency scale of the geophones is 5-1000 Hz. The results can be integrated to get displacement (µm) and derived to get acceleration. (14 p. 324) Acceleration sensors are seldom used since the particle velocity is usually the main element monitored.

The displacement sensors are large and hard to handle. In addition, they are very expensive. These sensors are not used at all when recording blasting vibrations. (14, p. 324)

The signal from the measuring sensor (usually geophone) is handled in a recording and printing unit. These recording units, seismographs, can be divided into two main categories: peak particle meters and analyze meters. Depending on the recording unit used, either PPV can be monitored or the full scale analysis to analyze the vibrations properly. The peak particle meters are mainly used to stay in the defined limits of the vibrations. Recording units can be programmed so that the recording units will not record when particle velocity is small, under the specified limit. (14, p. 325)

Examples of recording units:

Figure 6. 3-axial Sigicom Infra (15)

Sigicom Infra can be used with a battery or with mains current. Sigicom Infra is a multi-channel remote-used frequency, amplitude and PPV measuring device. It records from one or several sensors vibrations PPV, frequency, acceleration and amplitude time history. It can also be used to record and measure air shock waves. This device sends data to the recording program on a computer or to the user via an sms- message. (15)

Figure 7. 3-axial ABEM UVS1500 (15)

A device which functions with mains current or with battery. Records vibrations particle velocity, acceleration, frequency and amplitude time history in vertical or in all axis. (15)

5. Drill and Blast method in Scandinavia

Drill and blast method is very versatile method when excavating underground spaces and tunnels. Drill and blast method allows the profiles of the project to be almost anything possible. This versatility is seen in Helsinki, the capital of Finland. In Finnish conditions, drill and blast method is the most used method.

Other methods are not as competitive in Finland so far. (20, p. 8). Some underground structures can be for instance, civil defense shelters. These shelters may be used, during peace time, for exercise centers such as ice hockey halls, athletics facilities etc. In this chapter some interesting cases are examined.

5.1 Underground Swimming Pool in Itäkeskus, Helsinki, Finland

This underground swimming pool facilities remain in Itäkeskus, the eastern part of Helsinki. In emergency situations, the halls can be converted into shelters for 3800 persons. The facilities remain in two floors and can accommodate up to 1000 persons at a time. The halls have the average of 400 000 visitors per year. This project was excavated in solid rock. (20, p. 17)

Figure 8. Underground Swimming pool in Itäkeskus (20, p. 17) Photo from City of Helsinki Media Bank

This underground space includes three pools, 50 m x 19 m, 14 m x 11 m, 12,5 m x 10 m, cold water pool, jacuzzi, gym, solariums and saunas and so on.

5.2 Viikinmäki wastewater treatment plant, Helsinki, Finland

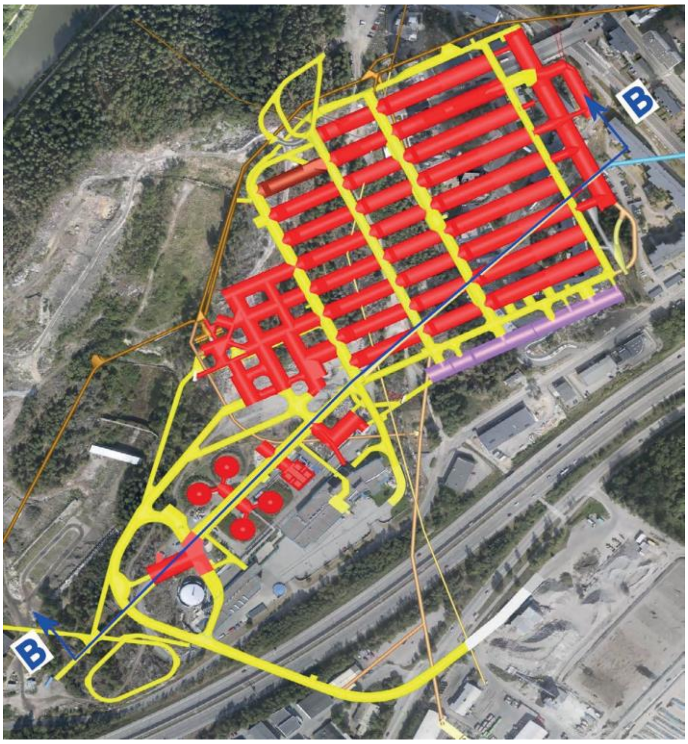

Figure 9. Aerial view of the Viikinmäki wastewater treatment plant (20, p. 35) image from City of Helsinki Real Estate Department

