CHALMERS

Groundwater chemistry and its influence on the selection of construction materials

– A review of four traffic tunnels in Sweden and evaluation of technical requirements

Master of Science Thesis in the master´s programme Geo and Water Engineering

PETER LIDÉN
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Department of Civil and Environmental Engineering
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Chalmers University of Technology
Göteborg, Sweden 2012

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Cover:
Construction of the City Line (Trafikverket, 2012)

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ABSTRACT

It is relatively unknown how groundwater chemistry related issues are addressed within the tunnelling industry and how the selection of construction materials in regard to groundwater chemistry and technical requirements is carried out. Recent research has shown that the groundwater chemistry can be altered through changes in hydrogeology and become more corrosive. There are uncertainties related to the degradation of construction material with respect to water chemistry in tunnel environment. Economic benefits may be achieved if groundwater is assessed comprehensively.

Four tunnels have been reviewed: The Kattleberg Tunnel, The Löttinge Tunnel, the Stockholm City Line and the Stockholm Bypass. Data concerning groundwater sampling, groundwater chemistry, geology, hydrogeology and construction material was collected to get an understanding of how the tunnelling industry deal with water chemistry related issues. In depth studies of degradation of construction material, groundwater chemistry and dynamic groundwater have been conducted. A prediction of changes in water chemistry has been conducted based on conceptual models for two of the tunnels.

The review of the tunnels showed that groundwater chemistry in respect to the construction material in some cases was incorrectly assessed which may be due to insufficient knowledge and ambiguities in the evaluation of corrosive water. Observations concerning construction material showed that sulphate resistant grout is selected in a routine way even if it is not necessary. Sulphate resistant grout is more expensive than regular grout. Dispensation of the requirements of extra corrosion protection on reinforcement bolts was requested for in two of the tunnel projects even though groundwater was assessed to be corrosive. The use of ordinary steel bolts is more expensive than using bolts with highest corrosion protection due to the requirement of shotcrete cover.

The evaluation of the technical requirements indicated that there is a need for assessing the corrosive aspects of water due to the fact that most degradation related processes are related to the influence of water. Suitable parameters and threshold values relevant for tunnel environment should be established for the new technical requirement TRVK-Tunnel since the old threshold values were developed for other purposes than tunnel construction. There is also a need for describing the risk with rock that hold strong water bearing zones since the influence of flowing water is a larger issue for construction material than the chemical composition of it, but the corrosion rate is highly dependent on the chemical composition of the water. Estimation of the hydraulic conductivity may be a suitable parameter for describing water bearing zones.

Keywords: Groundwater chemistry, tunnel, technical requirements, corrosion protection, bolts, shotcrete, grout, sulphate oxidation and chloride

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SAMMANFATTNING

Det är relativt okänt hur frågor som rör grundvattenkemi hanteras inom tunnelbranschen samt hur valet av konstruktionsmaterial görs med hänseende till grundvattenkemi och Trafikverkets tekniska krav. Ny forskning har visat att grundvattenkemin kan förändras till att bli mer korrosiv genom förändringar i hydrogeologin till följd av undermarksbyggande. Det finns osäkerheter kopplade till nedbrytning av konstruktionsmaterial med avseende på grundvattenkemi i tunnlar. Ekonomisk vinning kan uppnås om en utförlig bedömning görs av grundvattenkemin.

Fyra tunnlar har utvärderats: Kattlebergstunneln, Löttingetunneln, Citybanan och Förbifart Stockholm. Data beträffande grundvattenprovtagning, vattenkemi, geologi, hydrogeologi och konstruktionsmaterial har insamlats för att få en uppfattning om hur tunnelbranschen hanterar frågor som berör grundvattenkemi. Fördjupningar har genomförts på nedbryning av konstruktionsmaterial, grundvattenkemi och dynamiska grundvattenförändringar. Med hjälp av konceptuella modeller har prognoser för förändringar i vattenkemi gjorts för två av tunnlarna.

Utvärderingen av tunnlarna visade att i vissa fall så har grundvattenkemi med hänsyn till konstruktionsmaterial inte utförts korrekt vilket kan bero på otillräcklig kunskap och oklarheter i myndigheternas direktiv om hur utvärderingen av korrosivt vatten ska genomföras. Observationer gällande konstruktionsmaterial har visat att sulfatresistent injektering väljs på rutin även om det inte behövs. Sulfatresistent injektering är dyrare än vanlig injektering. Avsteg från kraven om extra korrosionsskydd begärdes för i två av tunnlarna även om vattenkemin bedömdes korrosiv. Användningen av vanliga bultar är dock dyrare än att använda bultar med högsta korrosionsskydd eftersom att de vanliga även behöver sprutbetongtäckas.

Utvärderingen av de tekniska kraven visade att det finns ett behov av att bedöma de korrosiva egenskaperna av vattnet eftersom de flesta degrationsrelaterade processerna är kopplade till påverkan av vatten. Lämpliga parametrar och gränsvärden behöver skapas för de nya tekniska kraven TRVK-Tunnel eftersom de gamla gränsvärdena var framtagna för andra syften än tunnelbyggande. Det finns också ett behov av att beskriva risken med berg som innehåller starkt vattenförande zoner eftersom inverkan av flödande vatten är viktigare än den kemiska kompositionen av det men korrosionshastigheten är högst beroende av den kemiska sammansättningen av vattnet. Bedömningar av den hydrauliska konduktiviteten kan vara en lämplig parameter för att beskriva vattenförande zoner.

Nyckelord: Grundvattenkemi, tunnlar, tekniska krav, korrosionsskydd, bultar, sprutbetong, injektering, sulfatoxidation, klorider

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Preface

This master thesis has been carried out from January 2012 to June 2012 at the Department of Civil and Environmental Engineering, Division of GeoEngineering, Chalmers University of Technology, Sweden.

First of all we would like to thank our supervisor at Chalmers Fredrik Mossmark for guidance and support throughout our project.

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Finally we would like to express our gratitude to all involved persons that through interviews have contributed with valuable information for this thesis.

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Peter Lidén and Sargon Saglamoglu

1 Introduction

When constructing a tunnel the water chemistry play a role in regard to the durability of construction material and the selection of them. There are many aspects of groundwater chemistry that determine if groundwater is corrosive towards material. It is relatively unknown how groundwater chemistry related issues are addressed within the tunnelling industry and how the construction material is selected. Research on durability of construction material exists but no research brings up how the tunnelling industry actually designs tunnels with respect to water chemistry or how they incorporate findings from research. Economic benefits may be achieved if groundwater chemistry is assessed thoroughly.

There are on-going researches concerning degradation processes of material performed by BeFo (Rock Engineering Research Foundation) and KIMAB (Swedish Corrosion Institute). A project initiated by BeFo investigates the corrosive environment of tunnels and degradation processes of construction material related to groundwater chemistry, groundwater flow and geology (BeFo, 2010). KIMAB develops techniques of controlling the corrosion protection on a bolt (KIMAB, 2010). There are uncertainties about corrosion related lifespan for fully grouted bolts and lifespan of the protective coatings of zinc and epoxy.

Other research has shown that the groundwater chemistry can be altered through changes in hydrogeology. Alterations in hydrogeology are often caused by anthropogenic actions like the construction of a tunnel which can lead to lowering of the groundwater table due to water that leaks into the tunnel. This can lead to an unfavourable change in groundwater chemistry (Mossmark 2010, Laaksoharju et al. 1999, Brettum & Løvik 2005).

TRVK- and TRVR Tunnel 11 are technical requirements and advices established by Trafikverket and came into effect on 1 February 2012 and replaced BV Tunnel. New requirements for determination of exposure and corrosivity classes for construction material have been established. Groundwater chemistry parameters and threshold values that lay ground for the selection of material have been removed. There is a need for more suitable parameters relevant for tunnel construction. Differences in the interpretation of groundwater chemistry of the two technical requirements will be discussed in this thesis together with an evaluation of the parameters.

In this thesis four tunnels were studied to get an understanding of how the tunnelling industries choose material in regard to water chemistry and technical requirements. Tunnels with a supposed life length of 120 years need to be built in a robust way and therefore an in depth study of how the tunnelling industry select construction materials in regard to water chemistry was performed. The four tunnels studied are the Kattleberg Tunnel, the Löttinge Tunnel, the Stockholm City Line and the Stockholm Bypass.

2 Objective

This thesis will focus on the interaction between groundwater chemistry and construction materials in traffic tunnels. The objectives:

- Evaluate how the groundwater chemistry in bedrock influences the selection of construction material for tunnelling projects in Sweden.

- Describe how the tunnelling industry handle water chemistry related issues. Collect data on how and when groundwater has been sampled and what type of parameters that have been analysed in order to decide the exposure and corrosivity classes for concrete and steel.

- Study the differences in technical requirements concerning the evaluation of corrosive water and the selection of corrosion- and exposure classes.

- Conduct an evaluation of suitable groundwater parameters and threshold values for technical requirements because the old threshold values were not developed for groundwater chemistry of bedrock and corrosion of construction material in tunnels.

- Predict if future hydro chemical changes may occur in the Kattleberg Tunnel and Löttinge Tunnel based upon the geologic- and hydrologic conditions in the surroundings of the tunnels. Evaluate if surrounding tunnel environment is prone to become more corrosive towards construction material.

2.1 Method

In this master thesis four tunnels have been studied to evaluate the importance of groundwater chemistry in regard to construction material. The four tunnels are:

- Kattleberg Tunnel
- Löttinge Tunnel
- Stockholm City Line
- Stockholm Bypass

Data from the four tunnels were gathered from persons that were involved in the tunnel projects. Data concerning geology, hydrogeology, groundwater sampling, groundwater chemistry, groundwater lowering and construction material was collected to get an understanding of how the tunneling industry deals with water chemistry related issues.

Interviews have been done with Trafikverket which is the authority that develops technical requirements that regulate the use of material regarding water chemistry. Literature review of the technical requirements BV Tunnel, Tunnel 99, Tunnel 2004 and TRVK/TRVR 11 have been carried out.

In depth studies of degradation of construction material, groundwater chemistry and changes in groundwater chemistry due to underground construction have been conducted. Groundwater that is assessed to be aggressive towards construction material will according to requirements lead to material that can withstand degradation better. Analysis of the tunnels and selection of construction material have been performed based on data collection and interviews to give guidelines and recommendation for future tunneling projects.

The degradation of construction materials is influenced by water chemistry. Experts within concrete and steel have been used as a sounding board for assessment of aggressive groundwater.

Prediction of groundwater chemistry has been carried out for Kattleberg Tunnel and Löttinge Tunnel based on conceptual models by Mossmark (2010).

2.2 Limitations

This thesis is limited to traffic tunnels in Sweden, therefore only technical requirements from Trafikverket will be reviewed.

The groundwater chemistry in tunnel projects will be analysed in regard to the impact on the reinforcement material and drainage systems. Degradation and corrosion of construction material can occur both at the outer and inner tunnel environment. This thesis focuses on groundwater chemistry in bedrock and therefore mainly the outer environment will be taken into consideration. The construction materials studied in this thesis are reinforcement bolts, shotcrete, waterproofing and drainage systems.

How the industry deals with groundwater chemistry and its influence on construction materials during operation and maintenance will not be assessed in this thesis.

Predictions of changes in groundwater chemistry and its influence on construction material will be analysed for 2 of the 4 tunnels located in different regions of Sweden with varying geological conditions.

3 Background to hydrogeology and hydrochemistry

This chapter will introduce the main mechanisms in hydrogeology and hydrochemistry. The process of groundwater recharge contributes to the hydro chemical composition and the properties of the groundwater. The groundwater in Sweden varies depending on the geological conditions and whether areas have been subjected to marine transgression.

3.1 Groundwater recharge

When precipitation falls down on the ground it will in most cases infiltrate the soil and by gravity be transported down through the soil layers. The groundwater will flow through the ground in directions dependent on topography. This is illustrated in Figure 1 below where the dotted lines describe the flow of the groundwater from recharge- to discharge areas. (Gustafson, 2009).

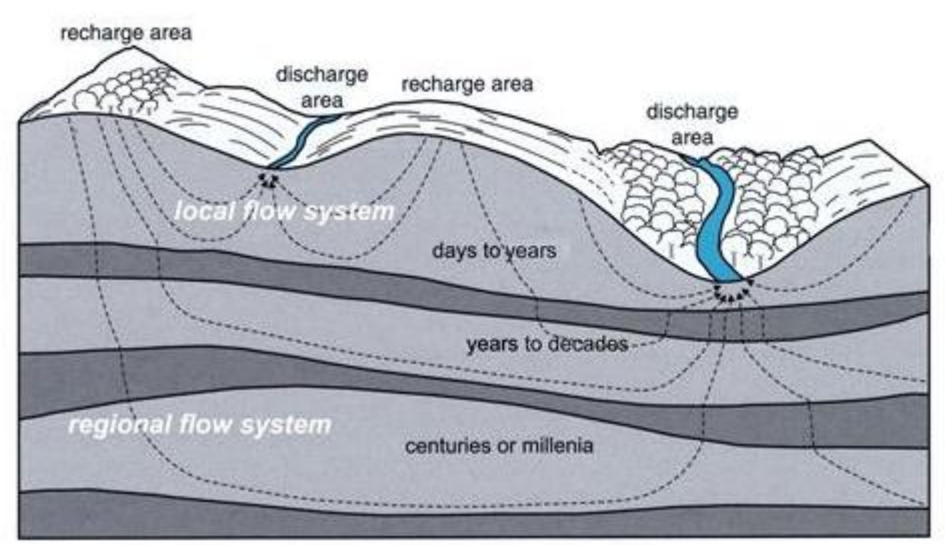

Figure 1: Illustration of groundwater flows from recharge- to discharge areas (MAC, 2011).

Hydro chemical processes in soil and bedrock

When the groundwater starts to infiltrate in recharge area the groundwater obtains its character because of chemical processes that take place during the transport of water down through the soil and bedrock. The chemical composition of the groundwater is highly dependent on the minerals present in soil and bedrock (Weiner, 2008). The deep groundwater or groundwater that has been exposed to chemical processes during its transport towards a discharge area is normally of good quality. Chemical weathering processes contributes to the character of the groundwater, processes such as hydrolysis, ion exchange and redox processes. Water that flows downwards receives higher ion strength and dissolved minerals e.g. magnesium (Mg^{2+}), potassium (K^+), calcium (Ca^{2+}) and sodium (Na^+) contribute to raise the pH-value and alkalinity. The oxygen decreases further down because it is consumed during degradation of organic material in the top soil layers (Gustafson, 2009).

The weathering tendency of soil and bedrock depends on which type of minerals they consist of. Calcite ($CaCO_3$) which is the main component of Limestone is the most easily weathered mineral and the hardest mineral to weather is the commonly occurring quartz (SiO_2) (Aastrup, et al., 1995).

3.2 Geology and hydro chemistry in Sweden

The chemical composition of groundwater varies depending on the geological location. According to Gustafson (2008) the groundwater in Sweden can be divided into different regions, however large differences within the same region can be found. The regions can be divided by the chemical differences of the groundwater based upon alkalinity, Na^+ and Cl^- content and the concentration of sulphate (SO_4^{2-}), see Figure 2 below. Alkaline groundwater is found in regions where the bedrock or soil contains lime. Skåne, Öland, Gotland, Jämtland, the area around Lake Siljan and Uppland are examples of regions with alkaline water. Groundwater with low alkalinity is found in the regions where the primary/parent bedrock is dominant such as the inner part of southern Sweden, Värmland and the inner parts of Norrland which have not been under marine transgression (Gustafson, 2008). The parts of Sweden with groundwater with low alkalinity are often linked to a lower pH value than groundwater with high alkalinity.

Bedrock groundwater with high sulphate concentration is not that common in Sweden (Gustafson, 2008). The median sulphate concentration in Stockholm groundwater is around 50 mg/L. Median value for Sweden is 16 mg/L (Jonsson, 1997). High concentrations of sulphate are often the result of influencing minerals in the bedrock containing sulphur (S) such as pyrite (FeS_2) (Aastrup, 1995). Sedimentary rock containing alum shale can give rise to high sulphate concentration in the groundwater.

The chloride (Cl^-) content in groundwater is linked to the latest glaciation; areas under the highest coastline have the highest concentration due to relic water. Salt water intrusion close to the coast is another cause for high concentrations. Eklund (2002) analysed the chloride content in crystalline rock and found that 25 % of the wells located below the highest coastline had a concentration higher than 40 mg/L while for the wells located above the highest coastline 25 % had a chloride content higher than 15 mg/L. High chloride concentrations can also be the result of de-icing agents like salt on roads.

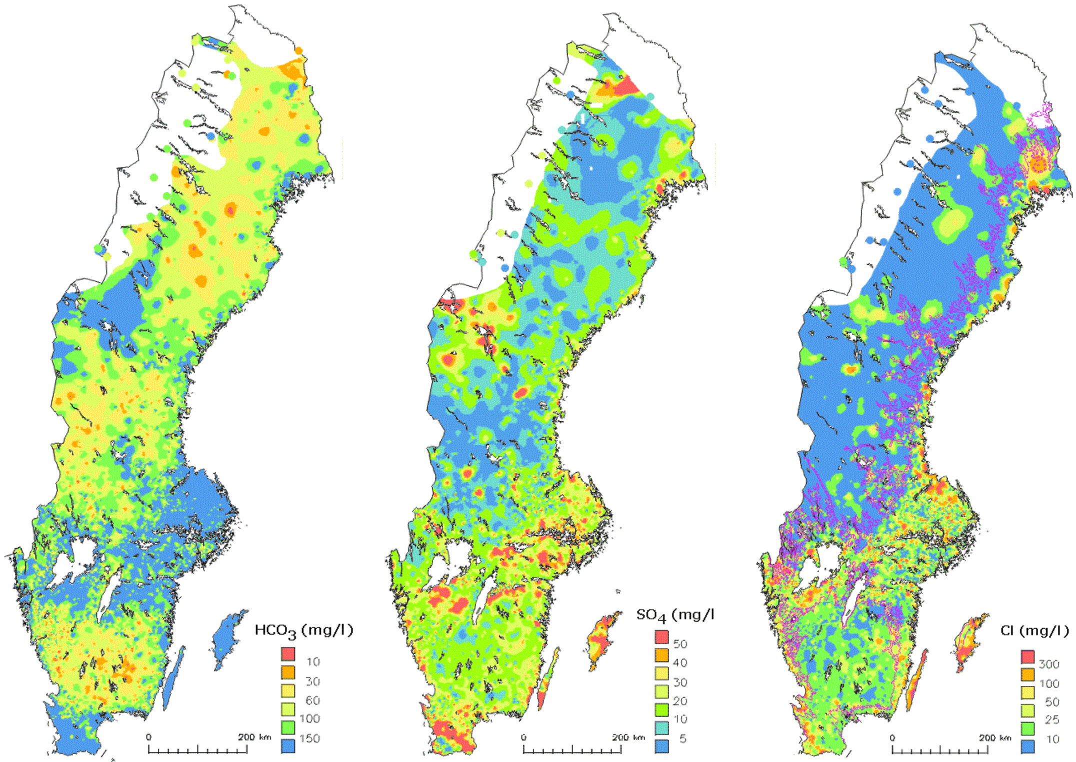

Figure 2: Illustration of alkalinity, chloride and sulphate contents in groundwater in Swedish bedrock (Aastrup et al., 1995).

