Comparison of injection technologies used for reinforcement in the construction of the tunnel in the Flynta Lycke area

Engineering thesis

Paulina Wawryca

Pawel Bilski

Szczecin 14.05.2012
# Table of contents

1. Introduction .................................................................................................................. 4
   1.1 Problem .................................................................................................................. 4
   1.2 Aim ....................................................................................................................... 4
   1.3 Method .................................................................................................................. 5
   1.4 Limitations ............................................................................................................ 5
2. Grouting as a method of sealing in tunnels ................................................................. 5
   2.1 General .................................................................................................................. 5
   2.2 Principles of grouting ............................................................................................. 6
   2.4 Grout mix properties ............................................................................................... 10
      2.4.1 Cement ........................................................................................................... 10
      2.4.2 Additives ........................................................................................................ 11
   2.5 Pre-grouting and post-grouting ............................................................................. 13
      2.5.1 Pre-grouting ................................................................................................... 13
      2.5.1.1 General ...................................................................................................... 13
      2.5.1.2 Pre-grouting on Hallandsås ...................................................................... 14
      2.5.2 Post-grouting ................................................................................................. 16
3. Geology .......................................................................................................................... 17
   3.1 General .................................................................................................................. 17
   3.2 Geology of Flynta Lycke ......................................................................................... 22
   3.3 Characteristics of rock masses present on site ......................................................... 23
      3.3.1 Gneiss ............................................................................................................. 23
      3.3.2 Amphibolite ................................................................................................... 23
      3.3.3 Dolerite .......................................................................................................... 23
   3.4 Geological hazards ................................................................................................. 24
      3.4.1 Water .............................................................................................................. 24
      3.4.2 Blocks and wedges ......................................................................................... 25
      3.4.3 Raveling/Running ground ............................................................................ 26
      3.4.4 Flowing ground ............................................................................................. 26
4. The aim of the project ................................................................................................. 27
4.1 History of the project ........................................................................................................33
4.2 Technology used in the project .....................................................................................40
  4.2.1 TBM .........................................................................................................................40
  4.2.2 Ground freezing .......................................................................................................51
4.3 Financing and organization of the project .....................................................................53
5. Technologies used in the tunnel .....................................................................................55
  5.1 General .........................................................................................................................55
  5.2 Rheocem 650 ...............................................................................................................56
    5.2.1 Description of the material .....................................................................................56
    5.2.2 Experience of use on Hallandsås ..........................................................................56
  5.3 Microfine 20 (MF 20) ................................................................................................59
    5.3.1 Description of the material .....................................................................................59
    5.3.2 Procedure of use MF 20 in Hallandsås ..................................................................59
6. Comparison of injection technologies .............................................................................64
7. Conclusions .....................................................................................................................68
List of references ...............................................................................................................70
List of figures .......................................................................................................................72
List of graphs and tables .....................................................................................................74
Appendices .........................................................................................................................75
1. Introduction

Hallandsås is a project that is well known in Sweden. This project has a long history with many companies trying to excavate the tunnel and many controversies which had an impact on the environment of the area like contamination it with RhocaGil. Since the project has been overtaken by a consortium called Skanska-Vinci HB in year 2004 the whole project starts to have a fresh start with many successes like excavation of the East tunnel in the summer of 2010.

1.1 Problem

In order to build the tunnel a new method has been implemented by using TBM. Even though the project seems to be doing fine, the geology of the horst is in most cases very surprising in regard to high water inflow of the groundwater and that the zone is situated on the Nature 2000 area. The area is one of the most difficult to build it in with the pressure up to 15 bars. Hallandsås has a varied rock mass consisting of amphibolites, gneisses and dolerite dikes. This rock mass in general is highly weathered and fractured containing a lot of groundwater. In order to reduce the water inflow and seal the rock mass many grouting techniques are used. Grouting is divided into post and pre-grouting and this work will focus on the second method. In order to seal the tunnel before TBM starts excavating rock mass the tunnel is sealed by injecting grout containing micro cement which has a very fast setting time.

1.2 Aim

Through the whole part of the East tunnel where TBM has excavated Rheocem 650 was used. In order to reduce the amount of grout injected and achieve better sealing properties Trafikverket has decided to test a new kind of micro cement called MF20. It was firstly tested at the end of the East tunnel for 2448 ring to see how the mix behaves when grouted, but the real test of MF 20 was done in a part of the area called Flynta Lycke. Since knowing how Rheocem 650 behaved and sealed in the same area but from the Eastern side it is possible to compare efficiency of both mixes. The aim of this work is to compare injection technologies in the Flynta Lycke area and show the best properties of the grout mixes for this tunnel.
1.3 Method

In this work both grout mixes, Rheocem 650 and MF 20, will be compared. Comparison is based on the results from the test that was done in September 2011 with using MF 20 and results that Rheocem 650 achieved in the same part in East Tunnel. Analysis is based on description of the using grout mixes and the way of using them on the project. Test with MF 20 was done during our practical placement in Hallandsås Project.