Viikinmäki wastewater treatment plant began operating in 1994. This wastewater treatment plant took 10 smaller treatment plants out of use (all from surface level). On the surface level of Viikinmäki, 3500 persons live above the tunnels. There are also several designs of building more residential buildings in Viikinmäki and in the wastewater treatment plant area. The wastewater treatment plant has a possibility of expanding in the future. (20, p. 35)

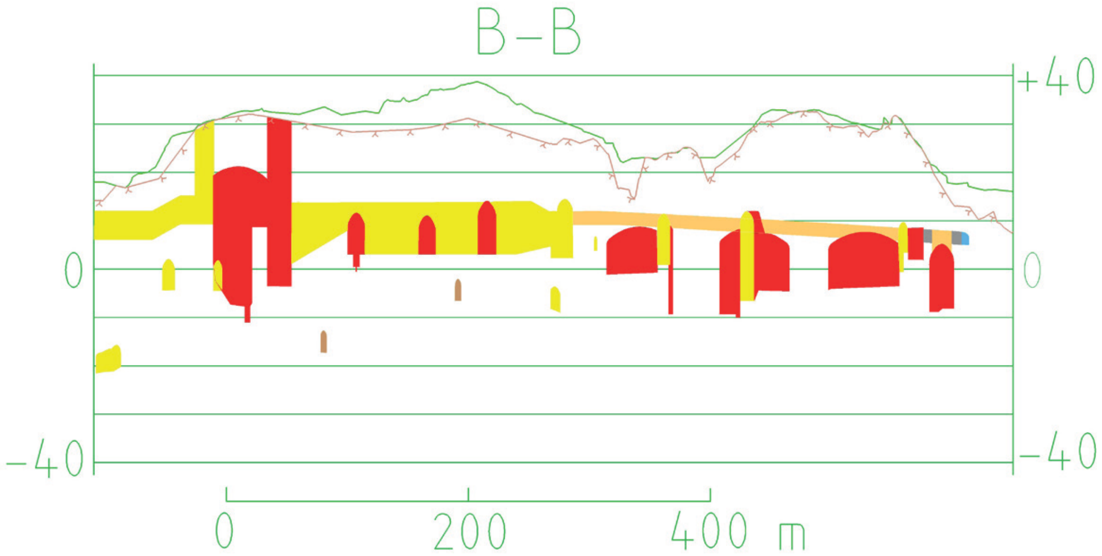

Figure 10. Longitudinal section of the wastewater treatment plant (20, p. 35)

In figures 9 and 10, the red colored profiles are treatment basins for wastewater. The yellow colored profiles are other underground spaces and maintenance tunnels.

5.3 Hartwall Arena ice hockey rink, Helsinki, Finland

The ice hockey rink was intended for training purposes. The rink was constructed in the rock below the nearby street of Hartwall Arena. The changing facilities locate at the same level with the practice rink. Construction was completed in the spring of 1999. The main dimensions of the hall are: width=31-32 meters, length 75 meters and roof height approximately 6 meters. The ventilation shaft was excavated through the rock to the surface beside the street. The property is owned by Helsinki Halli Ltd. Hartwall arena and the underground hall is the home arena of hockey club Jokerit. The hall is in constant use as Jokerit and its junior teams practice there. (21, p. 92)