3.3 Groundwater chemistry parameters

In this chapter groundwater chemistry parameters of interest are presented. The parameters are linked to the durability of construction material like concrete and steel. Guidelines of corrosion other than the Swedish technical requirements are also presented.

pH

To decide the acidity/basicity of an aqueous solution the pH is measured which is in a logarithmic scale. The pH value is a measure of the concentration of hydrogen ions H^+. Neutral water has a pH value of 7.0, if pH is under 7 it is seen as acidic and when over 7 as basic or alkaline.

Alkalinity HCO_3^-

The ability to withstand an acidification, i.e. neutralize acids is measured as alkalinity. It can be measured as mg/L HCO_3^- or in mEq/L.

Total hardness (Ca^{2+} + Mg^{2+})

The total hardness is a measure of the concentration of calcium Ca^{2+} and magnesium in mg/L. The term hardness is only used for freshwater. One German degree 1° corresponds to 10 mg/L calcium oxide CaO. Dividing German degrees (°dH) with 0.14 will correlate to the hardness in mg/L calcium.

Chloride Cl^-

Chlorides are present in all natural waters; the only difference is the concentration. Sea water has the highest and fresh water the lowest. Groundwater can contain substantial amounts of chlorides originating from relic seawater linked to marine transgressions. The chloride ion is of importance because its corrosiveness towards steel (Aastrup et al., 1995).

Electrical conductivity

Electrical conductivity is a measure of the ability to conduct electric current in an aqueous solution and is measured as mS/m. The conductivity is made up by the total content of dissolved ions but it is often used as a way of estimating the chloride content since a high conductivity value often correlates with high content of chloride. However, the relationship between chloride content and conductivity is site specific (Taube, personal communication)

Sulphate SO_4^{2-}

Sulphate is measured as SO_4^{2-} mg/L. Sulphate is a salt that derives from sulphur. Sulphide minerals like pyrite FeS_2 can be oxidized into sulphate. The concentration can be given in sulphate-sulphur SO_4-S and should then be multiplied by three to obtain the sulphate SO_4^{2-} concentration (Mossmark, pers. comm.).

Aggressive CO_2 mg/L

Aggressive CO_2 (excess CO_2) is free carbon dioxide dissolved in water. A certain amount of free CO_2 is needed to keep carbonates in solution and this part is not corrosive towards steel and concrete. The excess CO_2 not needed for maintaining equilibrium will act as corrosive towards steel and concrete (Gülich, 2010).

Ammonium NH_4^-

Ammonium is a weak acid that is often related to cattle management and the use of farmyard manure as fertilizer. Nitrification of ammonium is an acidifying process. Hydrogen ions are released when ammonium is converted to nitrite (US EPA, 2002).

Guidelines not related to technical requirements

The Swedish National Food Administration (2001) has set guidelines for drinking water that concern both health aspects and durability of pipe network. The threshold value for chloride is set to 100 mg/L and at this concentration water becomes corrosive. It can be mentioned that water begins to taste salty at a concentration around 300 mg/L (SEPA, 2000).

Other guidelines for corrosion have been developed by the California Department of Transportation (2003). Those guidelines are for steel piles driven in soil and extra corrosion protection should be given if:

- Chloride concentration is >500 mg/L.
- pH value is <5.5
- Sulphate concentration is >2000 mg/L

4 Alterations in groundwater chemistry due to anthropogenic activities

Recent studies and field investigation have shown that the ground water chemistry can vary due to anthropogenic actions like tunnel construction. When constructing a tunnel the hydrogeology of a certain area can change due to water that is leaking into a tunnel which will result in increased groundwater recharge and a lowered residence time for the water (Mossmark, 2010). Swedish authorities have requirements of how much water that is allowed to leak into tunnel constructions but this is not the only reason for a groundwater chemistry change, geology and hydrogeology play an important role.

4.1 Field studies with groundwater extractions that illustrate possible impacts from underground constructions

A field investigation has been conducted by Mossmark et al. (2008) for an area in vicinity to Lake Gårdsjön. A similar investigation was performed by Knape Hansén (2002) and Graffner (2005) for the area of Äspö island. Their findings are described below.

Gårdsjön

A field study was conducted by Mossmark et al. (2008) to see the effects of a groundwater extraction by measuring the chemical composition of groundwater together with an evaluation of runoff volumes. One catchment area at Lake Gårdsjön was studied during groundwater extraction and one similar catchment in the vicinity was used as an unaffected reference. The lake Gårdsjön is situated in the western part of Sweden. The extracted groundwater volume was measured together with continuous logging of pH, electrical conductivity (EC) and redox potential.

The catchment areas are characterized by gneissic granodiorite as bedrock that are covered with a thin layer of glacial till and organic soils (Samuelsson, 1985). 60 % of the overburden is glacial till formed during the most recent glaciation (Olsson et al., 1985). 5 % consist of organic wetlands (Nilsson, 1985). The highest shoreline was located 125 meters above sea level (m.a.s.l.) (Fredén, 1986) and the Gårdsjön area is located between 110 and 130 m.a.s.l.

The field study of Lake Gårdsjön showed that the groundwater extraction had effects on both runoff volumes and water chemistry. The important findings are described below:

- Decreased runoff volumes. It gradually increased after the extraction was terminated but was not fully recovered after 4 years.

- Concentration of sulphate had a steep increase during the autumns when recovery of water levels occurred in both lakes. At the same time a decrease in pH occurred due to the increased sulphate levels. Figure 3 below shows the relationship between pH and sulphate-sulphur. The concentration declined during the springs to levels somewhat higher than before the extraction started. According to Mossmark et al. (2008) the change in sulphate concentration can be a result of the aeration of the wetland during dry season that caused oxidizing of previously bound sulphur to sulphuric acid. The acidification was followed by increased levels of magnesium and calcium in the groundwater.

- The residence time of the groundwater decreased during the extraction which resulted in increased groundwater recharge. This changed the chemical composition of the groundwater to be more similar shallow water, resulting in decreased alkalinity and pH.

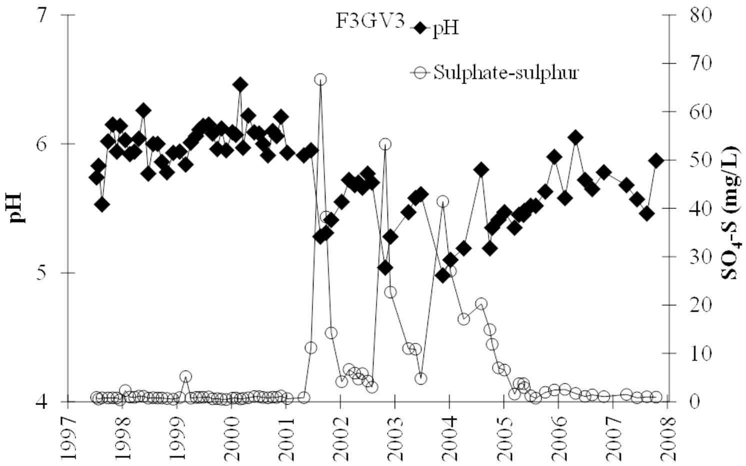

Figure 3: Time series of pH values and sulphate-sulphur concentrations in a shallow well located in organic soil of a wetland in the watershed of Lake Gårdsjön. The extraction period took place between December 2000 and April 2005 (Mossmark et al., 2008).

Äspö Island

A study of groundwater extraction was conducted on Äspö by Knape Hansén (2002) in corporation with a field investigation by Graffner (2005). Data was used and analysed by Mossmark (2010). The investigations showed a decreasing chloride content in the groundwater. The chloride content was lowered because the deeper located saline groundwater was replaced with shallow groundwater caused by an increased groundwater recharge. The same study showed a lowering of the pH and an increase of sulphate concentrations during groundwater extraction. See Figure 4 below.

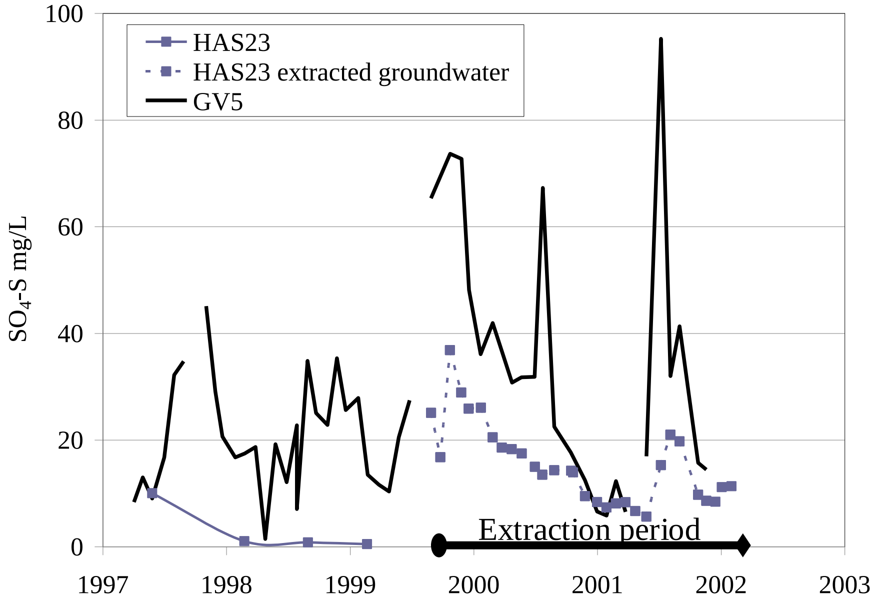

Figure 4: Changes in Sulphate concentrations during groundwater extraction. An increase can be noted during the extraction period (Knape Hansén 2002 and Mossmark 2010).

4.2 Tunnelling projects that have resulted in changes in groundwater chemistry

Experiences with changed hydro chemical compositions due to underground construction has been presented can be found in publications by Brettum and Løvik (2005), Laaksoharju et al. (1999) and Mossmark (2010). Some of their findings can be seen below.

Romeriksporten

One example of an anthropogenic activity that led to disturbance in the natural flow pattern for groundwater was the construction of the Romeriksporten railroad tunnel outside of Oslo, Norway. Observations of changed conditions in surface water and groundwater were noted during the excavation of this tunnel. Significant deviations in nearby water levels occurred and measurements in the lake Northern Puttjern revealed that the water level dropped nearly 6 meters in August 1997 (Brettum & Løvik, 2005).

The drawdown caused changes in the water chemistry, sulphate was oxidized to sulphuric acid and the acidification resulted in a pH value as low as 3.3 during construction phase. This acid pulse was registered during the construction phase and measurements of pH and sulphate showed large deviation from normal values (Brettum & Løvik, 2005). See Figure 5 below.

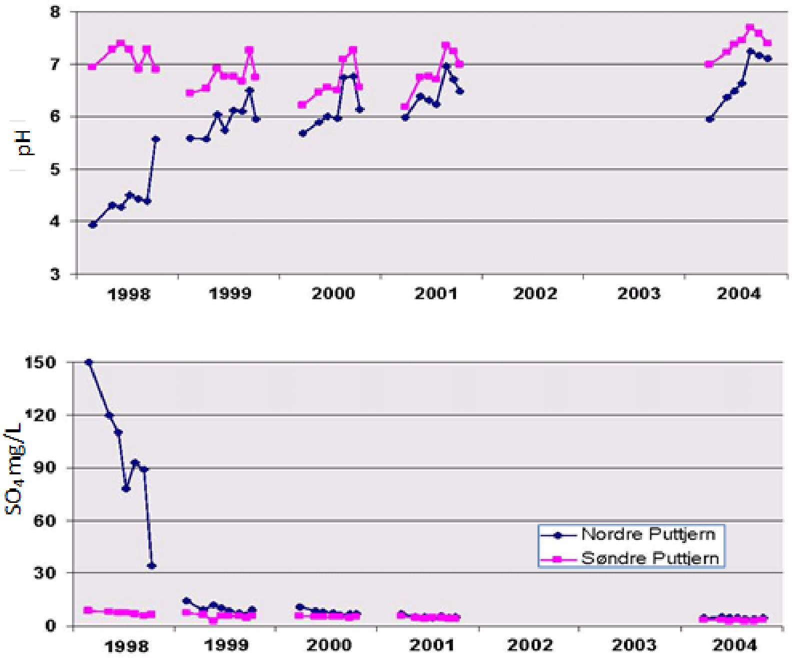

Figure 5: Changes in pH values and sulphate concentration during constructional and operational phases (Brettum & Løvik, 2005). The tunnel was completed in 1999.

The results from the measurements in the lake northern Puttjern was compared to the reference lake southern Puttjern which had similar hydro chemical composition before the impact of the tunneling. This comparison revealed that the tunneling excavation had an impact on the lake Northern Puttjern which changed the hydro chemical composition in the area (Brettum & Løvik, 2005).

Äspö Hard Rock Laboratory

During the 1990's the Äspö hard rock laboratory (HRL) was constructed in the municipality of Oskarshamn located in the eastern parts of Sweden. The research facility was built at a depth similar to a future repository for nuclear fuel and due to that a lot of research has been performed on subjects such as the surrounding hydrogeology and hydrochemistry. The research is performed in the laboratory which consists of tunnels in the bedrock down to a depth 460 meter. During the construction phase of the HRL, research was performed on hydrogeology and hydro chemistry by several researchers (SKB, 2011).

The bedrock and groundwater in the surroundings of Äspö Island have been subject to large historical changes since the most recent glaciation. The period with the Yoldia Sea raised the salinity in the Baltic Sea which has resulted in a high content of saline water in the bedrock. Water sampling during the construction of the tunnel showed that the excavation lead to upconing of deep saline water due to the leakage into the tunnel, see Figure 6 below (Laaksoharju et al., 1999).

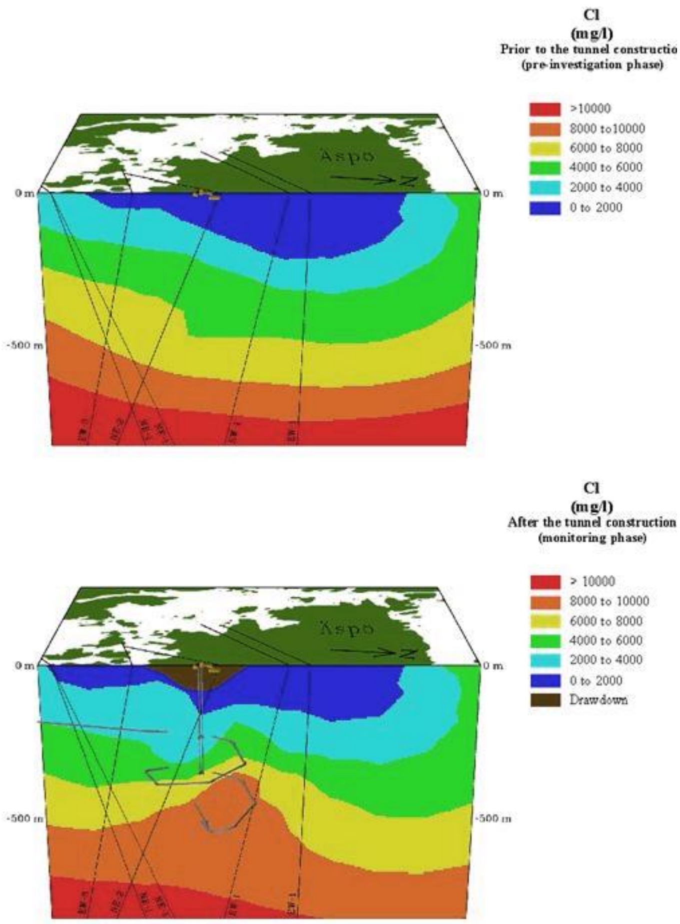

Figure 6: The top figure illustrates the salinity in bedrock groundwater prior the tunnel construction and the figure below shows the upconing effect due to the tunnel construction (Laaksoharju et al., 1999).

Hallandsåsen

In year 1992 the project with a railroad tunnel through the Hallandsåsen ridge in south western Sweden started. The bedrock in the area is at some locations highly fractured which resulted in a larger leakage and lowering of groundwater table (gwt) than expected. The Hallandsåsen is a horst consisting of mainly granitic gneiss with influences of dolerite dykes. On top of the horst wetlands of peat exist with fracture zones in close relation (Trafikverket, 2012).

During the construction phase of the tunnel changes in groundwater levels and hydro chemistry took place. According to Mossmark (2010) the above-lying wetland Flintalycke showed to be affected by the construction due to a lowering of the gwt with a resulting aeration. The impact on gwt and water chemistry is illustrated in Figure 7 below and it can be seen that sulphur most likely was oxidized to sulphate which lead to acidification.

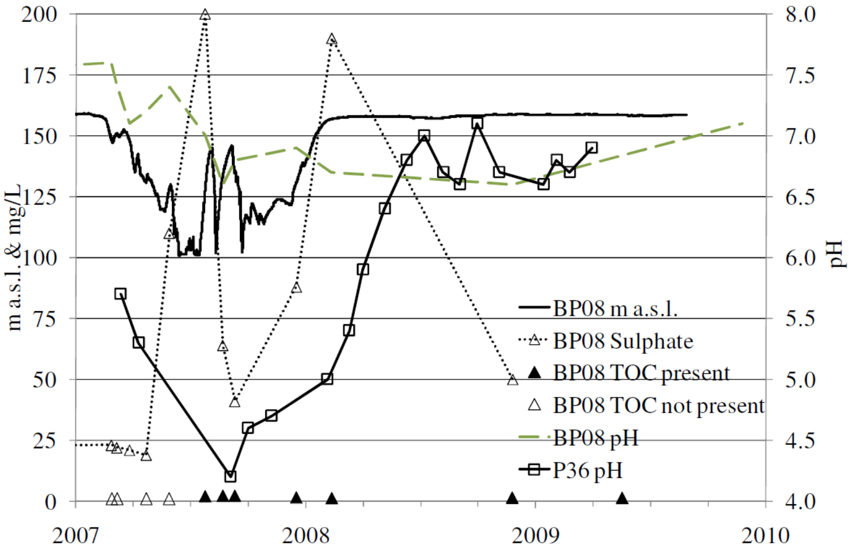

Figure 7: Compilation of water samples from borehole (BP08) and surface water (P36) in the wetland. The oxidation of the wetland resulted in higher sulphate concentrations and lower pH during construction phase (Mossmark, 2010).

In Mossmark (2010) it was concluded that the most significant disturbance to groundwater and hydro chemistry took place in discharge areas where the direction of the water flow was changed. Another finding was observed in the area of Lyabäcken. The mineral pyrite contains sulphur that was oxidized and caused the formation of sulphuric acid which lowered the pH value. The oxidation was caused by a drawdown of the groundwater table.

4.3 Prediction of changes in water chemistry due to underground construction

To predict a change in water chemistry conceptual models have been developed by Mossmark (2010). The three conceptual models feature different geological and hydro geological settings that involve recent marine transgressions, groundwater discharge/recharge areas and the influence of fracture minerals. Fracture minerals that can give rise to sulphur oxidation can be related to all of the conceptual models. The three models are:

- Groundwater discharge areas that have not been subjected to recent marine transgressions
- Groundwater recharge areas that have not been subjected to recent marine transgressions
- Areas that have been subjected to recent marine transgressions

Groundwater discharge areas that have not been subjected to recent marine transgressions

A change in water chemistry due to underground construction is very likely for this type of area that is often located in topographical depressions. The stratigraphy is made up by a layer of glacial till that is directly overlaid by organic wetlands (peat). Discharge areas are often represented by an underlying fracture zone that constitutes a hydraulic connection. Some of the changes that can be expected are:

- Discharge area can become a recharge area due to changed water flow. Water will flow from wetland to tunnel.
- Groundwater can become more similar to shallow water.
- Sulphur can become oxidized and form sulphuric acid which in turn will lower the pH and cause a release of magnesium and calcium.
- An increase of organic matter and more oxidizing conditions. Decomposition of organic matter can counteract the oxidizing conditions.