The work also included literature study where the grouting method is describe, information about geology of the Hallandsås area and the description of the Hallandsås Project with depiction of using construction methods.

1.4 Limitations

This work is based only of comparison and analysis of the injection technologies used in Hallandsås Project. The work will include only the analysis of two grout mixes – Rheocem 650 and MF20. It is possible that during working on this thesis the new grout will be tested but is not included in this work.

2. Grouting as a method of sealing in tunnels

2.1 General

Excavation of the tunnel is in most cases hard because of difficulty of proper prediction of rock conditions. That create huge possibility to encounter unstable ground. Other risk is potentiality presence of huge volume of high pressure ground water. Smaller amount of groundwater can also make problems in excavation of tunnels. Unstable ground conditions and groundwater are the most common reason for grouting in tunnels. Grouting technology is the process of injection special mix material into rock. The main reason of using grouting is strengthen rock, water tightness and tunnel layer stabilization. Protection of the tunnel that make grouting is also important as prevention of decreasing ground water level and reducing environment degradation. Grouting makes the tunnel more stable and durable [7]. There are two main types of grouting:

- pre-grouting (pre-excavation grouting);
- post-grouting;
which are used in sealing of tunnels. In some cases there are both types used but in most coincidence only pre-grouting is predicted.

2.2 Principles of grouting

Rock mass contains a lot of joint systems and grouting process should be based on them. In order to reach a good result it is important to indentify at least two joint systems present in rock mass and apply to them sufficient grout proportion, grout pressure and hole setting. Grouting is purposed to be done in two stages. Firstly, should be preformed course sealing and then fine sealing [5].

Geometry of joint systems is characterized by two things such as vertical and horizontal open joints. The first part is easy to recognize and easier to grout but the second which occurs at the top of the tunnel is really hard to predict [5].

The other important factor in grouting process is classifying rock masses present on site and their grout ability. This can lead to sufficient planning of grouting activities. Grout ability is according to T. Dalmalm said to be a function of the joint geometry and the filling of the joints [5]. A already mentioned joint systems can be classified in two categories. Firstly to their geometry they can be horizontal, vertical or both. Secondly, they can be open, gauge filled or a pattern of filled and unfilled joints. In regard to grout ability they can be divided into four classes [5]:

- straight forward
- moderately difficult
- difficult
- very difficult
Figure 1. One of many examples of grouting classification [5]

There are two acknowledged methods in regards of placing of the grout holes. First philosophy states that when the rock mass is watertight all drilled hole should be grouted at once where in other cases for grout curtains a split-spacing technology is used and most recommended. It states that there should be added an additional hole between earlier ones where length between grout holes is decreased.

On Hallandsås rock mass needs a bigger amount and shorter grout holes because it is not a homogeneous rock mass. On the north side of the tunnel near to Båstad rock mass has many small joint systems and that is why it was treated this way. Presence of joints which need to be sealed is a issue when choosing a grouting technology. Table number 1 shows how to choose the technological method is regard to joint size. When ++ means it is on big importance, + important and - not important. Factor is this tables states the size of a joint.
Table 1. The graph shows the importance when using apparatuses for different joint sizes [5]

<table>
<thead>
<tr>
<th>Technical issues</th>
<th>Factor</th>
<th>$\leftarrow 0.1\text{ mm}$</th>
<th>$0.1\text{ mm} - 0.2\text{ mm}$</th>
<th>$0.2\text{ mm}\rightarrow$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High pressure</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Low minimum flow</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>High max volume</td>
<td>-</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Small distance between</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>grouting holes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3 Requirements

In order to excavate the tunnel there are given some requirements that the company must follow. They consist of allowed water inflow and other additional requirements. This additional requirements concern avoid decreasing of the ground water table, devastation of installations and ensure health and safety level [5]. The additional requirements can be divided into three main group like in Figure nr.2 [11].
First of all there are environmental requirements which are managed by community. They are decided about sealing in the tunnel according to surrounding environment. The major aim of the community is to keep existing maintain of the environment and protecting of contamination. The decisions are made based on the geological and hydrological investigation. The community in most cases set the maximum water in-leakage.