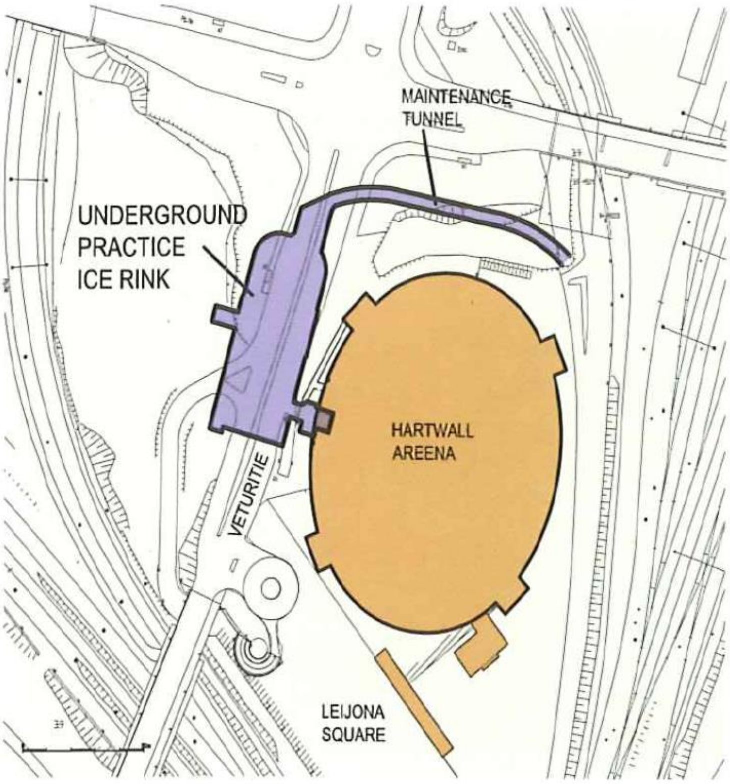

Figure 11. Underground ice hockey rink of Hartwall Arena (21, p .92)

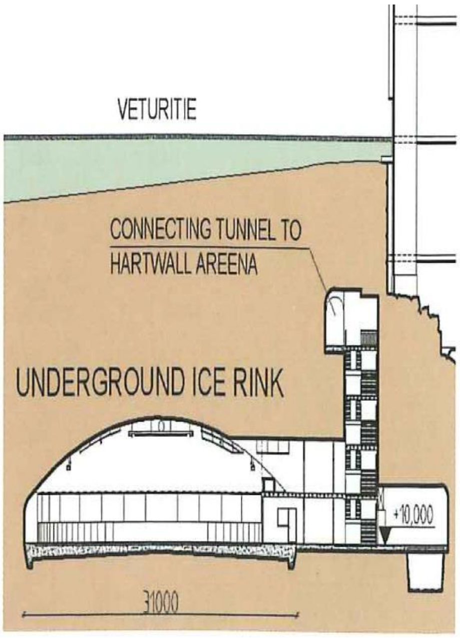

Figure 12. Cross section of the underground ice hockey rink (21, p. 92)

Figure 13. Ice hockey practice underground (21, p. 92)

5.4 West metro, Aalto-university station and metro tunnel, Espoo, Finland

Figure 14. The West Metro (Länsimetro) project (22)

The West Metro (Länsimetro) project was launched in 2009. The goal of the West Metro project was to connect Espoo to Helsinki with metro line. The existing metro of Helsinki would be connected to West Metro in Ruoholahti station in Helsinki. The Aalto-university (Otaniemi) station and metro tunnel project would be the most difficult spot vibration wise due to the laboratories and sensitive equipment of VTT (Finnish technology research center) and Aalto-university.