Groundwater recharge areas that have not been subjected to recent marine transgressions

This type of area will probably not experience a change in water chemistry due to underground construction. Soil type is usually glacial till and since a recharge area does not contain wetlands which are characterized as sulphur pools, sulphuric acid will probably not form under these conditions. A more possible outcome is changes in redox potential as water becomes more oxidized which in hand can affect the precipitation of iron and manganese.

Areas that have been subjected to recent marine transgressions

These areas are often covered with marine/post glacial clays on top of the layer of glacial till and can be in the form of a discharge or recharge area. This type of geological setting can resemble areas that have not been subjected to marine transgression. Main aspects to think about are:

- The clay layer can limit the hydraulic connection between groundwater in bedrock and groundwater in wetland.
- Clays of marine origin can have stored sulphur that can become oxidized if the wetland is dried up.
- Chloride in groundwater can be present due to the marine transgressions.

5 Construction material and related degrading processes

Construction material in tunnels like bolts, grout, shotcrete and drainage system can be based on the chemical properties of groundwater. Degradation processes related to construction material are found in this chapter.

5.1 Reinforcement Bolts

Reinforcement bolts are used to obtain a safe tunnel environment by increased bearing capacity. There are different types of bolts used in a tunnel: fully grouted rock bolt (cement embedded bolt), pretensioned rock bolt and split set bolts (Lindblom, 2010). Other types of bolts exist but most common are fully grouted rock bolts with no pretension (Ansell, 2007).

Corrosion on cement embedded reinforcement bolts

The corrosive environment of an embedded bolt can be divided into three zones, see Figure 8 below (Sandberg, 2007). The parts of the bolt that are embedded in cement are divided into two zones, the degree of corrosion becomes smaller as the cement further in the rock has no influence of oxygen from the tunnel atmosphere. Important factors of corrosion are the available amount of oxygen and flowing water. Chloride and sulphate are also of importance. According to Windelhed & Sandberg (2002) a bolt that has been embedded in cement in a correct way will offer good resistance against corrosion due to the alkaline environment generated by the cement.

1. Atmospheric corrosion in tunnel
2. Corrosion of cement affected by the vicinity of the tunnel
3. Corrosion of cement further in the rock

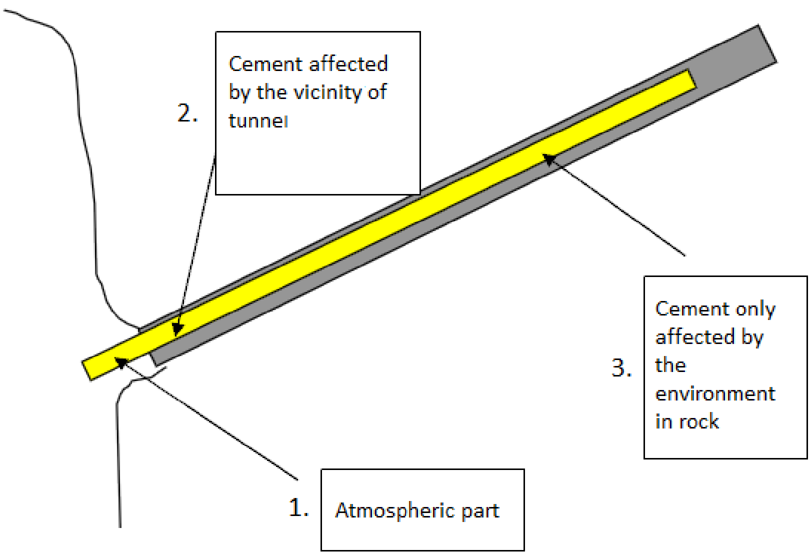

Figure 8: Cement embedded bolt in rock. Modified after Sandberg (2007)

The part of the bolt that is exposed to air will be affected by atmospheric corrosion; this is mainly dependent on the relative humidity, the amount of SO_2, NOx, Cl^- in the air and degree of particulate contamination (Windelhed & Sandberg, 2002). The corrosion rate is increased in the presence of dripping water; the rate is increased further if the water is aggressive meaning that the water has low pH and contains chloride (Sandberg, 2007).

According to Taube (pers. comm.) it has been noted that a bolt that is exposed to air and dripping water will have a corrosion rate of 5 µm/year for the protective zinc layer (hot dip galvanized) even though the water is not considered to be corrosive and have low chloride concentrations around 50 mg/L.

The cement embedment that is in contact with air will become carbonated. Swelling can occur when water reacts with cement, which can fracture the cement. This can lead to contact from air and water towards the steel (Windelhed & Sandberg, 2002). The corrosion of embedded bolts was examined in the Vindö Tunnel where it was found that the outer part of the bolt showed larger corrosion than the part of the bolt that was located deeper in the rock. 90 % of the rust attacks were located at the tunnel surface and 0.2 meter further in the rock (Sandberg, 2002).

The available amount of oxygen decreases further in the rock which means that the corrosion is limited by the available oxygen. The risk of corrosion is minor for a well embedded rock bolt only affected by the conditions in the rock. Problems with corrosion occur when water is flowing around the bolt and the cement is leached out. If the water contains chloride the corrosion of the steel will be faster. Groundwater sampling and determination of the hydro chemical properties of the water must be done to estimate the corrosion of an embedded bolt. A simple method for estimating the corrosive aspects of groundwater does not exist and this may be a reason for considering extra reinforcement before extensive investigations in vulnerable parts of the rock (Sandberg, 2007).

The grout in the rock increases the pH of surrounding water and the amount of calcium hydroxides. Bolts are passivated by the alkaline environment of fresh concrete which gives protection against corrosion. This protection can be degraded by water with low pH or chloride content (Gustafson et al., 2008). The protective effect of the alkaline environment cannot be accounted for because it is not permanent and will decline after a few years (Taube, pers. comm.). A certain water flow is required for the leaching process of concrete; if the process is slow it will result in a precipitation of calcite; CO_2 is being released to the air and calcite precipitates which may seal the fractured rock (Windelhed & Sandberg, 2002).

Sulphate reducing bacteria (SRB) can cause corrosion on steel bolts by reducing sulphate to hydrogen sulphide under anaerobic conditions (Schulze & Mooney, 1994). The hydrogen sulphide can be oxidized to sulphuric acid by sulphur oxidizing bacteria if oxygen becomes more present in groundwater. There are also bacteria that can oxidize sulphide into sulphate in the presence of sulphide minerals like pyrite (FeS_2) which can lead to increased corrosion (Botrell et al, 2000).

An examination of cement embedded bolts in underground constructions was conducted by Li (2000) where the environment of underground constructions was classified after the corrosiveness of the water and the rock mass quality. Chemistry parameters of the water that were examined were pH, oxygen and resistivity. Rock mass quality parameters where RQD and distance between fractures. The bolts that were heavy corroded were in wet environments while the bolts located in a dry environment showed less corrosion and could withstand corrosion at least 40 years. This indicates that the presence of water affects the corrosion of bolts in a negative way.

5.2 Shotcrete

A normal way to reinforce and seal the tunnel roof and walls is by using shotcrete. In all tunnels where the bedrock needs reinforcement due to fractured rock the shotcrete is used. The purpose of this type of reinforcement is to hinder falling rocks and to stabilize the tunnel structure. Shotcrete can be mixed with steel fibres for extra strength in reinforcement, a technique that is most common today though conventional reinforcing mesh can be found in old tunnels. The steel fibres are added to the cement before it is mixed with the water and thereafter shot/sprayed against the tunnel wall and roof (Lindblom et al., 2006).

The shotcrete differs from ordinary concrete because the hardening process needs to be fast. The adhesion to the surrounding bedrock is problematic and enforces the shotcrete to have other properties than regular concrete. For the fast hardening process an accelerator is admixed in the cement. Accelerators are of different types but the purpose is to affect the early hydration in the concrete. The accelerators create a stiffer gel with the involving cement particles and water. The accelerators are needed for the application of shotcrete but they also introduce problems (Lagerblad, 2007).

Degradation processes

Some accelerators contain alkali aluminates that react with the sulphate in the gypsum and the result is ettringite. This reaction is similar to the sulphate attack which occurs when the groundwater in bedrock contains sulphate and where the ettringite build up in the layer between the bedrock and the shotcrete; see Figure 9 below (Lagerblad, 2007).

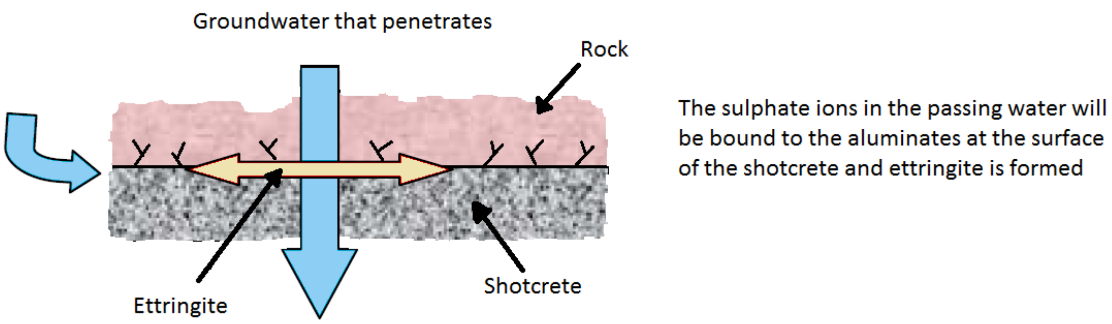

Figure 9: Illustration of ettringite formation, modified after Lagerblad (2007).

The ettringite will then cause swelling, cracking and result in a weaker reinforcement of the shotcrete. Today, most accelerators are alkali free because of the problems with the ettringite but the problem can still occur when there is high content of sulphate in the groundwater (Lagerblad, 2007).

Sulphate resistant cement (SR-cement) is normally used to prevent ettringite build up on the shotcrete. To achieve this the cement type has a low content of tricalcium aluminate (C_3A) (Lagerblad, 2007). A negative effect of the use of this type of cement with low content of C_3A is that it does not have the same ability to bind free chloride ions (harmful to steel) in comparison to non-SR-cement (Esping, pers. comm.). A study performed by Suryavanshi et al.(1995) concluded that SR-cement binds less free chlorides than ordinary cement.

Chloride does not have a negative effect on the cement but the reinforcing material of steel located in the cement can be exposed to chloride which can give rise to corrosion since the chloride can degrade the oxide layer of the steel (Gustafson et al., 2008). The corrosion products of steel have a higher volume, up to 10 times of steel and can make the cement crack (Sandberg, 2007). Figure 10 show the process of chloride induced corrosion.

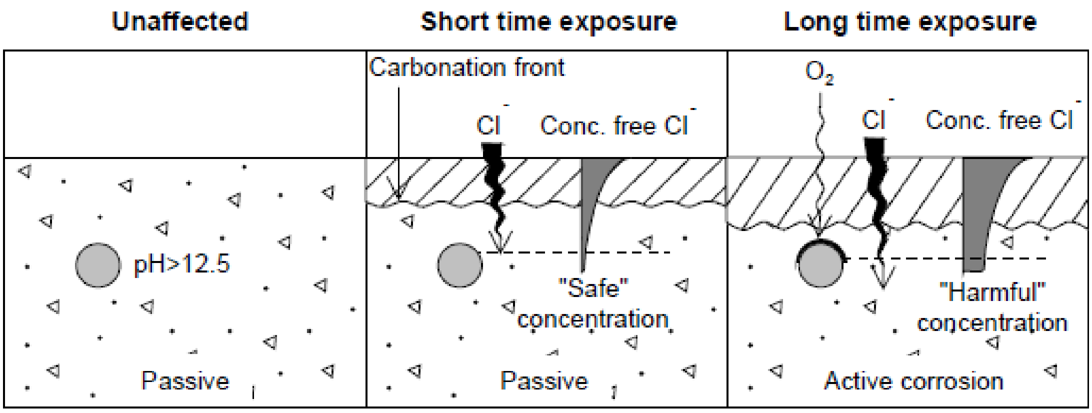

Figure 10: Schematic sketch for chloride induced corrosion (Nordström, 2005).

Conventional reinforcing mesh has a greater tendency to corrode compared to short steel fibre reinforcement according to an experiment by Nordström (2005). The shotcrete in the conducted laboratory and field experiments was exposed to high concentration of chloride which represents a corrosive environment. Other findings were that short fibres had less tendency to corrode compared to long fibres exposed to a corrosive environment (Nordström, 2005).

5.3 Grout

Grouting is performed in order to maintain a dry inner tunnel environment and to prevent changes in groundwater levels. It can be done before the tunnel is blasted and is then called pre-grouting, see Figure 11 below. Post-grouting is performed when the tunnel is blasted. Holes are drilled through the bedrock and cement is forced in by pressure to fill voids and joints of the bedrock. Post-grouting is often performed when in leaking water is an issue even when pre-grouting have been performed. Most common in Sweden is pre- grouting with cement but other grouting agents exist, such as silica sol. (Vägverket, 2000). Cement injected grout generates an alkaline environment in the rock with higher pH-levels than normal but this high alkalinity will decrease over time (Taube, pers. comm.).

In order to predict the amount of grout that is needed, an understanding of the hydraulic conductivity of the rock is of big importance. A common process in tunneling projects is to evaluate the hydraulic conductivity by doing an in situ Lugeon test also known as Packer test. Water is then injected into a borehole with constant pressure during a couple of minutes which finally results in the knowledge of the flow of water that can permeate the rock (Gustafson, 2009).

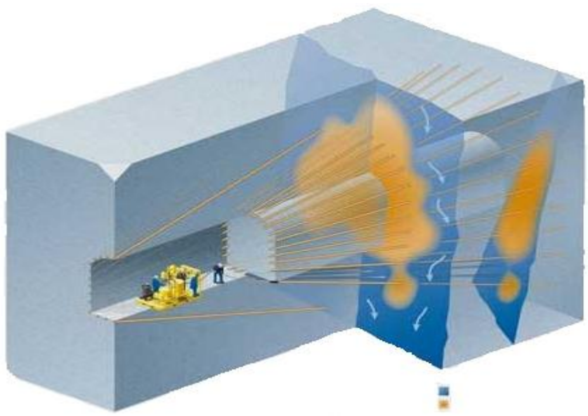

Figure 11: Grouting procedure in tunnel excavation. Orange represents grout and blue represents groundwater in rock (SKB, 2012).

Degradation of grout

The two main mechanisms that degrade cement grout are sulphate attack and leaching but there are several different processes that contribute to degradation:

- Leaching
- Sulphate attack
- Carbonation
- Alkali-silica reaction

In general the constructed tunnels have a reduced inflow of water over time meaning that the tunnel becomes better sealed. Nevertheless there are examples of tunnels that have experienced an increased flow over time due to the degradation of the cement grout in tunnels at the like in Suorvadammen hydropower plant. The characteristics of that water were the low content of ions (Gustafson et al., 2008).

The most important parameters that regulate leaching of cement are the pH value of the water and its content of calcium (Gustafson et al., 2008). Groundwater with low concentration of calcium and low pH value that flows in vicinity to the cement grout will leach out the cement faster compared to groundwater with higher values of the two parameters mentioned above. The groundwater dissolves calcium hydroxide which in turns increases the permeability of the concrete. If the grout has a low permeability and the groundwater is stationary the leaching takes place in form of diffusion which is a much slower degradation process. The rate of leaching through diffusion will become slower over time due to the build-up of unsolvable reaction products. Usage of cement with low water to cement ratio (w/c ratio) gives a less permeable medium (Gustafson et al., 2008).

Cement that is exposed to groundwater with high sulphate content will swell, leading to leaching and build-up of cracks (Vägverket, 2000). Since the grout is located within the bedrock swelling will have a positive effect by sealing the tunnel in most cases (Bodén, et al., 2001). SR-cement grout is more or less standard in tunnel constructing (SBUF, 2009).

Carbonation of concrete is when carbon dioxide (CO_2) in the air or in aqueous form in water dissolves the calcium hydroxides and calcium carbonate is precipitated according to formula 1 below.

$Ca(OH)_2 + CO_2 \Rightarrow CaCO_3 + H_2O$ *Formula 1*

This reaction lowers the pH value of the water and if more carbonate rich water flows through it will lead to leaching of the calcium in the cement. The permeability decreases when calcium carbonate is precipitated but the problems related to carbonation of cement grout are not clear. When calcium carbonate is precipitated it can form a protective layer for the rest of the grout or give a sealing effect if it is precipitated further downstream a tunnel.

Alcali-silica reaction will make the cement swell, this process is explained more in detail under the chapter 5.2. The swelling can be a positive effect for the sealing of fractures in rock (Gustafson et al., 2008).

5.4 Tunnel drainage

One of the most important factors in tunnelling construction in urban environments is to have as little leaking water into the tunnel as possible to avoid settlements of overlying soil. Tunnels have leakage of water even though grouting is performed and that water must be taken care of to maintain the operation of a tunnel (Ansell et al., 2007). Removal of ice during winter time and water removal during summer are examples of maintenance in traffic tunnels that can disturb the operation of the tunnel if the drainage system is out of function. Most of the cost associated with maintenance of tunnel is due to the in leaking water. There are different drainage systems that can be used to manage the inflow of water to an underground construction (Ekliden, 2008).

Clogging of tunnel drainage system

One of the occurring problems with drainage systems are that they get clogged by precipitates of iron, manganese and calcite caused by chemical or biological oxidation. Picture 1 shows precipitates of manganese, iron and calcite. Several parameters affect the formation of precipitates and the parameters of most interest are pH, Eh, geology, hydrogeology, water flow, type of bacteria and residence time of the water. Redox potential and pH are among the most important factors (Ekliden, 2008).

Picture 1: Left picture shows precipitates of manganese, middle picture displays precipitates of iron and the right picture shows calcite precipitates contaminated by iron (Ekliden, 2008).

The chemical oxidation dominates when pH is over 7 and the microbial oxidation takes place when pH is between 5.5-7.0 (Hargin, 2006). The dominating process that clogs a drain is the microbial precipitation and it is enhanced by lower Eh- value while the chemical oxidation requires a high Eh. The bacteria also require carbon as a nutrient source for the microbial oxidation, the organic material make up a large part of the formed precipitate (Ekliden, 2008).

The placement of a drain is determined when the tunnel is completed by ocular observation of the water bearing fractures (Ekliden, 2008). Precipitates can be observed during the first hours when the tunnel has been excavated. The identification of precipitates on a tunnel wall can influence how the drainage system will look and function (Andersson, 1991).

Drainage systems in tunnels are installed to keep a dry inner tunnel environment by directing the water flow to the pavement. Figure 12 displays what a modern drainage system can look like. The water drain consists of a channel where the water can be directed and insulation that is covered with shotcrete to prevent freezing. A drain can be made as “flushable” if precipitates are observed on the tunnel surface (Ansell et al., 2007).