In the second group the operating requirements are set up by the client. In this group the aim is to show all needed security demands for future users and that all necessary fittings are predicted. In Sweden in most cases the client is the Swedish Road Administration or the Swedish National Rail Administration.

The last group include work site requirements which are dependant from the contractor. The main purpose of this type of requirements is forecasting all threat on the construction site. The work site requirements include condition of working environment and safety on site.
2.4 Grout mix properties

Selection of grouting materials should take for consideration conditions like:

- tightness;
- rock properties;
- ground water conditions;
- environmental requirements.

When the conditions in construction zones are known it is possible to designed grout mix which will be adequate. It is possibility of three types of grouting:

- cementitious;
- chemical;
- cementitious and chemical compounds mix.

In most cases cementitious grouting is the most common but in some coincidence also chemical compound is used [19]. The most important for good result is proper grout mix which consist of cement, water and additives which could be liquid or solid types [5].

2.4.1 Cement

Cementitious products are well known on the market as a cheap, environmental friendly and lasting materials. This is the reason why using cement grouting is so common. In connection with grain size distribution, water/cement ratio and additives the properties of cement can be adjusted [19]. Cements used in grouting are divided into three groups [5]:

- Portland cement - produced with using limestone and clay which after burning gives cement clinker which is milled with gypsum, Portland cement produced in 1450°C;
- aluminium cement - produced with using limestone and bauxite which are burning in 1450-1600°C;
- slag cement - mixes of fine ground blast-furnace slag (45-85%) and Portland cement (55-25%).

It is possible to mix cements to achieve faster or slower hardening of grouting. For example compound of Portland cement and aluminium cement can provide a short hardening time. One of the most important coefficients for grouting aim is the maximum
cement particle size - $d_{\text{max}}$ [5]. According to the PN-EN 12715 the limit value for cement particle size (both micro-fine and ultrafine cements) is $d_{95} < 20 \, \mu m$ [10]. In the $d_{95}$ value 95% of the particles will pass through the sieve and the rest will stop because there are bigger than mesh sieve [1].

### 2.4.2 Additives

The additives that can be used on cement grouting are divided on liquid and solid. In the main cases producers have their own admixtures that are recommended to use with concrete cements. According to European standards volume that can be added to cement must be equal or less than 1% of weight of the cement. This requirements does not contain additives like pozzolan, fly ash, calcium sulfate or silica [9]. Otherwise added admixture should not overstep the amount given by producers.

Liquid additives

For charge cement flow properties and hydration a lot of admixture are added depending on that the cement should be accelerated or retarded. Cement accelerators are separate in two group:

- binder accelerators;
- strength accelerators.

The binder accelerators are used for achieve early hardening of grout material instead of strength accelerators which are used to rise the early strength. The most frequently used accelerator is calcium chloride which has impact on binding and strengthening. Up to 15% of calcium chloride can be use like a accelerator but then is huge possibility of lose the long term grout stability. It is also important that calcium chloride can acted like retarder since using for aluminates and slag cements. Alternative faster strength accelerators are potassium carbonate, sodium carbonate, calcium acetate and many others. Other binder accelerators are sodium silicate, sodium aluminates, sodium florid and others. Also aluminate cement can be accelerator for Portland cement [19].

Using of retarders are not so ordinary in grouting. If retarding is needed in grouting works plasticizers are then used. The most characteristic plasticizer is surface-active superplasticizer. The main aim of superplasticizers is slower hardening of grout which
affect of better penetrate. Normally w/c ratio with plasticizers is between 1.0-1.3 with comparison to w/c ratio without any additives is 3-4 [5].

Solid additives

The aim of solid additives is increase the strength of hardening grout, where normal addition of admixture is 20-100% of cement weight. The most popular solid additives is pozzolan which can be a natural material (volcanic tuff) or industrial material like fly ash, silica fume or slag. In most cases pozzolans are production wastes that can be used in other type of production like grouting where reducing the cost is possible. Pozzolans are not react with water but after minced and moisturized they can react with calcium hydroxide. In this reaction pozzolans can absorb the calcium hydroxide which is responsible of increasing of strength and durability. The most common pozzolans are [9]:

- natural pozzolan - mostly volcanic material or sedimentary rock with accurate chemical and micro-geological composition;
- silica fume - is a waste from production of silicon or ferrosilicon alloy. Silica fume particles are spherical with diameter less then 0.1 \( \mu m \). They are stabilize grout mix and reduce separation between particles in grout material.
- fly ash - is waste from power production in coal power station. Fly ash particles with the size of between 1 – 150 \( \mu m \). Fly ash added to grout mix will increase chemical resistance of grout material and their density but is still less productive then silica fume.
- fillers - fillers that can be used in grout mixes are fine milled stones, limestone, blast-furnace slag and fly ash. Fillers can stabilize the grout particles and accelerate hydration process.