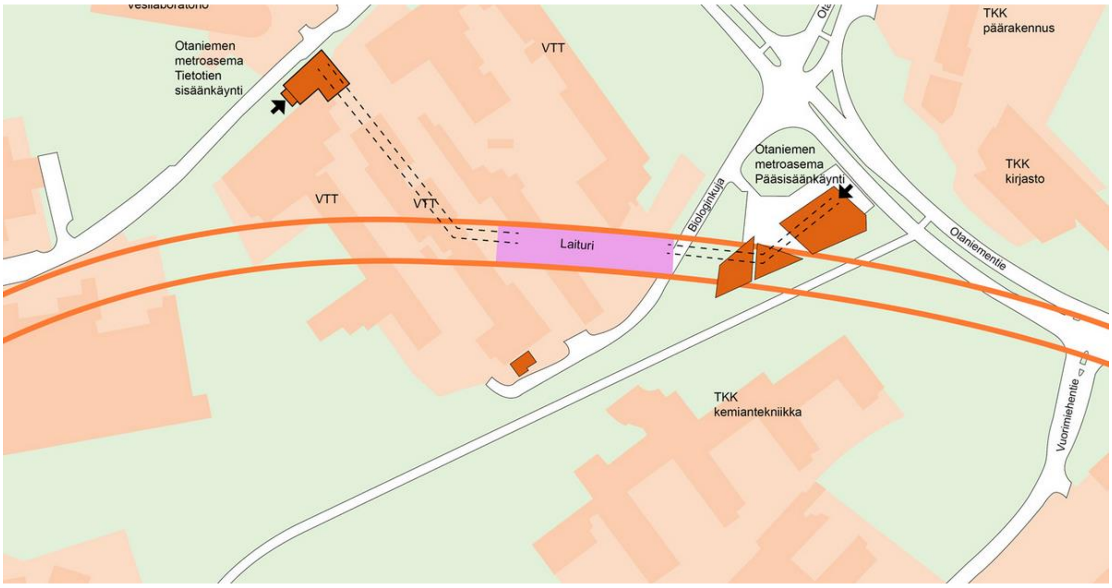

Figure 15. Aalto-university station and metro tunnels (22)

The Aalto-university station and metro tunnel excavation project was difficult due to near location of VTT and Aalto-university. VTT and Aalto-university laboratories were close and affected tunneling as the sensitive laboratory equipment was not to be harmed. As seen in figure 15, the laboratories are close (in figure, TKK=Aalto university, orange metro tunnels, dark orange entrances and purple the station area). The lowest limits in this project were 0,1 g (0,981 m/s^2). The engineers of the contractor (SRV Construction Ltd) calculated that the largest amount of charge was around 1 kg to stay within the limit of 0,1g. In the toughest part, the contractor drilled d=250 mm cut hole for tens of meters with a directional drill. SRV engineers designed that if the profile (36,16 m^2) was blasted in two sections, it would ease the vibrations with high end detonator numbers. So the profile was blasted with top and bottom heading. The bottom heading was excavated first. The round length from these two headings was 1 meters. With this information, it can be assumed that the k-factor and/or the frequency between the point of blast and the point of sensor was low and helped the contractor. As calculated in chapter 3.6, the k-factor and frequency weight in calculations. (23)

5.5 Northern Link, Stockholm, Sweden

The Stockholm Northern Link project (Norra Länken) was designed to connect European highways E20 and E4 with the Värtan- Frihamn port, which is the

Sweden’s most used port for passanger traffic to Finland, the Baltic States and Russia. The Northern Link project is 5 kilometer long, mostly underground expressway, which will become the third quadrant of the Stockholm’s inner circular expressway. Locally, this massive circular expressway is called “The Ring”. The Northern Link project consists of two parallel 3-lane main tunnels and complex of ramps and maintenance tunnels. The tunnel is 11 kilometer long, 9 kilometer of which are in rock. The tunnel was excavated with drill and blast method. The cross-sections consisted of 70, 90,120 and 260 m^2 for 1, 2, 3 and 4-lane tunnels. The tunnel is scheduled to open to traffic in 2015. (5)

Figure 16. The Northern Link (Norra Länken) location in Stockholm. (5)

The difficulty in this project was that, the tunnel was excavated beneath urban environment including public institutions, residential and commercial properties and an important city-state park. For example, five of the tunnels passed very close to the AlbaNova University Center. At one point, there was only 7 meter rock roof between the round and the center. AlbaNova center contains extremely sensitive equipment whose resistance to vibration was measured in µm/s. Short distance away, six of the tunnels cross a few meters under or over existing tunnels in the Stockholm metro. The disturbance to the metro and the research facitilies had to be minimal. Nitro Consult, a Swedish vibration consultant provided equipment to monitor vibrations, and took care of the attenuation of the sensitive equipment. Nitro Consult also assisted with ground investigations and helped solving issues in design and conducted a series of test blasts to obtain data about vibration transmission through rock.