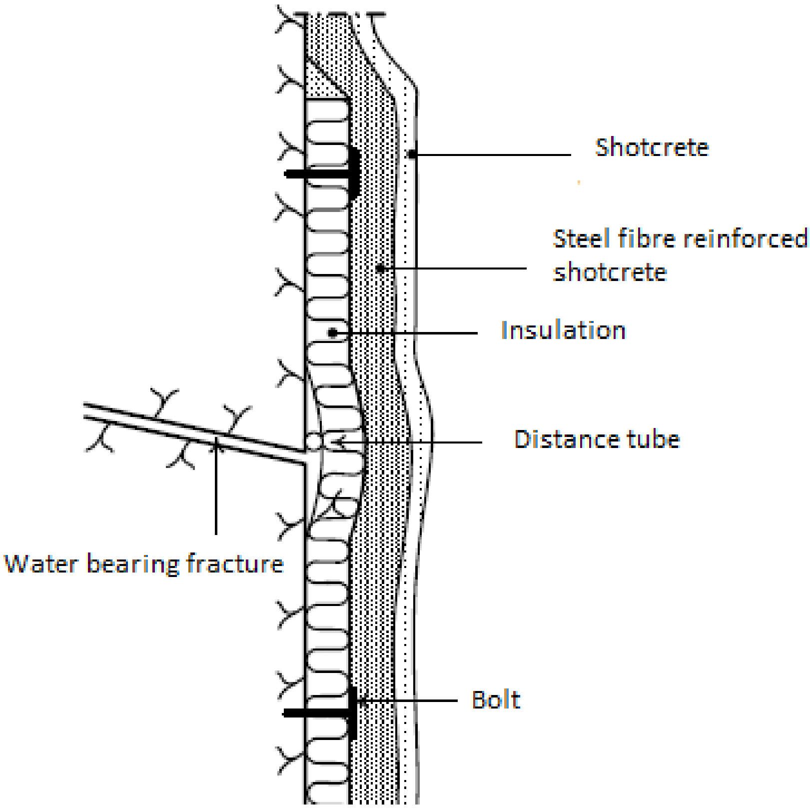

Figure 12: Conventional drainage system (Ansell et al., 2007).

6 Technical requirements on tunnel constructions

In 2010, two of the former authorities Banverket and Vägverket became a part of the new authority Trafikverket which is now responsible for planning, constructing and maintaining public roads and railroads. Trafikverket issues publications of technical requirements that regulate and give advices concerning construction and dimensioning of a tunnel in a road and railroad environment. Under the period 1999 to 2012 the technical requirements have been updated a few times. Before 2012 there were separate technical requirements for railroad and road tunnels but have now been replaced by the uniting TRVK Tunnel 11 and TRVR Tunnel.

This master thesis started in 2012, the same year as the TRVK/TRVR Tunnel 11 started to be valid which means that none of the projects evaluated have followed this standard. Prior the use of BV Tunnel 2004 the BVS 585.40 from 2002 was used for railroad tunnels. Prior the ATB Tunnel 2004 the ATB Tunnel 99 was used for road tunnels which was the first document that handled water chemistry and contained threshold values. These threshold values for assessing aggressiveness of groundwater were also incorporated into BV Tunnel 2004 (Trafikverket, 2012).

6.1 Description of the technical requirements

The technical requirements contain exposure and corrosivity classes for describing the type of environment concrete and steel are exposed to. The class defines what properties the material should have to withstand degradation. The exposure- and corrosivity classes differ between the different documents and also because there is a difference between railroad tunnels and road tunnels. The construction material is divided into different exposure and corrosivity classes depending on the environment for the construction material and the degradation process. The tunnel space is divided into an outer and inner environment, see Figure 13 below.

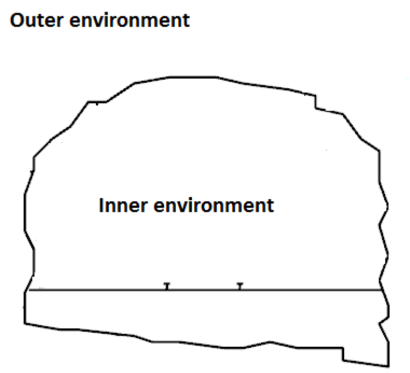

Figure 13: Exposure and corrosivity classes depend on the environment the construction material is exposed to. The rock that surrounds the tunnel is described as the outer environment and the traffic environment is described as the inner environment. Modified after Trafikverket (2011).

Two corrosivity classes exist for steel, one for inner environment and one for outer. The outer environment in the rock is dependent on the chemical properties of the groundwater/soil. Inner environment of steel is dependent on the climatic environment surrounding the bolt i.e. exposure of water or dry tunnel environment.

There are five main exposure classes of concrete, see chapter 6.2. They are divided after degradation processes of concrete; carbonation, freeze/thawing, exposure of chlorides from seawater or deicing agents (salts) and chemical attack.

6.1.1 TRVK/TRVR- Tunnel 11

TRVK Tunnel 11 is the newest edition of technical requirements for tunnel construction. TRVK Tunnel 11 shall be used together with TRVR Tunnel which contains advices and guidance of the dimensioning. The technical requirements became valid on 1 February 2012 and replaced BV Tunnel and ATB Tunnel. In this edition the chemical parameters that define aggressive water and its corrosiveness have been removed but the term “aggressive water” is still mentioned. If the water is classed as corrosive towards concrete according to SS EN 206-1 then it is also corrosive towards steel which will result in the highest corrosion protection. Criteria for marine environment have been removed and replaced. The exposure and corrosivity classes for concrete and steel constructions in surrounding rock, soil or water are given below in Table 1 (Trafikverket, 2011).

Table 1: Exposure classes and corrosivity classes according to TRVK-Tunnel 11 (Trafikverket, 2011).

Surface towards surrounding rock or soil	**Exposure class for concrete**	**Corrosivity class for steel construction**
Over groundwater table	XC2 XF3[2)]	Im3[1)]
In fresh groundwater	XC2 XF3[2)]	Im3[1)]
In salt or brackish groundwater	XS2 XF4[2)]	Im3
In soil or groundwater that can give rise to chemical attack according to SS EN 206	XA1 – XA3 XF4[2)]	Im3
Surface towards open water		
Fresh water	XC2 XF3[2)]	Im1
Saltwater or brackish water under LLW -1 m	XS2 XF4[2)]	Im2
Saltwater or brackish water between HHW +5 and LLW -1	XS3 XF4[2)]	Im3

1) For construction material of steel located in bedrock corrosivity class Im1 can be used if the water is assessed to be none aggressive and where the bedrock is systematically pre grouted or where bedrock of good quality do not need grouting

2) For a construction material in frost-free conditions the demand of XF class is not needed

The corrosion protection depends on Im class given in Table 2 below, the third column from left shows the protection measures.

Table 2: Description of the corrosivity classes Im1-Im3 (Trafikverket, 2011).

Corrosivity classes according to TRVK Tunnel	Type of environment	Corrosion protection measures
Im1	The groundwater is assessed to be none aggressive and the bedrock is systematically pre grouted or where bedrock of good quality do not need grouting	Untreated steel and cement embedment that fulfills the requirements according to AMA, EBE.1171.
Im2	Other environment	Hot-dip galvanized steel and cement embedment that fulfills the requirements according to AMA, EBE.1171.
Im3	Marine environment or the groundwater is assessed to be aggressive	Hot-dip galvanized steel combined with heat cure epoxy with a thickness off ≥ 80µm and cement embedment that fulfills the requirements according to AMA, EBE.1171.

Bolts that are exposed to air in the inner tunnel environment must be covered in shotcrete or be hot dip galvanized combined with heat cure epoxy with a thickness of 80 ≥ µm.

Chemical attacks on concrete by groundwater, soil and earth are evaluated by SS-EN 260-1.

6.1.2 BV Tunnel

BV Tunnel 2004 consist of technical requirements concerning railroad tunnels and has been valid from 2002-2012. The first edition was given out 2002 and was then updated in 2005, then replaced by TRVK 11 and TRVR 11. In BV Tunnel aggressive water is defined by the four parameters; alkalinity, conductivity, pH and hardness. This is for measuring how corrosive (aggressive) the water is towards steel in the outer environment of the tunnel, for example a bolt that is located in the rock.

The threshold values are listed below and the water is classified as aggressive if:

− *pH < 6,5*

− *Total hardness < 20 mg/L* ($Ca^{2+}+Mg^{2+}$)

− *Alkalinity < 1 mEq/L (Approximately 61 mg/L* $HC0_3^-$)

− *Electrical conductivity > 100 mS/m.*

Corrosion protection on the bolts increases if the water is classified as aggressive, then the highest corrosion protection for bolts are needed and can be seen in Table 2 above. The outer environment can be classed as marine which also results in the highest protective measure.

The criteria are listed below for the marine environment. If the water is aggressive according to the parameters above the outer environment is classed as marine (Banverket, 2005).

Marine environment refers to construction parts located in soil or rock:

− *Under free water surface with salt or brackish water*

− *Under free water surface with fresh water and soil- or rock cover less than 5 meters*

− *Under free water surface with fresh water when the rock holds strong water bearing zones.*

− *In areas with aggressive groundwater or surface water.*

The exposure and corrosivity classes for outer environment in Table 3 below for BV Tunnel are similar to TRVK Tunnel.

Table 3: Exposure- and corrosivity classes according to BV Tunnel (Banverket, 2005)

Surrounding rock or soil	**Exposure class with respect to carbonation/chloride corrosion**	**Exposure class with respect to freezing/thawing**	**Corrosivity class for construction steel**
Marine environment	XS3	XF4	Im3
Other environment	XC4	XF3	Im3 1)
Surrounding water			
Fresh water	XC2	XF3	Im1
Saltwater or brackish water	XS2	XF4	Im2

1) For construction material of steel located in bedrock corrosivity class Im1 can be used if the water is assessed to be none aggressive and where the bedrock is systematically pre grouted or where bedrock of good quality do not need grouting

Chemical attacks on concrete by groundwater, soil and earth are evaluated by SS-EN 260-1, same as in TRVK/TRVR 11.

6.1.3 ATB Tunnel 2004

ATB Tunnel 2004 consists of technical requirements and advices from Vägverket concerning road tunnels. The exposure and corrosivity classes are the same as in BV Tunnel. For road tunnels the main difference in exposure class and degradation process for concrete compared to BV Tunnel is the use of salt (chloride) as de-icing agent for roads. Corrosion protection measures are the same as in BV Tunnel (Vägverket, 2004).

6.1.4 ATB Tunnel 99

ATB Tunnel 99 is the predecessor to ATB Tunnel 2004 from Vägverket and was the first technical requirement that handled water chemistry. The exposure and corrosivity classes are different compared to the other technical requirements and are called environment classes. Concrete and reinforcement have one main class each while construction steel has two main classes for inner and outer environment (Vägverket, 1999).

6.2 SS EN 206-1

This standard is developed for concrete in several types of structures and environments. It is referred to in TRVK Tunnel, BV Tunnel, and in ATB Tunnel. The classes in Tunnel 99 differ but are similar in structure (Trafikverket, 2011). Exposure classes for concrete can be seen in Table 4 below and their subclasses can be seen in Appendix 5.

Table 4: Exposure classes for concrete according to SS-EN-206-1

Exposure class	Degrading processes	Explanation
XC	Carbonation	Corrosion compelled by carbonation
XD	De-icing agents	Corrosion caused by chlorides other than from sea water
XS	Sea-water	Corrosion caused by chlorides from seawater
XF	Frost	Freezing/thawing
XA	Chemical Attack	Chemical attack by aggressive water

To assess if there is a risk for chemical attack on concrete from aggressive groundwater the different technical requirements refer to the standard SS-EN 206-1, see Table 5 below. The standard describes which exposure class that should be used based on a number of different chemical components. The different classes of aggressive environments pass for groundwater with a temperature between 5 °C and 25 °C and with a velocity that can be regarded as stationary. The most unfavourable value of a single chemical component determines the exposure class.

Table 5: Exposure classes with regard to aggressive groundwater according to SS EN 206-1

Chemical component	XA1	XA2	XA3
SO_4^{2-} mg/l	≥ 200 and ≤ 600	> 600 and ≤ 3000	> 3000 and ≤ 6000
pH	≤ 6.5 and ≥ 5.5	< 5.5 and ≥ 4.5	< 4.5 and ≥ 4.0
CO_2 mg/l aggressive	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
NH_4^+ mg/l	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg^{2+} mg/l	≥ 300 and ≤ 1000	> 1000 and ≤ 3000	> 3000 up to saturation

6.3 VVMB 905

VVMB 905 is a document that describes water sampling and how to adjust water chemistry parameters depending on seasonal variations. This document is used for steel culverts in order to assess how corrosive the water is and was also referred to in BV tunnel, ATB Tunnel and Tunnel 99 (Vägverket, 1993). The threshold values for corrosive water in the technical requirements are related to this document but are valid for water that is flowing free inside a steel culvert which is not the situation for a bolt located inside a rock. Water can flow around a bolt located in the rock but it is often not a free flow (Helsing, pers. comm.).

7 Results from the four reviewed tunnels

The results from the studied tunnels show that sampling and classification of the groundwater is normally done in the planning phase of a tunnel project, see Figure 14 below. Sampling is performed in the early planning phase and the classification of the groundwater that leads to the decision of construction material is determined in the late planning phase. The sampling and selection of construction material is normally performed by consultants with review and approval from the contractor, which in most cases is Trafikverket.

The entrepreneurs are rarely involved in classification of exposure and corrosivity classes for construction material. This is confirmed by both Trafikverket and the entrepreneurs. (Taube, Montelius, Carlsson, Wilson, pers. comm.)

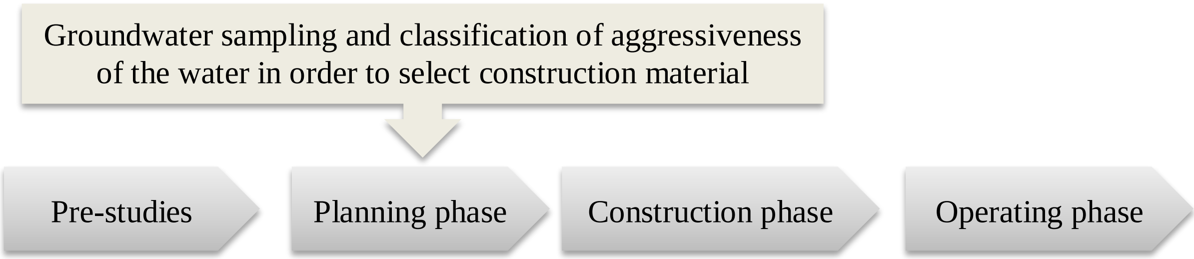

Figure 14: Phases of a tunnel project where it can be seen when the procedures for material selection is performed

Exposure and corrosion classes need to be established in the planning phase. A change in material type during construction phase can cause delays and be costly. Sampling during the construction phase is difficult due to the alkaline environment generated by the pre-injected cement grout (Taube, pers. comm.).

Reviews of how water chemistry has been assessed in regard to the selection of construction material for the four tunnels are presented in the following subchapters.

7.1 Kattleberg tunnel

A new double track railroad and road between Göteborg and Trollhättan in western Sweden is under construction in order to increase the availability and safety on the existing stretch. The railroad is partly located on a new stretch which required excavation in form of the Kattleberg tunnel. The tunnel is located between Älvängen and Hede and has a length of 1.8 km and is driven through crystalline rock, see Figure 15 to the right. Trafikverket is the contractor of the project. Bergab and Tyréns conducted the groundwater sampling. Veidekke excavated and constructed the tunnel. The excavation of the tunnel started in December 2009 with a breakthrough in June 2011 (Trafikverket, 2012).

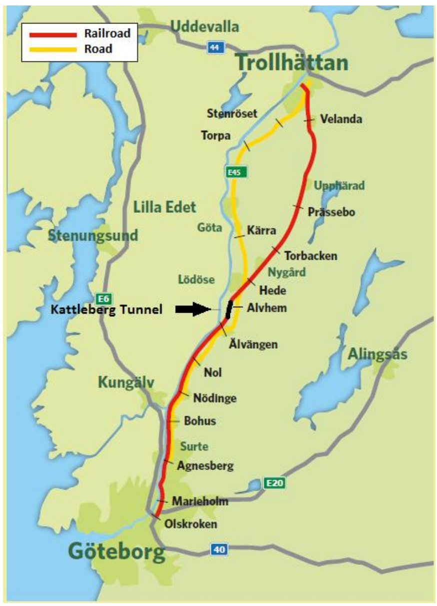

Figure 15: Illustration of BanaVäg i Väst with location of the Kattleberg Tunnel between Älvängen and Hede, modified after Trafikverket (2011).

7.1.1 Hydrological and geological conditions

The area of Kattleberg is located in the vicinity of the river Göta älv that runs west of the Kattleberg hill where the surface runoff and groundwater finally is drained out. A couple of wetlands are located in the depressions on the hill and some of them are close to the tunnel line. In

Figure ***16*** below the hydrogeological map below illustrates the tunnel (pink dotted lines in the middle), wetlands, hydrogeological flow (blue arrows), watershed (blue dotted lines), streams, and the hydrogeological area affected by the tunnel (black dotted line) (Bergab, 2005).

The highest point on the Kattleberg hill is +80 m.a.s.l (Tyréns, 2009). The whole area is located under the highest coast line after the most recent glaciation.

Figure ***16*** shows that the soil type for the area is dominated by clay (yellow) in the depressions on the hill and at the lowlands around it. Sand (orange) and glacial till (light blue) can also be found to a less extent. The thickness of the soil layers in the depressions varies from 10 meters (KBH1) to 20 meters (KBH8). The higher areas on the Kattleberg hill have outcrops (red) with thinner soil layers. The map also gives an indication on possible fracture zones in the depressions (black dotted lines in boxes) (Bergab, 2005).

The evaluation of the rock started in the summer of 2005 where 6 boreholes along the tunnel stretch were drilled in order to classify the quality of the rock. In late summer of 2007 two complementary core boreholes were drilled on locations above the tunnel, predicted to have weaker zones and low rock cover. The analysis of the cores from the boreholes showed that the bedrock in the area mainly comprises granitoids. Deeper evaluation showed that it was only borehole KBH5 in the south that contained notable amount of the sulphide mineral pyrite (Eliasson, 2006).

The hydraulic conductivity of the rock was evaluated with Lugeon tests in the drilled boreholes. The result indicated good quality of the rock apart from some depths in borehole KBH1 and KBH2 where the conductivity was much higher around the depths of 30-50 meters (Tyréns, 2009).