Additives to reduce bleeding and shrinkage

A huge problems with hardened grout is shrinkage and bleeding of grout. To avoid these problems the materials like bentonite or silica based products supposed to be used or low w/c ratio should be implemented. Bentonite is a material with great ability of water absorption even 500% and have a good influences on stabilization of grout material. Using of bentonite is decreasing because of existing on market micro-cement-based grout which
is more stable. The other popular additive is silica-based product called GroutAid which is great bleeding reducer and improve penetration properties [19].

2.5 Pre-grouting and post-grouting

2.5.1 Pre-grouting

2.5.1.1 General

Rock mass pre-excavation grouting was used for decades all over in many countries. It was mainly used and still is to reduce to maximum water ingress or to obtain better stability of the structure surrounding it and even to enhance mechanical properties of the rock mass intended to excavate. Pre-treatment can be divided in to pre-treatment of soils and pre-treatment of rocks. The latter pretreatment will be described in this chapter.

Pre-treatment of rocks is normally done from the tunnel face in extent to 50 m. In this type of the method the grout mixes contain regular W/C ratio. It is often done by regional companies using foreign consultants and suppliers. Specifications for these types of projects are often dependant on the maximum allowed water inflow (in this case by the Swedish Environmental Court). When using this method it is important to have a very wide and accurate site investigation including things like:

- good knowledge of rock mass structure, geology, nature and hydrogeology of the area;
- distribution of permeability of the rock mass and obtaining its good level that will match projects ingress limits;
- determination of a grouting goal;
- understanding for all workers the goal of the project;
- determination of weakness zones and foreseeing and already trying to reduce hazards that may occur during this process;
- establishing control and a good quality department surrounding the ongoing works etc.

Almost every excavated hole is a good information for the company to make a geological interpretation. Obtained while drilling these parameters include penetration rate, thrust and water inflow properties that in some cases disregard employing too many skilled geologists and help specialists to predict upcoming rock properties.
When grouting form the TBM face it is important to make probe drillings as well as grouting effectively. It is significant that these injections should not overlap on each other and no treatment area should remain. On Hallandsås it is kept 10 m overlap between drilled holes [3].

The biggest advantage of pre-grouting is reducing water ingress while excavating and reducing impact on ground waters surrounding the project. Another thing is that is significantly enhances parameters of rock masses and consumes less grout than post grouting. Finally it helps TBM to advance regularly through the tunnel. This method has also few disadvantages. It can sometimes interrupt excavation works or blasting can release fractures of the rock mass again. When pre-grouting is done from the surface it is usually considered more expensive. The last problem is that in most cases it is hard to locate the leaking points and inject grout directly to them [1].

2.5.1.2 Pre-grouting on Hallandsås

Pre-excavation grouting is done using a micro fine grained cement in order to control the groundwater ingress towards the front of the tunnel. In most parts of the Hallandsås tunnel continuous pre-grouting was used using 35 m long fans because of the predicted high water ingress that could damage severely progress rate. This method is often dependant on forward probe drillings which are done regularly in order to measure water ingress and are done to maintain 10 m overlap between probe holes drilled. Pre-grouting apart from controlling water inflow in a stable rock but is also used on already mentioned flowing ground and running ground in order to reduce to minimum this hazard from happening [11].

Pre-excavation grouting or pre-grouting is a method of grouting where from the tunnel excavation face boreholes are being drilled into the rock and grout is being injected and allowed to set before advancing with drilling in order to have a sealed rock volume [7]. Openings in the cutter head allow many positions of drilling (Figure 3).
Figure 3. The picture above indicates probe and pre-extraction grouting positions. In green there are mentioned 7 inner face positions, in pink 26 outer positions and in yellow 30 channels through the shield skin which are in 10° and 13° angles [11].