In Mr. Donald Jonson's (CEO of the Nitro Consult) article (5) about the Northern Link project, Mr. Jonson describes a vibration-wise difficult spot: 110-125m^2 section tunnel which was driven parallel to and 10 meter distant from existing heating-supply tunnel. The peak particle velocity value (determined on the basis of earlier test blasting done by Nitro Consult) was 100mm/s in any direction. (5)

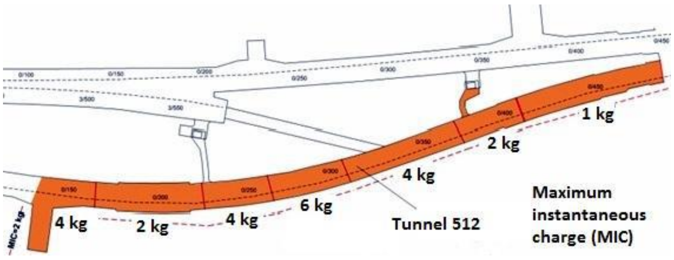

Figure 17. MIC limits in Tunnel 512 (5)

To achieve maximum productivity and to stay in the PPV limits, the contractor (JV Hochtief-Oden Tunneling) introduced Orica i-kon VS, fully programmable electronic blast initation (EBI) system after excavating with non-electronic detonator and surface detonator combination. According to Mr. Jonson, the contractor found out that non-electronic detonator-surface detonator system was not reliable, as the contractors goal was to blast one hole at the time in over 250 drill hole round. The non-electronic detonator system has range of uncertainty in the described delay time. The usage of EBI system with Orica SHOTPlus-T blast design software with NCVIB software and accurate drill rig navigation system proved that the tunnel could be excavated with maximum advance rate. The contractor was able to maintain the desired full-face advance rate of 6 meter/blast and was able to stay in the PPV limits. As result, the tunnels were completed 2 months ahead of schedule. (5)

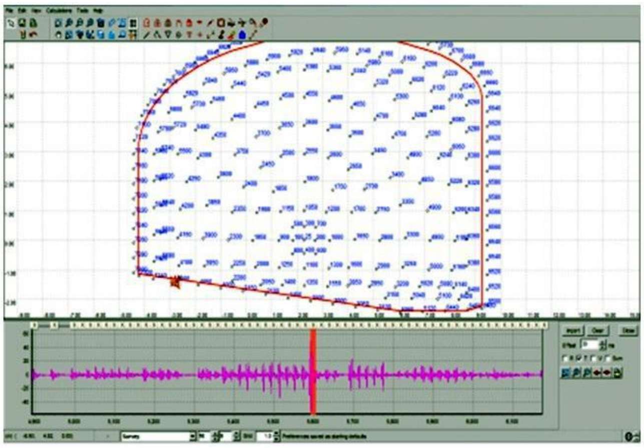

Figure 18.Orica SHOTPlus-T and NCVIB system to compare the recorded waveform with the initiation sequence. (5)

6. Summary

The guideline values of the standards of each country vary. This is interesting to me since the rock quality is mainly the same in Finland, Sweden and Norway. It seemed to me that the Finnish standard was basically a copy of the Swedish standard with exception that it was simpler to user than the Swedish standard. Iceland is the easiest standard for the user to analyze since it is so simple. During this thesis as I discussed with a contractor in Iceland, he told me that vibrations are not a limiting factor in tunneling in Iceland since most of the projects are done outside of urban environment and the existing structures.

The interesting part was when a reference case was calculated with the standards of each country. The results were surprising as Norwegians do not use distance in the definition of PPV allowed, the result is way higher compared to others. The other interesting part was that for example the Finnish standard allowed smaller PPV values in longer distances but in shorter distance, Finnish standard allowed the biggest PPV value.

I believe that these results are only theory and the k-factor and the frequency of each country's soil and rock material vary so much that proper comparison cannot be done. Only Finnish and Swedish results were close to each other and that is basically because the Finnish and Swedish standards are similar and the rock conditions are similar.

7. List of figures

8. List of tables

Table 19. Attenuation measured behind the gap (14, p.355)

Table 20. Guideline particle velocity values for curing concrete (19)

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