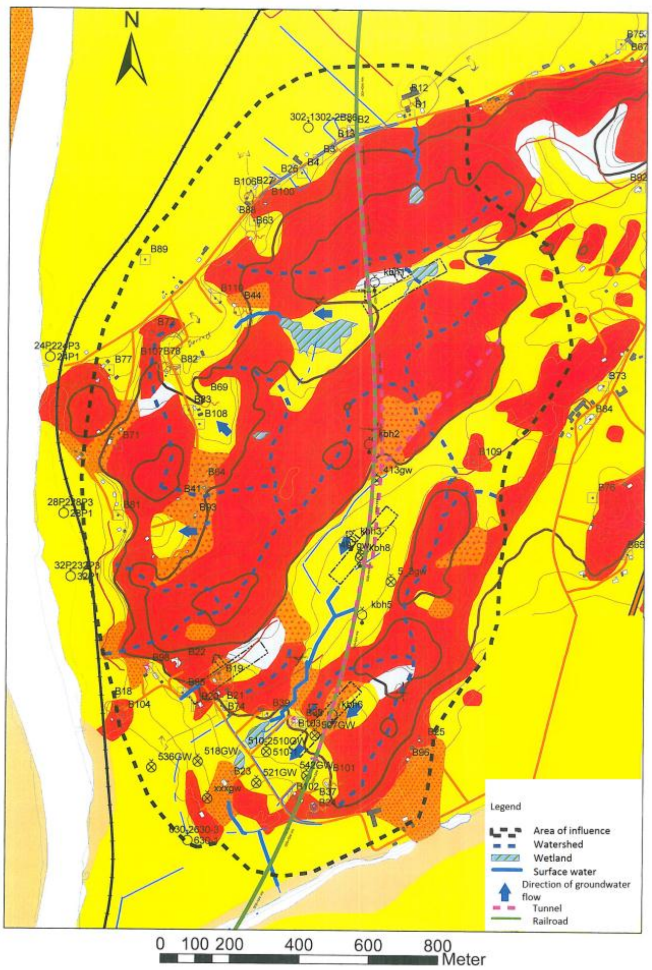

Figure 16: Hydrogeological map over the Kattleberg area, modified after Bergab (2005).

7.1.2 Purpose of groundwater sampling

Data from sampled water have been handed out from Bergab who conducted the first sampling in late spring of 2005, the second sampling was conducted by Tyréns in spring of 2008. The main intention with the sampling was to:

- Establish a control program in form of a well inventory for the domestic households located in the area of influence.

Well inventory was performed before the construction phase began in order to obtain the chemical status of unaffected wells and after the tunnel is constructed to see if a negative change occurred. These samples were also used to determine the aggressiveness of the water towards construction material.

7.1.3 Results from groundwater sampling

Water was sampled from 39 wells within the control area and 33 of them were classified as aggressive according to BV Tunnel. In total 58 samples were taken and 47 of them showed aggressiveness according to BV Tunnel. A large part of the groundwater samples were taken from drilled rock wells and according to Jansson (pers. comm.) none were taken from the core boreholes along the tunnel stretch. Data on groundwater chemistry from the well inventory have been compiled and results are shown in Table 6 below.

Table 6: Water samples from the wells that are aggressive according to BV Tunnel. Total amount of samples is shown within parenthesis. Data according to well inventory made by Bergab and Tyréns.

Parameter	**pH**	**Hardness mg/L**	**Alkalinity mg/L**	**Conductivity mS/m**	**SO_4-S mg/L**
Threshold value	< 6,5	< 20	< 61	> 100	> 200
Amount of aggressive groundwater samples in soil	3 (9)	7 (9)	6 (9)	0 (9)	0 (9)
Amount of aggressive groundwater samples in rock	2 (49)	35 (49)	6 (49)	4 (49)	0 (49)
Total amount of aggressive groundwater samples	5 (58)	42 (58)	12 (58)	4 (58)	0 (58)

Most of the samples showed a very soft water with concentrations of calcium below 20 mg/L which is aggressive according to BV Tunnel. Plots of pH/hardness for the rock wells can be seen in Figure 17 below.

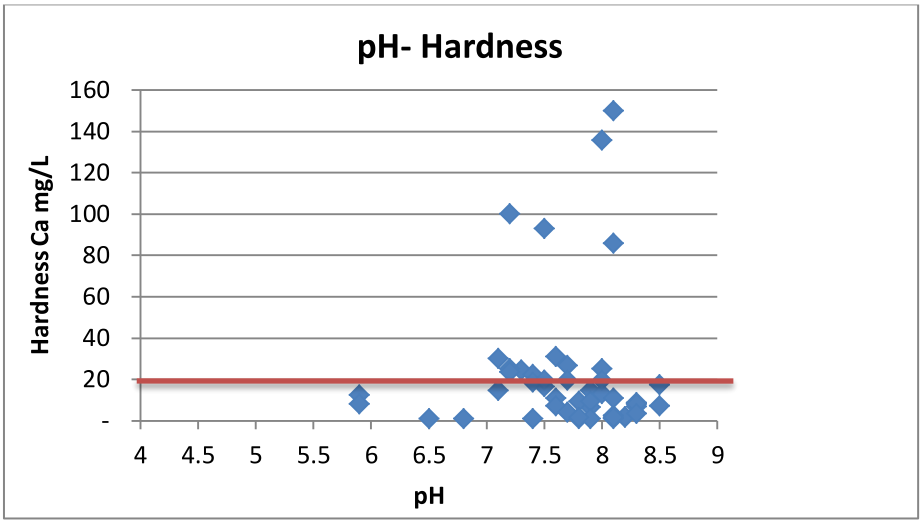

Figure 17: Water samples from the rock wells. Samples below the line are aggressive according to BV Tunnel. Data according to well inventory conducted by Bergab and Tyréns.

Three of the wells had a very high conductivity and can be related to high amount of chlorides. The pH value was over 6.5 in most of the cases, often higher than 7 and with an average of 7.6. Average values for pH, alkalinity, conductivity, hardness, chloride and sulphate for soil and rock well can be found in Table 7 below.

Table 7: Average values for the wells within the area of influence. Data according to well inventory conducted by Bergab and Tyréns.

pH	**Alkalinity (HCO_3 mg/L)**	**Conductivity (mS/m)**	**Hardness (Ca mg/L)**	**Chloride (Cl mg/L)**	**Sulphate (SO_4 mg/L)**
7.6	118	50	25	84	23

Rain data from SMHI together with the groundwater levels from SGU were used to correct the sample values according to VVMB 905. Most of the values should be corrected upwards but will still be assessed as a corrosive environment according to BV tunnel due to the fact that the hardness is very low.

Estimating the chemical attack on concrete according to SS EN 206-1 requires the concentration of aggressive carbonic acid which is missing in the well inventory.

Groundwater lowering due to tunneling construction

Groundwater lowering was observed in groundwater tubes, bore holes and private drinking water wells, for location see Appendix 3. The tunnel is almost completed and it is not sure that the groundwater levels have stabilized yet due to the complexity of the rock and its fractures. The groundwater lowering information was handed out by Trafikverket and is found below in Table 8 together with information about recovery of groundwater levels (Innala, pers. comm.).

Table 8: Compilation of groundwater level variations in boreholes, wells and groundwater tubes along the tunnel stretch during construction (Innala, pers. comm.).

Borehole(KBH) well(B) groundwater tube(GW)	Groundwater lowered (meters)	Recovery status of well
KBH1	10	Recovered
KBH2	20	Not recovered
KBH6	15	Not recovered
B1	25	Not recovered
B109	15	Not recovered
413_GW	4	Not recovered
5_3GW	Dry	Not recovered

Ground water lowering in 5_3GW may not be due to the tunneling, enormous amounts of masses have been dumped in vicinity which may have changed the groundwater flow. Clay was found in borehole B1 due to leakage from a casing tube which makes it difficult to estimate if the levels have recovered in vicinity of the borehole (Innala, pers. comm.).

7.1.4 Construction materials

The selected construction material for the tunnel is based on water sampling performed by Bergab during early planning phase and by additional sampling in late planning phase performed by Tyréns. Selection of construction material was performed by Tyréns in late planning phase with approval from Trafikverket (Jansson, pers. comm.). The materials that are used in the tunnel can be seen below (Wilson, pers. comm.).

- Bolts – B500BT, conventional reinforcement steel, lowest corrosion class Im1.
- Shotcrete – The shotcrete that is used has high sulphate resistance, low alkali content and admixed steel fibers.
- Cement embedment for reinforcement bolts has high sulphate resistance.
- Grout – Injection 30, SR-cement with low alkali content.

A new type of drainage system, Rockdrain, was installed in the Kattleberg tunnel to evaluate its properties compared to conventional drainage system. Rockdrain consists of a channel net system where the water can flow through, see Figure 18 below. It mainly differs from the conventional drainage system on two points; being less inflammable and that the drainage system is flushable. Inspection of precipitates can also be done. Costs related to maintenance of the Rockdrain should be lower if the Rockdrain system lives up to the expectations (Melander, 2011).

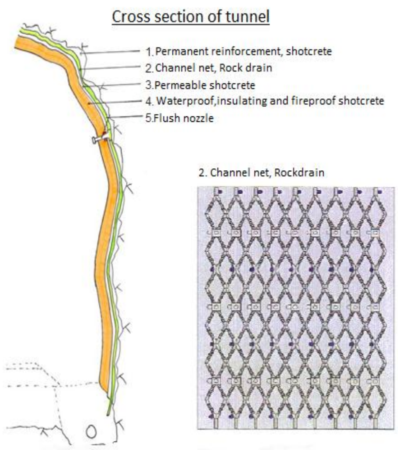

Figure 18: Illustration of the Rockdrain drainage system (Melander, 2011)

The machines used for drilling during construction required substantial amount of water. The county administrative board had set a maximum limit for the usage of municipal water for the tunnel project. Veidekke had to reuse the outgoing water from the tunnel. The outgoing water is transported through three sedimentation tanks which contain oil- and sludge separators and pH adjuster. Iron chloride was used to precipitate particles and this may have caused the drilling equipment to corrode during the time water was reused.

Sample values of outgoing water from March, June and October showed high concentrations of sulphate (>100 mg/L) and conductivity (>100 mS/m). The pH was not obtained but the alkalinity was generally low (<30 mg HCO_3^-/L). The water was pH adjusted with sulphuric acid which is the reason for high sulphate concentrations (Eddnan Husein, pers. comm.).

7.1.4 Prediction of changes in water chemistry due to underground construction

The Kattleberg hill includes local recharge areas as well as discharge areas that have been subjected to marine transgressions. Factors that can give rise to a change in water chemistry are presented below:

- On top of Kattleberg hill there is a wetland area that is located in the northern part, see Figure 16 above.
- Most of the depressions have deposits of clay in varying thickness, which can be related to the latest marine transgression.
- The sulphur content of the rock was generally low but the wetland may have a sulphur pool. KBH5 contained pyrite in smaller amounts.
- Groundwater levels were lowered during construction, up to 25 meters, the groundwater level has only recovered in one of the boreholes as of May 2012.

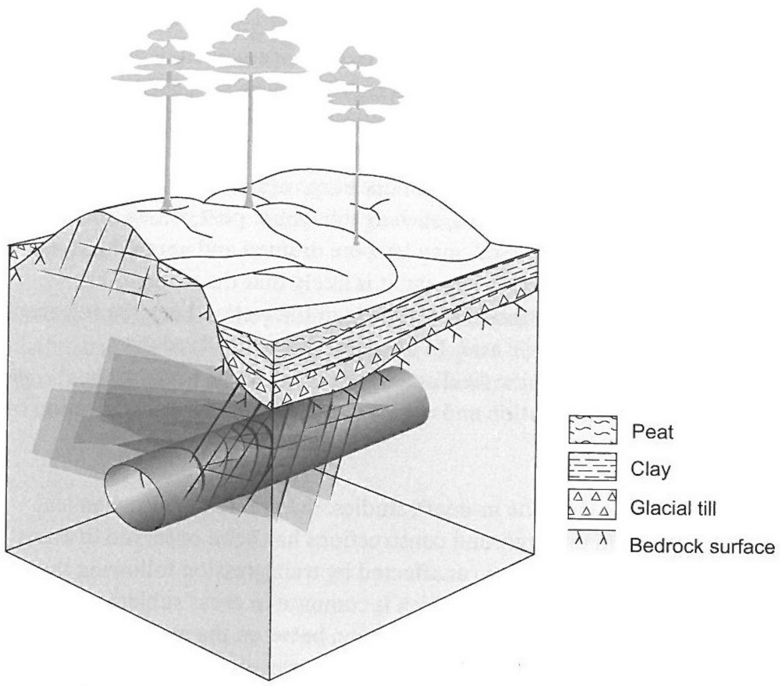

Figure 19: Illustration of the geological conditions at Kattleberg hill. Figure according to Mossmark (2010)

The wetland area gives an indication of a discharge area which can contain sulphur. Since groundwater levels were lowered in vicinity of the tunnel a possible aeration of the wetland might have occurred. This may have resulted in an acid pulse. Outgoing water from the sedimentation facility showed high contents of sulphate but this can be related to the sulphuric acid used for pH adjustment. Since the clay is of marine origin it may also contain sulphur that can be oxidized. Since no measurements were done an actual change in water chemistry is hard to obtain. Due to the grout an alkaline environment is created that affects the water chemistry. Water sampling during construction is therefore difficult. This buffering ability will then be reduced until the concrete have lost its reactivity after a few years. This buffering ability may withstand an acid pulse during construction phase.

Chloride from relic saltwater may be present in the area and some of the wells indicated a high concentration in groundwater. Four wells in the surrounding area showed chloride concentrations from around 300 up to 1000 mg/L. Groundwater with high amount of chlorides have higher density than ordinary freshwater and will be deeper located. An up-coning effect can occur where the deeper located groundwater with high chloride concentration will flow towards the tunnel and make it more corrosive.

The clay layer may limit the hydraulic connection between the groundwater in wetland and groundwater in rock. A scenario where the deeper located groundwater will resemble surface water due to a change in hydrogeology can be interfered by the clay layer since it does not allow a rapid groundwater formation.

In leaking water to the tunnel is now well under the limit and this is a parameter that controls changes in the groundwater chemistry. If a tunnel construction have succeeded in limiting the amount of in leaking water a very little change will occur. A persistent change in water chemistry is not likely for the Kattleberg tunnel. However, several groundwater levels have not recovered yet.

7.2 Löttinge Tunnel

The Löttinge Tunnel is 1.1 km long and is a part of the road stretch Norrortsleden that is located north of Täby in Stockholm, Sweden, see

Figure ***20*** below (Vägverket, 2004). The tunnel had its construction start in October 2005 and in November 2006 there was a break through. Excavation for the 18 meter wide tunnel was performed with the method drill and blast. The tunnel was thereafter divided with a concrete wall for the east and west going traffic. The Swedish Transport Administration is the contractor of the tunnel and NCC had a turnkey contract including the maintenance for the following 15 years (NCC, 2012).

Figure 20: Illustration of Norrortsleden with the location of the Löttinge Tunnel between Täby and Täby Kyrkby, modified after Vägverket (2004).

7.2.1 Hydrological and geological conditions

The tunnel is driven through a hill with a northeast-southwest direction. The surrounding geology in the area is characterized by granite, gneiss and pegmatite (NCC, 2005). For more detailed information about the geological conditions see Figure 21 below.

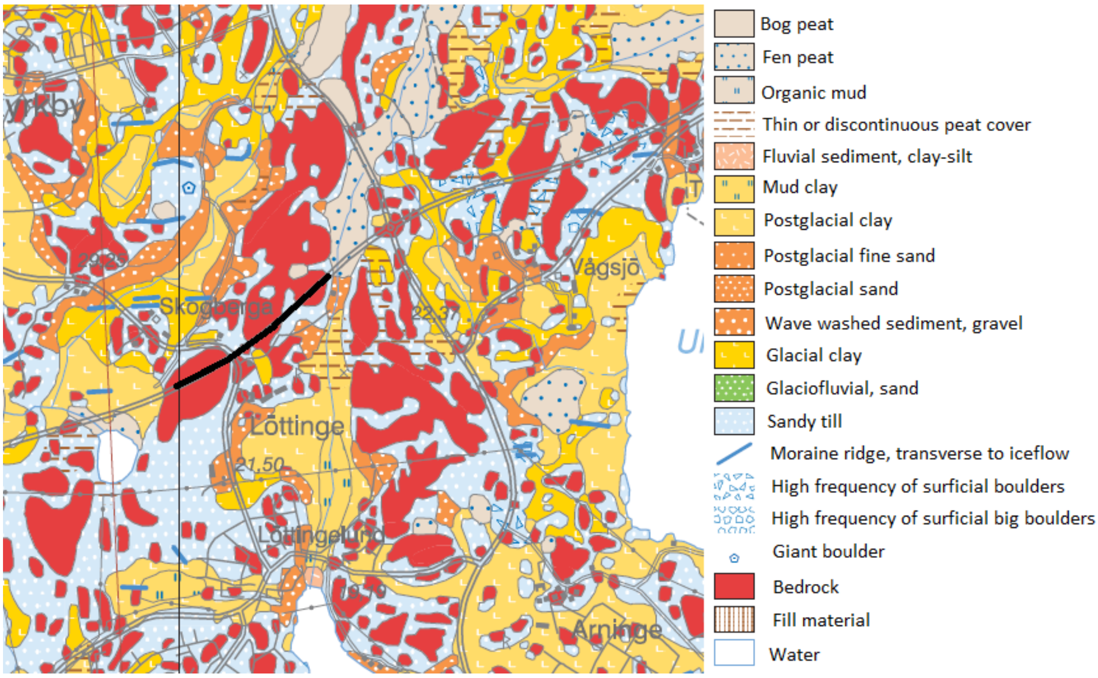

Figure 21: Quaternary deposits in the Löttinge area. The surface area is mostly covered with bedrock and sandy till. Fen peat can be found north east of the tunnel. The tunnel is illustrated with a black line (SGU, 2012).

The topography and rock cover over the tunnel differ along the tunnel stretch. The highest point of the rock is 58 m a.s.l. and around 40 m a.s.l. in the depressions. The low altitude indicates that the whole area has been under marine transgression (J&W, 2002).

In Figure 22 it can be seen that above the tunnel there are two depressions which are filled with clay or friction soil with a thickness of up to 3 meters. Much of the rock is exposed at the surface and the rock cover varies from 8 to 30 meters. Figure 22 shows eight core boreholes made during pre-investigation which was analysed in order to classify the quality of the rock. The pre-investigations like boreholes and for example seismic investigations indicated that the rock was of good quality with mediate to low frequency of fissures. Core bores from the eastern part indicated clay at depths of 3 and 13 meters inside the fissures (NCC, 2005). No mineral analysis was performed for the bedrock in the area (Dalmalm, pers. comm.).

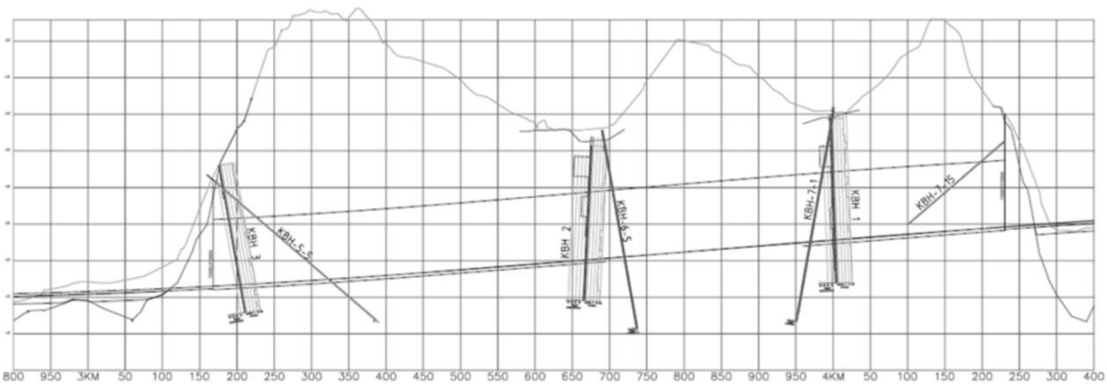

Figure 22: Profile of the tunnel with locations of the core boreholes (NCC, 2005).