In order to reach all outer positions and borderlines there are 3 drill rigs which are installed eternally but a brief installation is also available from the centre of the shield or on the erector. There is an area considered for a grout plant but on the TBM there is also a material storage and handling area available. For this project all grout mixes for pre-extraction grouting consist of only cement, water and superplatiziser and W/C is from 0.8 to 1.0. In order to make injections effective, limit the grout spread and getting the ground sealed there have been stop criteria created. There are 2 of them consisting of stop pressure (cannot reach 30 bars pressure) and stop volume (5000 liters/35m hole) [11].
2.5.2 Post-grouting

Post-excavation grouting takes place in a zone that has been excavated but because of too big water ingress pressure grouting must take place. This method is complementary to pre-grouting because it help to seal off water leakages not completely done by pre-grouting. It was noticed that post grouting is more effective when it has already been pre-grouted because it blocks all the fractures or openings before the water starts to flow into them.

There are few advantages of this method. It does not affect excavation works since they are already made and it is easier to plan. Another advantage is that a lower pressure can be used. Unfortunately, as many methods it has some disadvantages. Firstly water leakages are really hard to predict and even if one can see leakages water can find another way. Secondly if not used with pre-grouting it seems to be less effective, more expensive, usually more time consuming and sometimes a problem of grout wash out is experienced [7]. Post-grouting works are showed in Figure 4.

Figure 4. Post grouting on Hallandsås
3. Geology

3.1 General

The project is placed in the Southern part of Sweden in a region called Skåne with the biggest municipality in Malmoe. This region is widely known for its varied geology consisting of numerous types of bedrock. Geology surrounding Malmö is pretty much the same as found in Denmark such as young Mesozoic and Cenozoic sediments. Whereas in the north side it is Precambrian crystalline bedrock. It also must be mentioned that there are other sediments like of Cambrian age (diversified Alum shales and quartzites), Ordovician age (complex shales and mudstones), Permian, Triassic and Jurassic sediments (chalk, bioherms, sandstones, siltstones). It can also be mentioned that the landscape has also a lot of Carboniferous dolerite (diabase) dykes and intrusions. The geology is dominated by a massive formation called Teisseyre-Tornquist zone (Figure 5) [25].
The whole fracture and fault system in Hallandsås was formed in the Paleozoic between Cambrian and Silurian age and it has been active ever since. The biggest and last movements in Southern Sweden and especially in Halladsås have taken place from 70 million to 100 million years ago. This means that it had happened from the Triassic to Cretaceous period. In result rock plinths have raised above the bedrock and several horst have been formed including Hallandsås. While in Teisseyre-Tornquist zone the rock weathering has reached far down. Generally already weathered rock which is eroded form the surface has been preserved in a lowered tectonic blocks and fractured areas. This is one of the reasons the rock masses are massively heighten and there occurs a problem while drilling. There are three major tectonic zones found across the tunnel road which caused already mentioned uplifting movement which caused severe weathering and crushing along two sides of the horst. One of the most major problems was encountered while
working in the Mölleback zone. This zone is very complex in terms of its geology consisting of silty clayey material with a very fractured part consisting of very high water pressure. Unfortunately, because of this severe fracturing the horst is almost all saturated with the ground pressure of water almost up to 15 bars. The most common type of rock found in the horst area is Precambrian gneiss. Other rocks present in the area are sheets and dikes of amphibolite which is a dark-coloured rock and also granite, diabase and Permian dolerite dykes (Figure 6) [11].
Figure 6. Geology of Denmark and south of Sweden taking into consideration geological periods [25]
Figure 7. History of geology of the Hallandsås Project [21]
Concluding Hallandsås is a horst of a long history of tectonic movements. It is also considered heterogeneous in terms of fracturation and weathering. Horsts are found in fault zones and are caused by parallel movements in the crust (Figure 8).

![Scheme of horst definition](image)

Figure 8. Scheme of horst definition [22]

### 3.2 Geology of Flynta Lycke

The "Flynta Lycke zone" is situated approximately between east rings 515-720, or west rings 500-710 (see Appendix 1). The zone is approximately 460 m wide. It is characterized by heterogeneous rock conditions. Gneiss, amphibolite dikes and dolerite dikes interact in this zone. Furthermore several zones of weathered rock are crossing the tunnel stretch (this means fractured zones with softer rock). The weathered zones and the contact zones between the different rock types are common as water bearing structures. Since the rock is quite water bearing some pre-treatment have been needed from the TBM in this zone and also barriers has been built behind the machine. The most distinct character of the Flynta Lycke zone is the big Flynta Lycke dolerite dike. This dike is about 60 m wide and it stretches from way below the tunnel level almost all the way up to the ground surface, and acts like a big water tight wall in the ridge. It acts as a boundary
between two big ground water magazines. This is taken use of when the tunnel is built. In
the dolerite dike good and tight barriers are built, sealing of the water from the south of the
dike, meaning a fresh start of the water budget on the north side of the dike, since no water
can find its way through the water tight dike.