The hydraulic conductivity of the rock was evaluated through Lugeon tests. The conductivity was analysed in the boreholes and based on this 4 different classes of rock types were determined. These rock types were used in order to decide the amount of grout for different sections of the tunnel. The results from the tests showed that higher conductivity values occurred in the depressions and at the openings of the tunnel but the overall impression was that the rock quality was good to very good (NCC, 2005).

A hydrogeological investigation was performed and the area of influence was defined, see Figure 23 below. The area is drained in a south-western direction and there are no wetlands above the tunnel but a fen peat area is located North West of the hill. Most of the annual 650 mm precipitation will be transported away from the hill as surface runoff or evapotranspiration and a smaller amount will infiltrate the rock, 20-80 mm/year. The groundwater lowering in the area of influence was predicted to be low both due to the relatively good quality of rock and the pre-grouting (J&W, 2002).

Figure 23: Illustration of the tunnel location in black with the surrounding area of influence in thin red line, modified after J&W (2002).

7.2.2 Purpose of groundwater sampling

Groundwater sampling was conducted at two separate occasions, in August 2005 by NCC and in November 2005 by WSP, to evaluate the chemical properties of the water. The purpose of the sampling was to determine:

- Selection of cement grout. SR-cement if groundwater concentration exceeds 600 mg/L SO_4^{2-}
- If the groundwater is aggressive according to Tunnel 99.
- Chemical attack according to SS-EN 206-1.

7.2.3 Results from groundwater sampling

Groundwater was sampled from three drilled boreholes out of eight in the first field investigation, insufficient water for analysis was obtained from the other boreholes. Water was purged out of the boreholes before the sampling to obtain representative water. Results from borehole KB1, KB6-5 and KB8 from the sampling in August are presented in appendix 3 and locations of the boreholes can be seen in Figure 22 above. Water was analysed in situ to see if there was deviation between analysis in lab and analysis in field (NCC, 2005).

The boreholes are located in the eastern part of tunnel and to get a better understanding of the western part another field investigation was done in November. Three private wells were examined that are situated on the western part and water from KB1 and KB6-5 was also examined once again together with a new borehole KB7-1. The results from November's sampling can be found in Appendix 3 (WSP, 2005).

Average values from samples can be found in Table 9 below. Almost half of the analysed samples showed low pH values where KB1 showed the lowest with a value of 5.5. The alkalinity was also low according to Tunnel 99, almost half of the groundwater samples were under the threshold value. In total there were four out of ten samples showing aggressiveness according to Tunnel 99 and seven samples were aggressive according to SS EN 206-1 if in situ sample results are excluded (WSP 2005, NCC 2005).

Table 9: Average values from the samples in core boreholes and wells. Data according to WSP (2005) and NCC (2005)

pH	**Alkalinity HCO_3^-**	**Conductivity (mS/m)**	**Hardness (Ca^{2+} mg/L)**	**Chloride (Cl^- mg/L)**	**Sulphate (SO_4^{2-} mg/L)**
6,6	74	22	29	27	15

Groundwater from borehole KB1 and KB8 were aggressive towards steel according to Tunnel 99 in the first investigation. KB6-5 was classed as aggressive if pH is adjusted down with 0.5 units according to VVMB 905. All samples from the boreholes were corrosive towards concrete. The second field investigation showed that groundwater from KB 6-5 was not aggressive even with adjustment according to VVMB 905, however the results are similar. KB1 and KB7-1 were classified as aggressive. One of the private wells exceeded the threshold value for excess CO_2. High concentration of chloride was found in two of the wells which can indicate relic water. All results are shown in Table 10 below (WSP 2005, NCC 2005).

Table 10: Results from water sampling in core boreholes and private wells in vicinity to the tunnel (WSP 2005, NCC 2005).

Borehole(KB) Well (L)	**Aggressive according to Tunnel 99**	**Parameter exceeded (Tunnel 99)**	**Chemical attack according to SS-EN 206-1**	**Parameter exceeded (SS-EN 206-1)**
KB1	Yes	pH, tot. hardness, alkalinity	XA2	pH, CO_2,
KB6-5	No	-	XA1	CO_2
KB 7-1	Yes	pH, tot. hardness, alkalinity	XA1	pH
KB8	Yes	pH, tot. hardness, alkalinity	XA2	pH, CO_2
L1	No	-	XA1	CO_2
L2	No	-	-	-
T7	No	-	-	-

Groundwater lowering due to tunneling construction

In order to not affect the water supply and quality for the private wells within the area of influence a control program was established. Measurements of the levels in the private wells together with a couple of groundwater tubes were controlled. Figure 24 below shows the different levels for four of the studied wells and tubes. The private wells showed large fluctuation due to the fact that they are used as water supplies and they are therefore hard to interpret with respect to the tunnel excavation. The relatively stable water levels in the groundwater tubes indicated that groundwater lowering due to the excavation was low. The demand for leakage of water into the tunnel was 5.5 l/min/100 m and that was achieved with good margin (NCC, 2008).

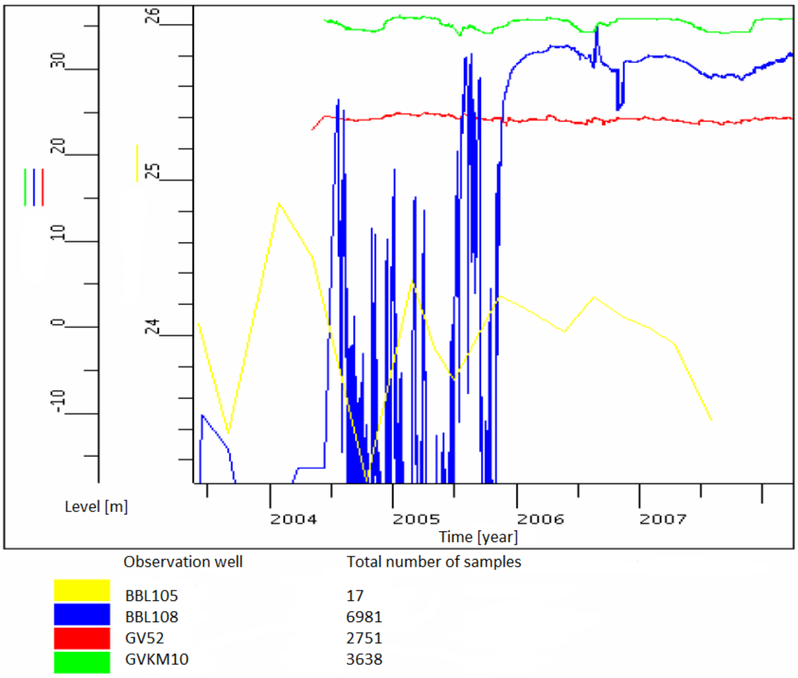

Figure 24: Water levels in groundwater tubes (GV) and private wells (BBL), modified after NCC (2008)

7.2.4 Construction material

Reinforcement bolts

The groundwater samples from the boreholes were classified as aggressive for some parts of the tunnel. NCC requested for dispensation from the requirements in Tunnel 99 because they wanted to use the bolts of low class for the whole tunnel although aggressive groundwater was found in the eastern part of the tunnel. The Swedish Road Administration accepted this request which would have resulted in use of bolts of lowest corrosion class. NCC realised that even though the lowest class could be used it would be more beneficial to use coated bolts of higher class because then they could waive the requirements of shotcrete coverage. A shotcrete cover would be more expensive than duplex treated bolts. The bolts that finally were installed were of class Im3, duplex treated bolts. The cement embedment around the bolts in rock is of SR type (Dalmalm, pers. comm.).

Drainage

NCC had several ways to determine what type of drainage system that was going to be used in the tunnel. Samples of groundwater were collected in the tunnel at various places along the stretch, one test in each of the two tunnel openings and two tests in each valley. There is an increased risk for precipitates in valleys with low rock cover or/and human activity which is the reason for two samples.

Concentration of Fe_2^+ and pH value determines the selection of drainage system (NCC, 2006):

- Concentration of Fe^{2+}> 1mg/L equals drainage class one (flushable)
- Microbial precipitation dominates at pH values between 5.5-7.0, chemical precipitation dominates at pH values >7 and neither microbial- or chemical precipitation occurs at pH<5.

Ocular inspection of formed precipitates at the tunnel wall can also be carried out to determine the type of drainage system (NCC, 2006).

The drainage system could also be selected after a Lindblad-Påsse (1986) test which indicates the risk of precipitate formation. Groundwater leaking into the tunnel was tested after Lindblad-Påsse. Water was filled in a one litre bottle and the bottle was left with a few centimetres of air. The bottle was shaken and stored in 15-20 degrees Celsius for a day. If brown coloured precipitates are formed a flushable drainage system should be selected (NCC, 2006). For Löttinge Tunnel none of the tests indicated precipitates which resulted in the selection of a conventional drainage system along the whole tunnel stretch (Dalmalm, pers. comm.).

Shotcrete

The used shotcrete was C35/45 0-8 S4 sulphate resistant. Steel fibres of the type Dramix 65/35 were admixed into the cement (Dalmalm, pers. comm.).

Grout

The grout that was used in the tunnel was the cement based product Rheocem 650 non-SR (Dalmalm, pers. comm.).

7.2.5 Prediction of changes in water chemistry due to underground construction

The Löttinge Tunnel runs through two smaller hills with overburden of clay/sandy till in the topographical depressions. The valleys of Löttinge Hill have deposits of clay that can be related to the latest marine transgression. Northeast of the tunnel a fen peat area is located which indicates a discharge area. This type of area resembles a groundwater recharge area that can be vulnerable for underground construction in the aspect of changes in groundwater chemistry, see Figure 21 above.

Sulphur analysis of the rock was not done for Löttinge Tunnel so it is unknown if the bedrock contains high amounts of sulphur that could have been oxidized. The fen peat area can contain sulphur which could have resulted in a change in groundwater chemistry if groundwater table was lowered. Groundwater levels were recorded in the valleys and no major change was registered and the leakage of water into the tunnel was below threshold value. This indicates that aeration may not have occurred because of the stable groundwater levels. The groundwater table drawdown was around two meters.

Löttinge Tunnel has probably not experienced a change in water chemistry due to underground construction since it requires a drawdown in groundwater table which did not occur.

7.3 The City Line

The City line is a 6 km long commuter train tunnel situated in the centre of Stockholm that runs between Tomteboda and Stockholm south rail station, see Figure 25 below. Construction of the City Line will result in doubled track capacity from two to four tracks and 2 new train stations will enhance the mobility. The tunnel will be completed in 2017. Trafikverket has planned the tunnel in collaboration with Stockholm City, Stockholm County Council and Stockholm Transport (SL). The tunnel construction is divided into eight stretches with many consultants and entrepreneurs involved (Trafikverket, 2012).

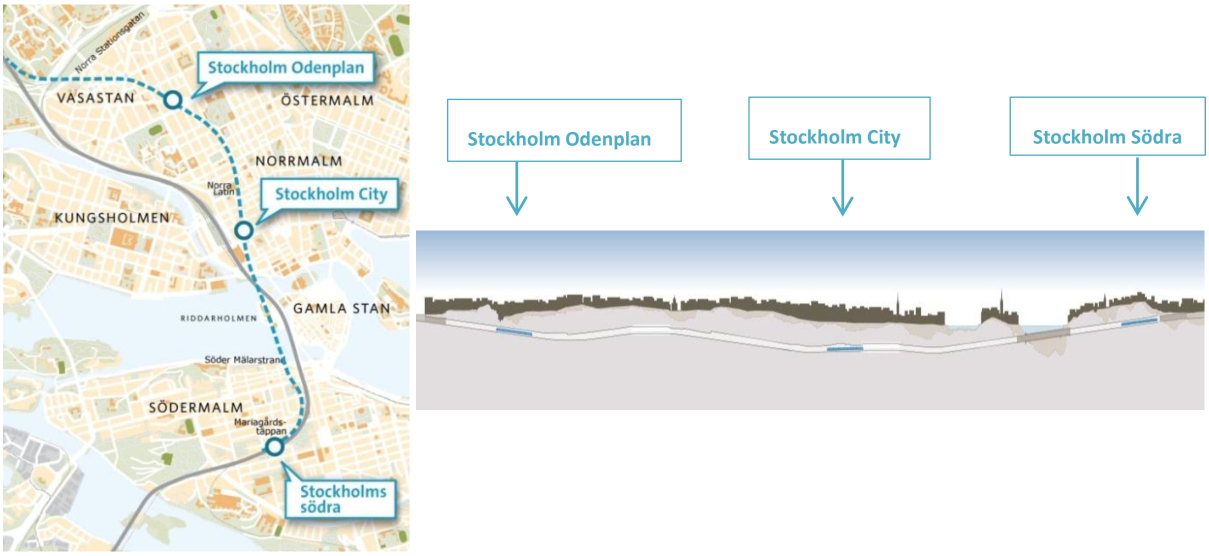

Figure 25: The blue dotted line illustrates the tunnel stretch. The figure to the right shows the profile of the tunnel (Trafikverket, 2012).

The larger part of the tunnel will be blasted through crystalline rock that constitutes young granites and gneiss of mostly good quality although weakness zones exist in mostly east-west direction. Most of the groundwater flows in these weakness zones (Banverket, 2007). Brunkebergsåsen that runs in south-north direction east of the tunnel stretch constitutes the main water bearing zone in the overburden. Clay layers can be found in depressions outside the Brunkebergsås that have been deposited on a friction layer that lies on the bedrock. A submerged concrete tunnel will be placed between Söder Mälarstrand and Riddarholmen and it is made up by three prefabricated 100 meter long concrete elements (Banverket, 2007).

7.3.1 Purpose of groundwater sampling

A group of experts containing consultants within the City Line project has been founded to develop uniting guidelines for dimensioning of the tunnel reinforcement and to set exposure and corrosivity classes in regard to water chemistry. These guidelines have been developed to ensure that the requirements on the bearing capacity are fulfilled and are valid for the entire tunnel.

The purpose of the water sampling and documentation was to:

- Explain the data that founded the decision of selected corrosion protection measures.
- Declare the selection of corrosion protection on permanent rock bolts according to BV Tunnel.

7.3.2 Results from groundwater sampling

The sampled groundwater was collected from boreholes and drainage water from SL:s traffic tunnels. Over 20 samples were taken and the results showed high conductivity (>100 mS/m) from almost all sample locations, only two boreholes were under the threshold value. This may be an indication of relic water or de-icing salts. pH values where stable with an average of 7,5 and alkalinity concentrations were around 200 mg/L HCO_3^-. The total hardness was well over the threshold value in all samples with an average of 165 mg/L Ca^{2+}. Sulphate concentration was not measured in this investigation because it was not needed for estimating the aggressiveness of groundwater according to requirements in BV Tunnel for bolts (Rosengren, 2006).

Additional sampling was done at 8 different locations in SL:s traffic tunnels and in 3 boreholes which all showed high conductivity (Rosengren, 2006).

Doubts about the accuracy of the sampling results was brought up due to the suspicion that shallow groundwater hade poured down in the sampled boreholes because bad sealing of the casing tube and that this water did not represent the groundwater in the bedrock. This suspicion cannot be applied to the samples done in SL:s traffic tunnels and boreholes that have been drilled in existing tunnels. An additional sampling of two boreholes was done to control the accuracy of the results and they found that the results were similar to the previous samples. The entire stretch was classified as “marine” due to the aggressive water (Rosengren, 2006).

7.3.3 Construction materials

The outer environment was assessed to the highest corrosivity class Im3 which results in cement embedded bolts that are duplex treated. Due to the fact that the tunnel environment is divided into an inner and outer environment in BV Tunnel it was brought up that this can result in a bolt with partial protection. The outer environment can be classed as Im3 which results in the highest corrosion protection, the part of the bolt that is in inner tunnel environment can either be covered with shotcrete or also be duplex treated to fulfill the requirements. This was not seen as a practical design since it would require a different corrosion protection system. Therefore it was decided that the entire bolts plus accessories would be given duplex treatment (Rosengren, 2006).

Duplex treated bolts were used throughout the entire tunnel stretch due to the marine environment. Dispensation from the requirements was brought up from the consultants but was denied by Trafikverket. The reason for requesting for dispensation of duplex treated bolts was that a fully grouted bolt offers good protection against corrosion and the fact that it would be more economic because these bolts are cheaper (Rosengren, pers. comm.).

In the City line it was decided that if the water is assessed to pose a “chemical attack” on concrete according to SS EN 206-1 then the outer environment shall be classed as Im3 for the bolts. The approach to the problem was that if water can leach out the cement embedment locally, the rest of the intact embedment will still offer good bearing capacity. A local attack on a steel bolt will on the other hand result in lost bearing capacity if the bolt corrodes and breaks off (Rosengren, 2006).

SR-cement grout, Injektering 30 and Rheocem 650 SR was selected for the City Line. The selection of grout was based on properties like penetrability of grout and not on SR-properties (Holmberg, pers. comm.). Information on how the shotcrete was evaluated was not obtained.

7.4 The Stockholm Bypass

In the western part of Stockholm a new linking motorway will be constructed in order to connect the Södertörnsleden with the Norrortsleden and to relieve the congestion on the currently heavily trafficked Essingeleden. The road stretch will be 21 km of which 18 km will be constructed underground in form of two tunnel tubes with three lanes in each direction. The tunnel project is now in the planning phase and the construction is planned to begin in year 2013 (Trafikverket, 2012). The tunnel will be constructed through crystalline rock with the method drill and blast and the rock constitutes young granites and gneiss (Vägverket, 2005). As seen in Figure 26 below, the tunnel will pass under some larger water filled depressions and the largest one is the lake Mälaren. The Mälardalen is characterized by graben which means that the area has been exposed to big movements with resulting fault zones and weakness zones that can be heavily water bearing. When the tunnel passes under larger surface waters the rock cover will be between 20 to 30 meters (Trafikverket, 2012).The overburden is mainly glacial till at higher elevations and deposits of clay on top of the glacial till at lower elevations (Vägverket, 2005).

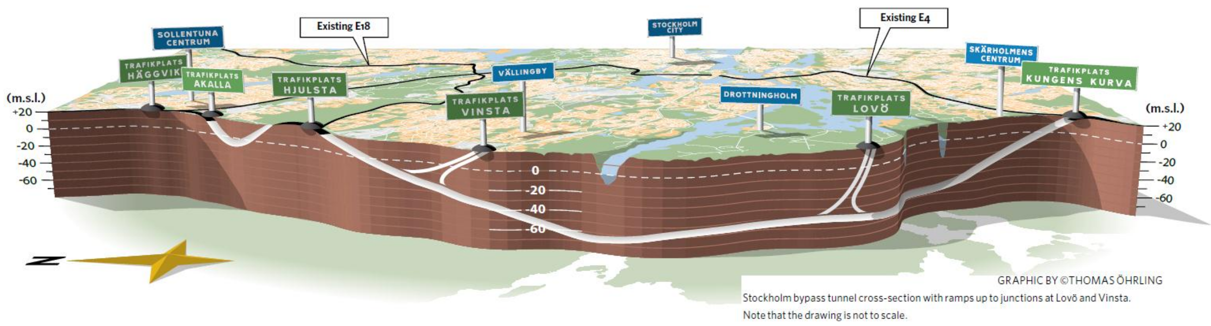

Figure 26: Sketch of the Stockholm Bypass (Trafikverket, 2012).