3.3 Characteristics of rock masses present on site

As mentioned above the three most dominant rock masses present on site are
gneiss, amphibolite and dolerite. The first rock is mostly Precambrian gneiss which has
metamorphosed from granite. In most cases it contains quartz, sodium-calcium, amphibole
and many others. Another rock is Amphibolite which is a metamorphous rock type and is
usually less slaty than gneiss. It contains amphibole and feldspar. The last of the most
common rock types is dolerite which contains plagioclase (feldspar), pyroxene and opaque
[24].

3.3.1 Gneiss

Gneiss is of the most dominant types of rock found in the Hallandsås horst. MINERALS WHICH ARE MARKED AS GNEISS ON SITE DIFFER IN TERMS OF SIZE; COLOUR, MINERAL CONTENT AND, IN SOME WAYS, STRUCTURE BUT THEY ARE GENERALLY MEDIUM GRAINED. ROCK MASSES WHICH ARE THICKER AND BIGGER ARE ALSO INCLUDED EX. GNEISSIC GRANITE AS WELL AS PEGMATITE DIES. GNEISS STRIKE DIPS GENTLY (20º–40º) TOWARDS THE NW OR W [2].

3.3.2 Amphibolite

Amphibolite appears on Hallandsås as sheets, lenses in gneiss rock masses but
mostly as large coherent masses. It is a dark coloured rock that is generally fine-grained.
As experienced it mostly contains garnet which is a red coloured material. Amphibolite
strikes towards W direction and is present in a form of 5-15 m wide sheets [2].

3.3.3 Dolerite

Dolerite has been located using a magnetic survey. It is greyish-black rock that has
intruded in gneiss and amphibolite rock mass. Dolerite dikes which are present on site are
considered to be from fine to medium grained rock. Since found in a magnetic survey it
was uncertain whether the rock was dolerite or magnetic amphibolite but on site no
difference in tunneling viewpoint has been found [2].
3.4 Geological hazards

Hallandsås is facing a lot of geological hazards which are enlisted below. In order to prevent them from happening it is important to apply engineering solutions. The best solution was the design of the current TBM used at the site named "Åsa". It was designed to keep a strict control over the big water inflows and for working when a static water pressure is above 10 bars which is quite unusual for tunnel works. It can also work in a hard and abrasive rock mass as well as with soft rock and mixed face conditions. Also a big advantage is doing pre-treatment in this case grouting from the TBM. Another thing is doing pre-treatment by freezing in the Mölleback zone as a result of poor rock conditions [11].

3.4.1 Water

One of the biggest hazards while tunneling is water trapped in existing rock masses. Water can cause damage when it is released and flows into the tunnel or its properties can affect negatively the construction. At Hallandsås big water inflows are a huge problem. Controlling water inflow was the main problem during the whole history of the project as well as not decreasing the level of ground water in the area. Ground water conditions at Hallandsås are regarded as very specific in few aspects, like the high ground water pressures, high storage capacity of the rock mass and the high hydraulic conductivity even reaching $k=10^{-4}$ m/s. Other thing is the fragile environment with many protected areas, where most of them are Nature 2000 classified.

As already mentioned rock properties are very complex. Rock erosion system makes a three dimensional flow channels of water. Another significant feature in the rock mass are large and small structures allowing the groundwater to be transported really far and fine narrow cracks which are able to maintain big amounts of water which is one of the reasons why there is so much water. These reasons and already mentioned big fracture frequency are the main reasons why it is hard to build tight annulus surrounding tunnel lining. In that case it is necessary to use pre-grouting with very big amounts of grout and really good penetration properties.

High water level and a huge water ingress affecting water levels during former excavations had an impact on the current requirements on this contract like the strict amount of water that ought to be drained from the tunnel. These requirements in Sweden are controlled by the Environmental Court. All activities that have an impact on ground
water need that kind of permission. After the company got the permission to perform tunnel works it had some conditions they had to fulfill. One of them and probably the most significant one was that up to 100 l/s of groundwater can be discharged from the tunnel measured as an average of 30 days. The horst is divided into aquifers closely related to the tectonic blocks. The part that contains the biggest amount of water in the north part whereas the south part because of bigger presence of amphibolite dykes seems to be a lot less drier. One of the most ultimate water inflow happened form the east tunnel was 400 l/s. Constant monitoring and careful planning has a huge impact on the whole tunnel excavation process in order not to exceed the limit of the water discharged from the ground waters and the limit of water flowing to the TBM of 250l/s. Good water management and control is one of the key factors to have an efficient production and optimizing the TBM drive [11].