7.4.1 Interpretations of groundwater chemistry during early planning phase

An early investigation was performed by a consortium for the Stockholm bypass including a number of companies. One task was to evaluate the chemical composition in the groundwater for a larger area in Stockholm and also for the area of influence of the tunnel (Landin, pers. comm.). The investigation was made in the early planning phase and done in order to get a wide picture of the area and to provide a basis for the late planning phase. The groundwater was evaluated from databases with groundwater chemistry where some of the parameters in the requirements can be found (Trafikverket, 2011).

The following requirements are mentioned:

- Selection of cement grout: SR-cement if groundwater concentration exceeds 600 mg/L SO_4^{2-}.
- Assess if the groundwater is aggressive according to BV Tunnel.
- Assess a chemical attack according to SS-EN 206-1.

The groundwater that was analysed came from a large area in Stockholm and contained more than 750 wells of both soil- and rock type. The studied parameters were pH, alkalinity, hardness, conductivity, sulphate and chloride. A cumulative distribution was performed for all wells (Trafikverket, 2011). The result can be seen in Figure 27.

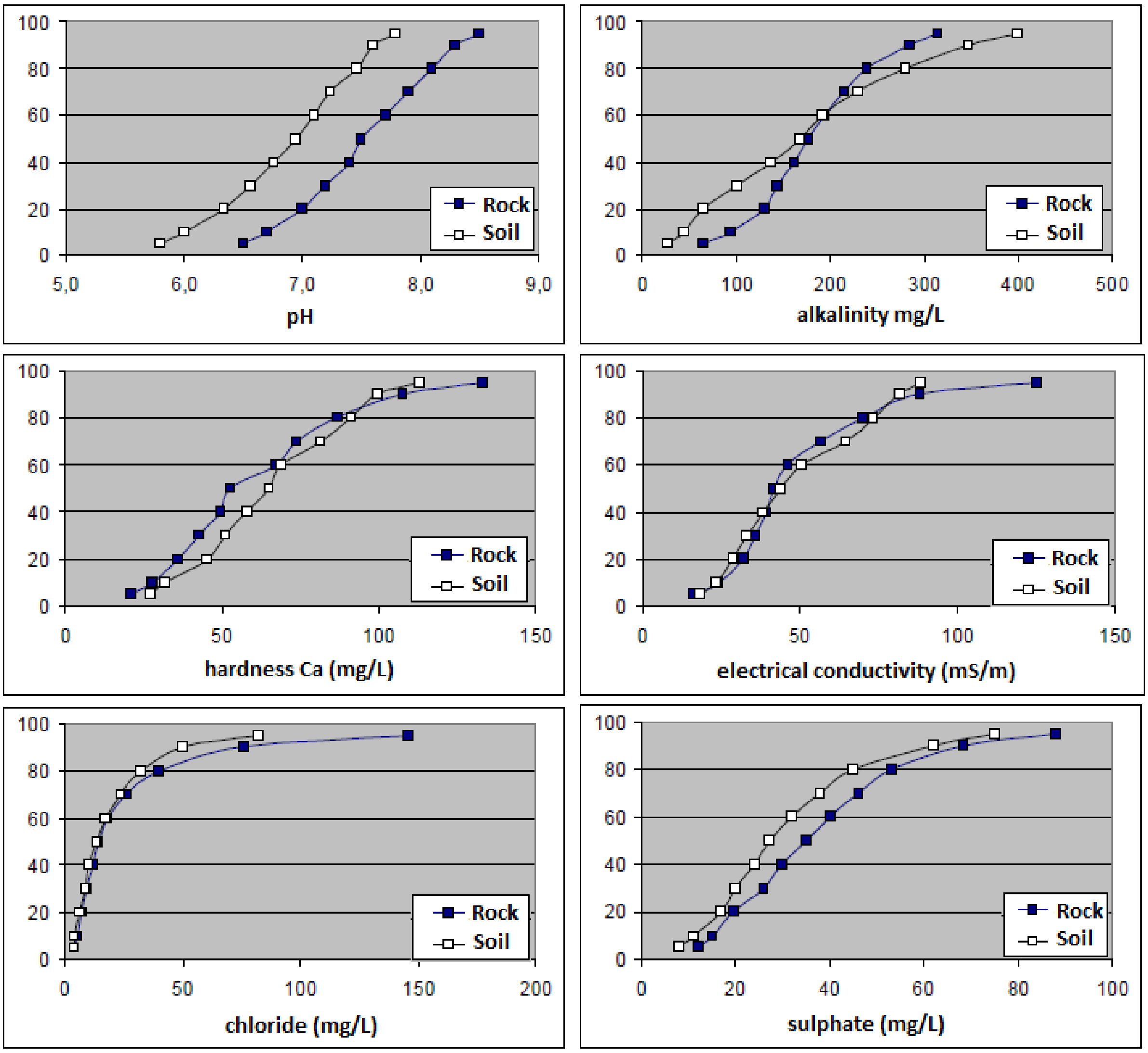

Figure 27: Cumulative distributions for the six parameters. Rock wells are illustrated with black lines and soil wells with white lines (Trafikverket, 2011).

The area of influence was also studied by help of the data from the wells but only the relevant ones in close relation to the future tunnel. For this area 5 samples from soil wells and 4 samples from rock wells were classified as aggressive, which were 25 and 7 percent respectively. Some of the wells had more than one parameter that indicated aggressiveness. The aggressive groundwater samples are compiled in Table 11 below. It is of importance to mention that many wells had a lack of data regarding some parameters which means that more wells could have been classified as aggressive according to BV Tunnel (Trafikverket, 2011).

Table 11: The Amount of aggressive groundwater samples within the area of influence. The amount of aggressive samples out of all 750 wells in parenthesis (Trafikverket, 2011).

Parameter	**pH**	**Hardness mg/l**	**Alkalinity mg/l**	**Conductivity mS/m**	**SO_4 mg/l**
Threshold values	< 6,5	< 20	< 61	> 100	> 200
Amount of aggressive groundwater samples in soil	3 (22)	1 (3)	1 (24)	1 (2)	0
Amount of aggressive groundwater samples in rock	1 (31)	2 (52)	1 (30)	2 (4)	0
Amount of aggressive groundwater samples in total	4 (53)	0 (55)	2 (54)	2 (6)	0

The investigation also highlights future scenarios with alterations in groundwater chemistry. Issues mentioned are:

- The up-coning effect from deep relic saltwater.
- Sulphate oxidation due to lowering of groundwater and shorter retention times which may lead to increased groundwater formation.
- Influence of cement grout on groundwater chemistry.

According to Landin (pers. comm.) the early planning phase is not governing for the future construction. All the requirements for corrosion classes and the methodology for adaption to this will be done in the late planning phase and the criteria for it is under progress. There is an ambition to estimate the effect of alterations in groundwater chemistry and its impact on the groundwater quality, both in the tunnel surroundings and at in leaking drainage water that may influence the construction. The issue concerning chlorides is of great importance for the Stockholm bypass and it has been included as a risk factor from the start of the planning phases.

8 Discussion

In this chapter the results from the studied tunnels are discussed and analysed one by one and followed by an evaluation of the new technical requirements TRVK/TRVR tunnel.

8.1 Kattleberg tunnel

A large part of the water samples showed aggressiveness with respect to the calcium concentration according to BV-Tunnel which was extremely low. The water was sampled on two occasions and both showed low concentrations even though the hardness is corrected upwards according to VVMB 905. According to Jansson (pers. comm.) most of the sample locations were far away from the tunnel stretch. This and the fact that the calcium concentration was the only aggressive parameter was the explanation of dispensation from the requirements of extra corrosion protection.

It is not known why there was no water sampling from the core drilled boreholes that are in very close vicinity of the tunnel. However, the water samples from rock wells close to the tunnel stretch also indicated very low concentrations of calcium. Most of the sampled water was taken from rock wells which showed higher calcium content compared to the few wells dug in soil. Groundwater sampled from the soil wells had lower pH value, alkalinity and calcium concentration.

To evaluate the chemical attack, aggressive CO_2 should be measured. This was not done in this project and the reason for that might be that the classification of water was evaluated based on the well inventory that did not contain information about aggressive CO_2. In the Löttinge Tunnel this was analysed and the aggressive CO_2 was the parameter that had most influence on the classification. If aggressive CO_2 would have been analysed this may have resulted in a different classification of chemical attack according to SS-EN 206-1. Since an evaluation of aggressiveness in groundwater only was done through a well inventory the aggressive CO_2 was not analysed. Aggressive CO_2 is a parameter that according to the national food administration is normally not within the control program for drinking water when doing a well inventory. Wetland areas are characterized by high concentration of aggressive CO_2 that can degrade the concrete. The calcium concentrations were low and in combination with aggressive CO_2 this may be a corrosive environment for the concrete.

Since the concentrations of sulphate in Swedish groundwater generally are low, the use of SR-cement grout is not necessary for many sites. The requirements from Trafikverket state that SR-cement grout should be used if the threshold value of 600 mg/L SO_4^{2-} is exceeded. Recent literature and conversations with consultants describe the swelling of grout as a positive effect because of the sealing effect. This effect is according to Dalmalm (pers. comm.) not a problem for grout and the SR-cement grout criteria should not have been incorporated in the requirements. However, this cannot be applied for shotcrete because the swelling will in this case cause the cement to break. SR-cement grout is commonly used nowadays even though it is not needed in most cases. The difference in cost is around 5 % higher compared to regular grout (Månsberg, pers. comm.). In the Kattleberg Tunnel, SR-cement grout was used even though the sulphate concentration was much lower than the threshold value.

It is difficult to evaluate how corrosive the groundwater of Kattleberg actually is based on the current and previous criteria since the threshold values were developed for water that flows free in a steel culvert. Low calcium concentrations were observed and this could be an indication of that the groundwater may have more tendency to dissolve calcium carbonate then to precipitate. However, the technical requirements have threshold values that are supposed to be followed but there is a need for more suitable values that are relevant for tunnel construction.

8.2 Löttinge tunnel

The Löttinge Tunnel had a different contract form compared to other tunnels ordered by Trafikverket. The contract included total responsibility and maintenance for the first 15 years of operation; this is an uncommon contract form. The documentation gives the impression that the analysis of the groundwater and its influence on the construction material has been thoroughly performed. Thoughts and actions in the planning/construction phase may be better performed when there is a responsibility for the following maintenance.

The groundwater of Löttinge tunnel was assessed to be slightly corrosive according to BV Tunnel but dispensation of the requirements of extra corrosion protection was granted by Trafikverket. The driving force for the dispensation was economic benefits, ordinary steel bolts embedded in cement costs less than bolts that are duplex treated. But if ordinary bolts are used there also has to be a shotcrete coverage which will make the total cost associated to the bolts higher according to the technical requirements. Duplex treated bolts were used although according to Dalmalm (pers. comm.) it may have been better to cover the bolts even though they are duplex treated. According to Sandberg (2002) a bolt has most rust attacks at the part of the bolt that is exposed to air and shotcrete cover will reduce the risk of atmospheric corrosion.

8.3 City line

The consultants approach to the problem with corrosion is that flowing water that is aggressive according to SS EN 206-1 can leach concrete and then cause the bolt to corrode if the flowing water can transport the degradation products. A chemical attack on concrete by corrosive groundwater according to SS-EN 206-1 would then result in the highest corrosion protection for the bolts in the City Line (Rosengren, 2006). This means that if the groundwater has too high concentration of aggressive CO_2 or magnesium this would result in the need for usage of the highest corrosion protection for the bolts according to SS EN 206-1. When measuring the chemical parameters of groundwater to estimate the chemical attack the flow is not taken into consideration and the flow of water is probably a larger issue than the chemical composition of it. This means that estimating the aggressiveness for steel material using threshold values from SS EN 206-1 may not be appropriate due to the fact that it does not reflect the flow of water.

Dispensation of the requirements of duplex treated bolts was also requested for in the Stockholm City Line where the groundwater was assessed to be corrosive according to BV Tunnel. A cement embedment usually offers sufficient corrosion protection and this was the reason for the requested dispensation (Rosengren, pers. comm.). Dispensation was not granted by Trafikverket. This scenario is similar to the one in the Löttinge Tunnel project. However, in the City line they may not have considered the required shotcrete cover that probably would have resulted in a more expensive tunnel.

Groundwater that contains high concentration of chlorides may be problematic due to the fact that SR cement has a lower ability to bind free chlorides. Tunnels in areas subjected to marine transgressions and de-icing agents i.e. the City line will most likely be exposed to high concentrations of chlorides. This may be unfavourable for steel embedded in SR-cement. However, SR cement still offers better protection against sulphate attack that causes ettringite formation and reduces the adhesion. In the City Line SR grout was used. The selection of grout was according to Holmberg (pers. comm.) not based on the SR-properties. Instead is seems as if the grout was selected in a routine way without reflecting over sulphate present in groundwater. The median value of sulphate in groundwater in Stockholm is according to Jonsson (1997) 50 mg/l. This can be compared to the threshold value of 600 mg/L.

8.4 Stockholm Bypass

Out of the four studied tunnels the Stockholm Bypass was the only tunnel that still is in planning phase. The planning is still under progress but unlike the other tunnels it can be noticed that chlorides, up-coning effect and sulphate oxidation have been discussed early in the project. The chloride concentration has been investigated as a risk factor but how it will be evaluated in regard to construction material is unknown. Threshold value for chloride concentration does not exist in neither of the technical requirements BV Tunnel and TRVK Tunnel. Sulphate oxidation and up-coning effect of chlorides was mentioned in the early planning phase which is interesting since these depend on alterations in groundwater chemistry due to the construction of the tunnel. Clear models or methods do not exist yet for analysing water in regard to these two effects, however models are under development according to Mossmark (pers. comm.). As mentioned in earlier chapters it is difficult to take groundwater samples during construction phase since pre-grouting affects the groundwater chemistry. Neither BV Tunnel nor TRVK Tunnel requires that the groundwater should be analysed from these parameters so additional project specific requirements would then be needed.

8.5 Technical requirements from Trafikverket

The new technical requirement TRVK- Tunnel and technical advice TRVR- Tunnel have removed the old threshold values for estimating the corrosiveness for steel that was present in the expired BV Tunnel. After conversations with Trafikverket it was discussed why the water chemistry parameters were removed. A reason for this was that the threshold values were developed for steel culverts but also because the incorporation into the requirements had been forgotten. Therefore there is a need for adjusting the parameters if they should be brought back to the technical requirements.

Conductivity was one of the threshold parameters in the old technical requirements and it is a measure of all dissolved ions. This parameter was used as an indication for the chloride content by Trafikverket. According to Taube (pers. comm.) the correlation between conductivity and chloride concentration is site specific and can differ meaning that there is a need for replacing this parameter. TRVK and BV Tunnel uses the terms “fresh water”, “brackish water” and “saltwater” to define what type of environment the concrete and steel will be exposed to. Since these terms are used, threshold values for the chloride content depending on type of water should be set to get an easier classification. The chloride concentration 100 mg/L is set by The National Food Administration and indicates when water becomes aggressive towards pipe material. Chloride concentration of brackish water is often estimated to be higher than 300 mg/L. California Department of Transportation have developed corrosion guidelines that consider a soil/groundwater to be corrosive if chloride concentrations are above 500 mg/L. A new threshold value for chloride could be established somewhere in between but a proper investigation should be performed to establish new guidelines.

TRVK 11 approach to groundwater chemistry is that if groundwater is aggressive towards concrete according to SSEN 206-1 this result in the highest corrosivity class for steel. If the threshold values in SSEN 206-1 can be used for more than concrete is not known.

In the previously expired BV Tunnel there is a requirement of highest corrosion protection if the tunnel is under *free water surface with fresh water when rock hold strong water bearing zones* which describes the flow of water. This may be a vague statement but it describes the hydrogeology more than any of the parameters in TRVK 11. All of the projects studied have done Lugeon tests for estimating the hydraulic conductivity of the rock. The hydraulic conductivity may be a suitable parameter for describing the groundwater flow. However, this is difficult to estimate due to the fact that the test results only represent a limited rock volume.

9 Conclusions and recommendations

Groundwater chemistry in respect to construction material is often not of high priority in tunnelling construction. It may be based on the fact that it is difficult to estimate the corrosive aspects of groundwater, and also since groundwater in Sweden is usually non corrosive. It is an assignment for a hydrogeologist and material technician to estimate the corrosiveness of a tunnel environment. Knowledge should be combined to achieve the best results.

Sampling of groundwater to estimate the corrosive aspects is performed in the early planning phase and the classification of exposure and corrosivity classes is done in the late planning phase. Delays in material supply are costly; therefore sampling and classification need to be performed in the planning phase.

SR-cement grout is selected routinely even in cases where it is not beneficial. The swelling effect associated with sulphate attack is not a negative action on the grout since the swelling has a sealing effect. SR-grout was selected for two of the tunnel projects based on other properties then the sulphate concentration of the groundwater. Ordinary cement grout was selected for one of the tunnels due to the knowledge of the degradation process concerning sulphate attack. SR-cement grout is around 5 % more expensive than regular cement grout.

It is probably more expensive to use ordinary steel bolts than bolts with highest corrosion protection due to the requirements of shotcrete cover on bolt accessories when ordinary steel bolts are used. The extra corrosion protection on a bolt is seen as equivalent to the shotcrete cover according to the technical requirements.

The influence of flowing water is probably a larger issue for construction material than the chemical composition of it. Degradation of cement and corrosion related damage will be more rapid if the flowing water also is assessed to be corrosive. In TRVK-Tunnel there is a need for describing the risk with rock that holds strong water bearing zones. Hydraulic conductivity of the rock is often calculated in tunnelling projects and gives an indication of water flow in rock, however this only represent a small limited rock volume.

The new traffic document TRVK- Tunnel has removed the threshold values that were to be used to the determination whether or not groundwater is aggressive. Suitable parameters and threshold values that are relevant for materials in tunnel construction should be established for TRVK-Tunnel since the old threshold values were developed for steel culverts with flowing water.

One of the threshold values in the old technical requirements, electrical conductivity, was used as an indicator for chloride concentration. Terms like freshwater, brackish water and saltwater are used in the technical requirements and these terms relate to chloride concentration. The correlation between chloride concentration and electrical conductivity is site specific depending on other dissolved ions why a threshold value for chloride should be established. Other guidelines exist for assessing corrosive water and could be incorporated in the technical requirements.

In Kattleberg Tunnel it is likely that a change in groundwater chemistry have occurred during construction phase due to drawdown of the groundwater table. The groundwater table of Löttinge Tunnel was stable which probably did not result in large changes to hydrochemistry. However, no measurements were done to confirm how a change in water chemistry might have occurred at either tunnel.

Trafikverket manages data and documents for constructed and on-going traffic tunnel projects in Sweden and when planning this thesis it was assumed that the sought data would be available in their database. The procedure to request access to documents did not work as planned due to ambiguity on what type of data that was stored and the accessibility of them. The only way was to contact people that have been involved in the project which in forehand requires a total understanding of organizational structure of the tunnelling project. Full insight in the databases would have been better for the total understanding of how the industry handles this issue.

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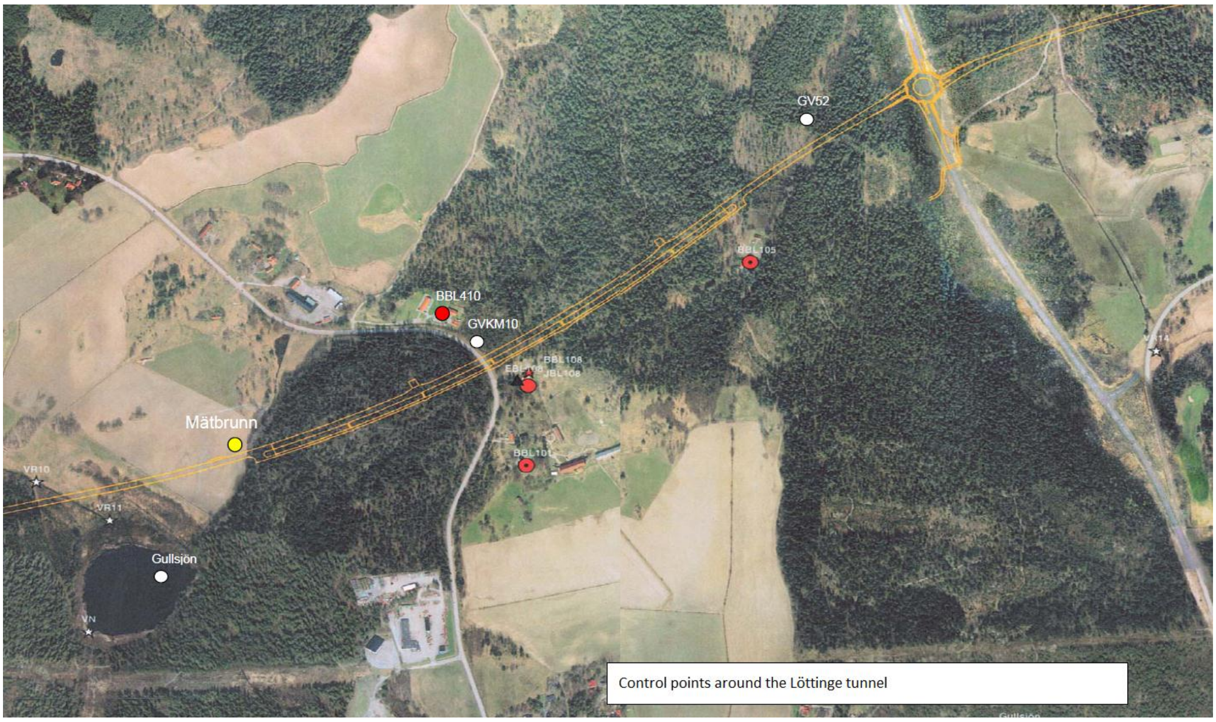
Appendix 1

Control points for measurement of groundwater levels around the Löttinge hill.



Appendix 2

Results from field investigation August 2005 Löttinge Tunnel. Parameters that are aggressive towards steel according to Tunnel 99 are marked in red, blue marking is parameters that are aggressive towards concrete and two colours means that the water is aggressive towards both material types. Sample analysis results under column Yoldia (Yoldia Environmental Consulting AB) represent field measurements while other results are from lab. Value in parenthesis is corrected downwards according to VVMB 905.

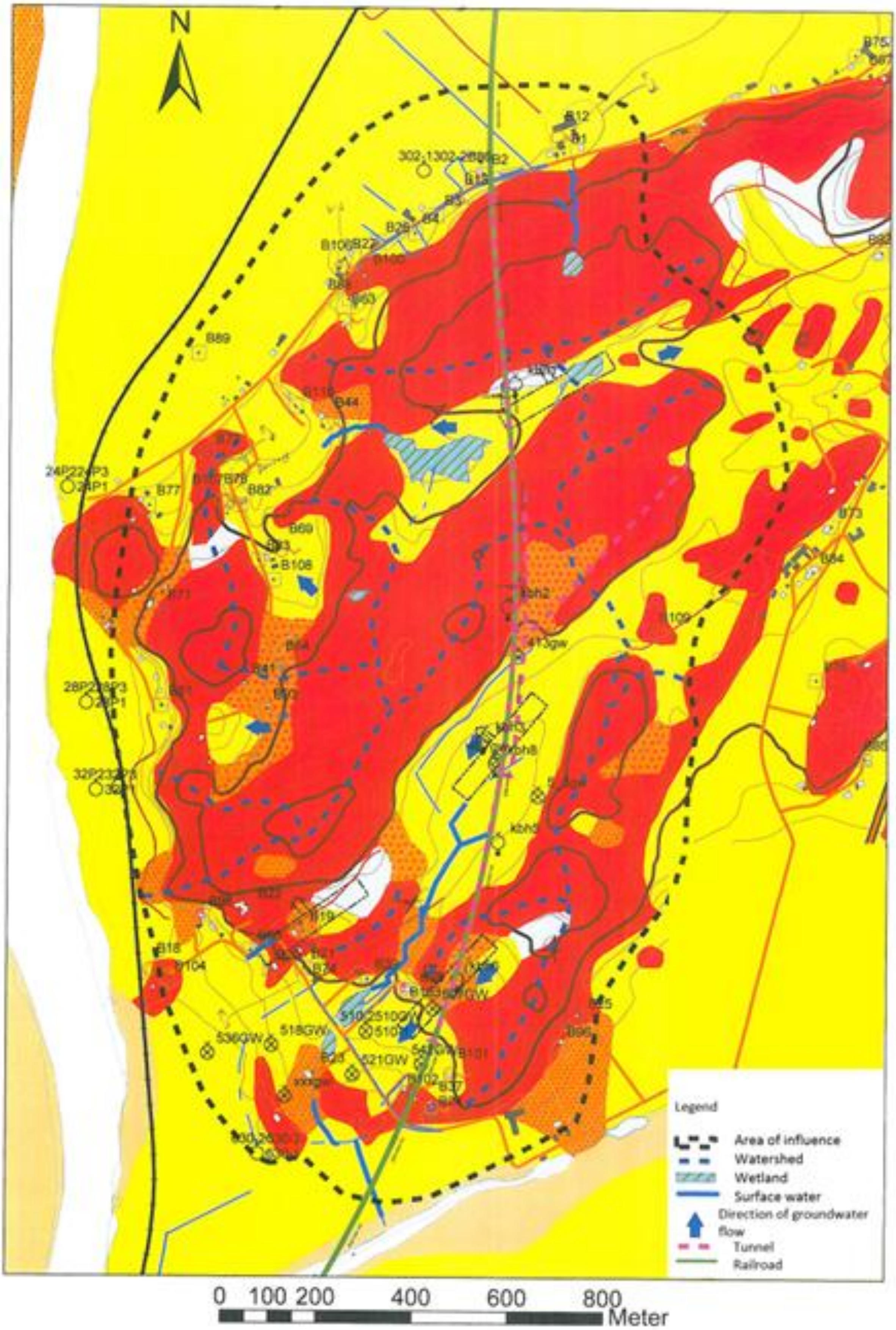
	Borehole							
	KB6-5			KB1		KB8		**Unit**
Parameter	Sample 1	Sample 2	Yoldia	Sample	Yoldia	Sample	Yoldia	
pH	6.8 (6.3)	6.8	6.95	5.5	5.61	5.9		
Tot. Hardness (Ca+Mg)	34.3	32.1		6.4		15.7		Mg Ca/L
Conductivity	20.0	20.0	17.7	5.7	5.2	10.0	9.1	mS/m
Alkalinity	1.4	1.4		0.14		0.42		mekv/L
Sulphate SO_4	12.0	11.0		7.2		11.0		mg/L
Chloride Cl	9.0	9.4		5.0		4.9		mg/L
Aggressive carbon dioxide (CO_2)	25	25		50		70		mg/L
Ammonium NH_4	<0.01	<0.01		<0.01		<0.01		mg/L
Ammonium – Nitrogen NH_4-NO_3	<0.01	<0.01		<0.01		<0.01		mg/L
Calcium Ca	32	30		4.9		12		mg/L

Results from field investigation November 2005 Löttinge Tunnel

	Borehole			Private well			
Parameter	KB6-5	KB1	KB7-1	L1	L2	T7	**Unit**
pH	7.1	6.3	6.3	6.8	7.7	7.6	
Tot. Hardness (Ca+Mg)	46.4	7.9	7.9	22.9	36.4	78.6	Mg Ca/L
Conductivity	33	6.8	8.3	60.0	27.0	67.0	mS/m
Alkalinity	2.13	0.23	0.18	1.08	1.97	3.11	mekv/L
Sulphate SO_4	16.0	12.0	13.0	23.0	15.0	25.0	mg/L
Chloride Cl	27.0	7.6	7.3	110,0	7.0	100	mg/L
Aggressive carbon dioxide (CO_2)	19	16	13	24	4.5	4.5	mg/L
Ammonium NH_4	0.11	<0.01	<0.01	<0.01	<0.01	<0.01	mg/L
Ammonium – Nitrogen NH_4-NO_3	0.089	<0.01	<0.01	<0.01	<0.01	<0.01	mg/L
Calcium Ca	43	5.9	6.0	19.0	30.0	60.0	mg/L

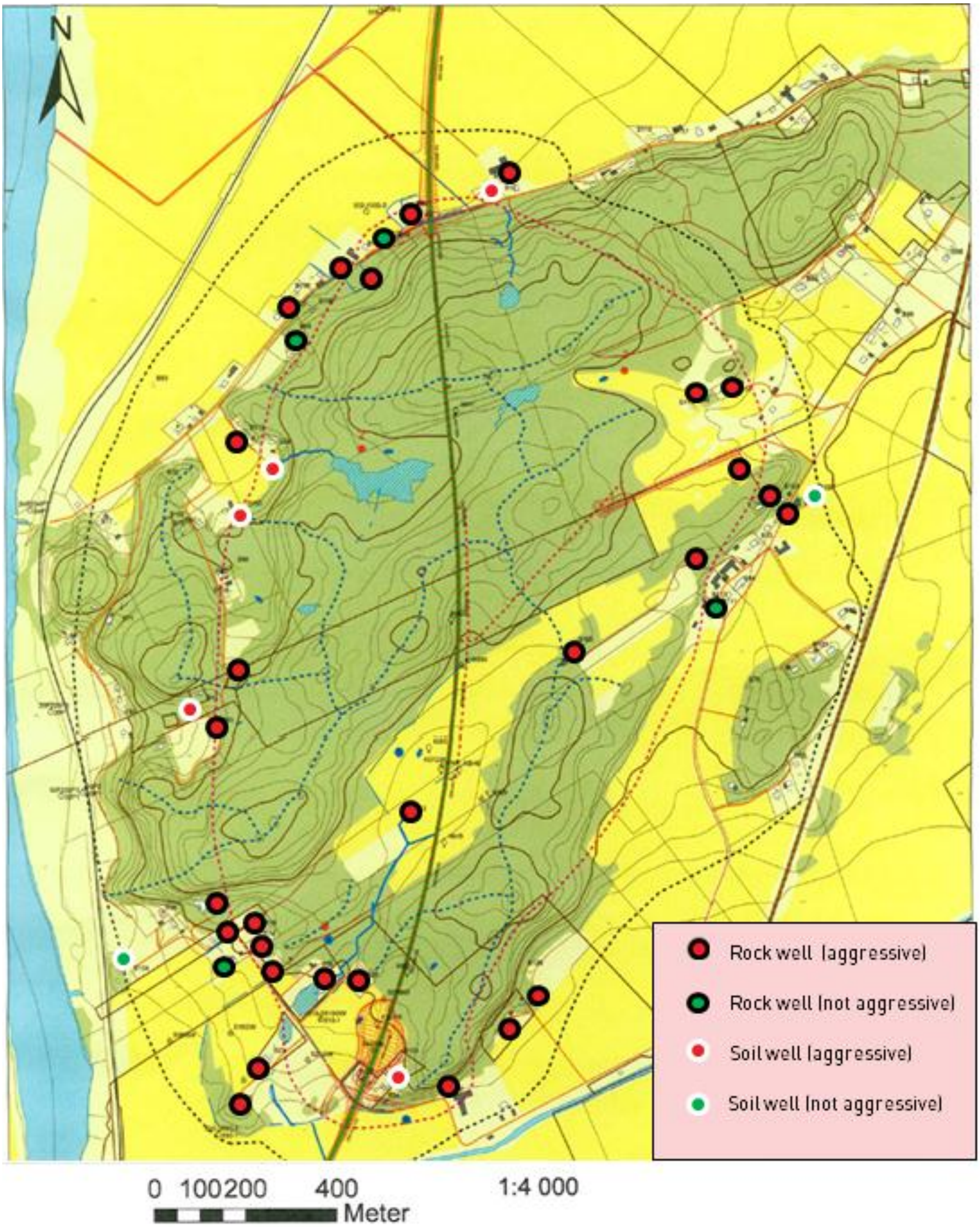
Appendix 3

Hydrogeological map for the Kattleberg area. Core boreholes and groundwater tubes can also be seen along the tunnel stretch.



Appendix 4

Location of aggressive groundwater samples from well inventory in the Kattleberg area.



Appendix 5

Groundwater sample data from Kattleberg Tunnel handed out by Bergab and Tyréns. Red markings of parameter value indicate aggressiveness according to BV-Tunnel. Blue markings represent a high chloride concentration.

Id	date	pH	Alk.	Cond.	Hardness	Chloride	Sulphate	NH4	Mg	Well type
B115	2007-04-18	7,3	48	19	24	15	13	0,071	4	Rock
B114	2007-04-18	7,6	79	26	11	20	21	0,064	2	Rock
B113	2007-03-09	7,2	280	76	100	94	42	0,19	25	Rock
	2008-03-28	7,5	280	78	93	87	40	0,15	24	
B112	2007-03-09	8,3	150	30	7	10	5	0,98	4	Rock
B109	2007-01-16	8,2	150	34	2	12	14	0,81	<0,5	Rock
	2008-04-02	8,2	150	32	2	12	14	0,09	<0,5	
B110	2005-09-06	8,3	170	42	9	30	15	0,077	3	Rock
	2008-04-03	8,3	170	40	8	31	15	0,11	3	
B88	2005-06-07	7,1	93	31	30	30	19	0,01	5	Rock
B44	2005-05-24	7,2	52	20	17	19	15	0,01	4	Soil
	2008-04-03	7,2	47	18	16	22	14	0,01	4	
B93	2005-05-24	6,5	21	12	1	16	8	0,01	1	Rock
B41	2005-05-24	7	18	13	12	18	10	0,01	2	Soil
					0					
B64	2005-05-24	6,8	11	13	1	22	13	0,01	2	Rock
B39	2005-05-24	8,1	120	32	1	16	23	0,01	<0,5	Rock
	2008-04-01	8,1	110	28	2	15	23	0,02	<0,5	
B37	2005-05-24	6,3	19	18	15	32	13	0,039	4	Soil
	2005-05-03	5,8	10	19	16	37	16	0,045	4	
B85	2005-05-24	7,5	110	34	19	31	21	0,01	4	Rock
	2008-04-01	7,5	98	27	16	24	19	<0,01	4	
B74	2005-05-24	5,9	8	18	12	32	16	0,032	2	Rock
	2008-03-28	5,9	11	9	8	10	12	0,02	1	
B21	2005-05-03	7,8	110	33	1	27	24	0,021	1	Rock
	2008-03-13	7,9	110	30	6	26	22	<0,01	1	
B20	2005-05-03	7,2	120	36	25	31	30	0,026	5	Rock
	2008-03-28	7,4	120	33	22	27	28	<0,01	4	
B23	2005-05-03	7,4	280	55	1	17	15	0,045	<0,5	Soil
	2008-04-01	7,9	300	53	14	20	12	0,05	3	
B18	2005-05-03	7,8	190	50	67	39	36	0,28	9	Rock
B25	2005-05-03	8,3	140	42	8	39	20	0,018	1	Rock
	2008-03-27	8,5	140	38	7	36	21	0,02	1	

Id	date	pH	Alk.	Cond.	Hardness	Chloride	Sulphate	NH4	Mg	Well type
B38	2005-05-03	7,8	96	30	9	24	21	0,026	2	Rock
	2008-04-01	7,9	98	28	9	24	20	<0,01	2	
B1	2005-05-03	7,9	110	33	1	21	25	0,033	<0,5	Rock
	2008-04-02	8,1	120	30	2	19	25	0,03	<0,5	
B3	2005-05-03	7,6	120	35	31	26	29	0,057	2	Rock
	2008-06-11	8,0	130	33	25	23	23	0,03	2	
B2	2005-05-03	8,5	150	39	17	28	23	0,035		Rock
B26	2005-05-03	8	140	310	207	1000	73	0,15	24	Rock
	2008-04-02	8,1	150	280	150	840	53	0,12	31	
B22	2005-05-03	7,6	78	26	7	18	22	0,015	10	Rock
	2008-04-01	7,7	72	22	26	17	21	<0,01	12	
B19	2005-05-03	7,2	72	25	24	22	22	0,01		Rock
	2008-04-01	7,7	72	21	4	16	21	<0,01	1	
B4	2005-05-03	8	130	45	13	49	22	0,032		Rock
	2008-04-02	8,1	130	36	11	34	19	0,03	<2,1	
B12	2008-04-03	8,1	120	30	2	20	24	0,03	<0,5	Soil
B27	2008-04-03	8,0	170	240	136	660	48	0,02	28	Rock
B96	2008-03-28	8,3	130	31	3	22	16	0,02	1	Rock
B120	2008-04-25	8,1	200	280	86	760	53	0,19	17	Rock
B122	2008-03-13	8,0	160	140	19	290	74	0,09	6	Rock
B123	2008-03-13	7,4	110	28	19	17	23	0,03	4	Rock
B124	2008-04-02	7,5	100	29	19	27	20	<0,01	4	Rock
B125	2008-04-01	7,8	300	52	2	15	12	0,04	<0,5	Rock
B127	2008-04-02	7,8	140	34	24	23	22	<0,01	4	Rock
B128	2008-04-02	7,7	95	33	19	24	23	<0,01	4	Rock
B131	2008-06-11	6,4	21	20	15	32	20	<0,01	4	Soil
B132	2008-04-02	7,1	36	10	14	8	5	<0,01	2	Rock

Appendix 6

Exposure classes according to EN 206-1

Class/ designation	Description of environment	Informative example where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/ thaw, abrasion or chemical attack	
	For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation (Where concrete containing reinforcement or other embedded metal is exposed to air and moisture)		
XC1	Dry or permanently wet	Concrete inside buildings with low humidity. Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete subjected to long-term water contact. Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity.
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3 Corrosion induced by chlorides other than from sea water (Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including deicing salts from sources other than sea water)		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools. Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides. Pavements. Car park slabs

4 Corrosion induced by chlorides from sea water (Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water)		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing salts (Where concrete is exposed to significant attack from freeze-thaw cycles whilst wet)		
XF1	Moderate water saturation, without de-icing agents	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agents	Vertical concrete surfaces of road structures exposed to freezing
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zones of marine structures exposed to freezing
6 Chemical attack		
XA1	Slightly aggressive chemical environment	
XA2	Moderately aggressive chemical environment	
XA3	Highly aggressive environment	