3.4.2 Blocks and wedges

In a number of rock masses loose wedges are being shaped by interrelated fractures and joints and they can be different in terms of size and shape and their stability is assumed by joint orientation and conditions.

Normally the problem of blocks and loose wedges in rock tunneling are solved by applying shotcrete or bolting. When excavating with the TBM this method is impossible to use however the constructed segments and rings are designed to carry the block loads. Unfortunately, a problem occurs when block instability happens ahead of the cutter head which may lead to blockage or excessive wear. These failures were expected when the rock mass is poor. The biggest fracturing occurs in gneiss and amphibolites where in amphibolites the joint conditions seem to worse and therefore block problems happen more often in this kind of a rock.

After the TBM had launched 2 km ahead a large collapse had taken place because of poor block stability. The biggest over break occurred in the face of the TBM. These are the reasons why TBM has to work more in a crushing than cutting mode. This in the end resulted in slowing the progress of the excavation and big damages of the cutter head and the muck transportation system.

Concluding, reasons for block instability are: low stress, low joint strength and unfavorable joint orientation [11].
3.4.3 Raveling/Running ground

Raveling ground is a big loss of strength of the rock mass or its loosening and it is dependent on time. It can extremely shorten the stand up time of the rock mass and it is a big problem in the excavation works often leading to collapses. Raveling ground is a material that runs into the tunnel and one of the techniques to stop it or slow it is by using shotcrete. It is actually less dangerous than flowing ground because no water is involved in such process. On Hallandsås it is mostly occurring on the MBZ.

Typically when this occurs already fractured and weathered rock loosens and decreases its strength leading to instability of the tunnel roof or a wall and in some cases to a severe collapse. Raveling occurs both in gneiss and amphibolites because of their fracturation, weathering and few other factors. As this problem cannot be solved by shotcrete a stand up time has be applied which may differ from an hour even up to few days dependant on the weathering. Running ground and raveling are very related at this project. Running ground takes usually place when weathered rock masses are present.

This problem is being dealt with by full pressurization of the TBM [11].

3.4.4 Flowing ground

Flowing ground happens when stored in rock or unconsolidated soil water flows into the tunnel. In result the liters of mud can flow for a long time and their amount can be extremely big. Flowing ground is considered to be the worst above all geological hazards.

This hazard is the biggest reason to apply freezing in the MBZ area. After applying this method occurring of this hazard is a lot less possible but cannot be ruled out. In order for this risk to be present few things must be fulfilled. Firstly rock or soil must be with none or small cohesion and there must be a big level of water pressure. Second thing is a high water excess and the material present at the site must have a high hydraulic conductivity and big water inflow must occur. In general, flowing ground occurs in less weathered parts of the rock mass because in more weathered blocks contain more clay and the transport of water is small.

Concluding, these conditions only exist in the MBZ area which has a high permeability, high water pressure and high weathering [11].
4. The aim of the project

In 1885 a rail track along Hallandsås ridge was built (Figure 9). The track is a part of the West Coast Line, which is one of the most important rail lines in Sweden (Figure 10). This line is a straight connection between Norway and Denmark since the opening of the Oresund Bridge. The section between Båstad and Förslov from the beginning was problematic. One-track rail was really winding and steep. The trains could not reach full speed and transport maximum freight weight. Due to that only four trains could run along the track, which made this part a bottleneck of the West Coast Line. In 1988 government created a special department responsible for infrastructure called Banverket (later transformed into Trafikverket). The aim of Banverket was the reconstruction of the infrastructure network in particularly rail lines [26].

Figure 9. Opening the rail station in Båstad [26]
Swedish government expected that the traffic ought to be more efficient, safe and more environmental friendly. According to Banverket the decision had an aim to move a part of traffic from road to rail. Of course that was not easy, but currently most of tracks in Sweden are in a really good conditions. The modernization of the West Coast Line become one of the most important issues. 85 per cent of this line is already rebuild into double-track, but Hallandsås is still a “missing link”. West Coast Line is modernized for a high-speed trains (250 km/h) and also to improve safety issues. Full modernization of track enables effective freight transport along west coast where most of cargos go by road and will be more efficient for long-distance passengers. Building a tunnel through Hallandsås ridge is an easy way to eliminate the possibility of delays of trains in winter caused by snow or track icing. Tunnel in this part will make an opportunity for 24 trains to run per hour in comparison to 4 trains per hour that can go today (Figure 11). Tunnel through Hallandsås will increase the speed of trains in this part from 80 to 200 km/h and will improve the safety because of elimination of 20 dangerous level crossings. It will be a huge chance for moving part of traffic from roads and making track efficient and safe [26].
Figure 11. Amount of trains that will run after building a tunnel in comparison with current situation [26]

Skåne is the southern region of Sweden. With the entry into the European Union in 1995 and opening of the Oresund Bridge in 2000 country has a new opportunities. Region has a connection with the rest of the Europe and must still improve its network of infrastructure to be capable of extensive carriage through its territory to the rest of Scandinavia. The main part of the transport runs by road and is focused on the western part of Skane, where run European roads E6/E20, E22 and E4. Together with West Coast Line and Southern Main Line being the most dominant modes of transport [11]. They combine the most important ports and centre of major cities (Figure 12) [17].
The level of road transport, both private and freight in last 10 years has dangerously increased. Currently, approximately 80% of private transport centres are situated around road transport but the same situation looks in the transport of goods (Figure 13).
22% of all transport of goods in the ports is the transportation to and from Skåne. The most popular line of transportation is the relation between Sweden and Germany, Sweden and Denmark, Denmark and Norway, Norway and Poland. The most common place to which and from which goods are transported is Gothenburg (18%). Almost half of the goods from ports direct to road between Helsingborg and Malmo (Figure 14). In Helsingborg this value is distributed on the road E6/E20 and E4. Road E6/E20 which is going through Hallandsås ridge takes about 46% of transported goods (Figure 15) [18].
Almost 83% of roads transport are operated by semi-trailer lorry (Figure 16).
The data indicates that the most important role in Swedish transportation plays road transport. This is the reason why it is so important to transfer part of this amount to rail. However for arise such a situation it is necessary to improve the flow on the West Coast Line.

4.1 History of the project

In 1992 Project Hallandsås had began. In order to construct the tunnel the company Kraftbyggarna was created. The company started construction of the tunnel using tunnel boring machine (TBM) called "Hallbor" (Figure 17). TBM Hallbor was designed for hard rock only and for working in an open mode. Unfortunately TBM was not suitable for the geology of the Hallandsås ridge. In 1993 the company was forced to change the construction technique. They started excavating tunnel using a conventional technique called blasting. After excavating 3 km of the tunnel on 1995 Kraftbyggarna gone bankrupt and was forced to leave construction site [26].

Figure 16. Type of vehicles used for transport goods in Skåne [18]
In 1996 Skanska became the new contractor of the project. The company started excavation the tunnel by blasting as the first contractor did. Skanska also excavated access tunnel in the middle called MidAdit. In the summer a huge leakage of groundwater had taken place in the north tunnel. In order to protect the dry out of the ridge the company decided to use a chemical sealant called Rhoca Gil manufactured by Rhone-Poulec. Rhoca Gil is a chemical grouting product used in construction of tunnels to prevent leakage into the tunnel. The sealant as a liquid is injected into cracks and then starts polymerising, which is causing hardening of the product. In 1997 they had discovered that the part of the product had not hardened well due to the connection with hard water and huge water inflow. This effected contaminating water with the acrylamid in the Hallandsås ridge. Leakage caused a great environmental disaster among the fish and the cattle which drunk the groundwater. In the risk zone about 370 of the cattle was put down and the crops were destroyed. In addition 330 000 kilograms of milk were liquidated. 310 wells were tested to detect the level of acrylamide, in 29 of them water was contaminated. In all of the households which were close to contaminated wells there had been delivered water by tankers. During the investigation the level of contamination was examined and how long would it take to get back to the primary level. Swedish government, Trafikverket and Skanska were obligated to compensate the losses of people living in the Båstad district. After brief decontaminating the area in years 1998-2000 Trafikverket with Swedish government conducted a research of any possibility to continue the project. The major aim of the research was elimination of further damage that this project can cause. They came to
an agreement that this project can be continued if a water resistant lining in the tunnel will be used and that a tunnel will be excavated by a specially constructed tunnel boring machine. One of the most important conditions in order to have a permission to continue the project is a continuous monitoring of the environment and meticulous information delivered to the residence of the ridge. From 1997 when the contamination had taken place Skanska has started to introduce new environmental management systems. The new habits include permanent environmental control and control system for chemicals which are used on the construction site but also in the office. Due to that Skanska become the first international construction company with certification according to the ISO 14001 standard. ISO 14001 is an internationally recognized quality standard that specifies the method of implementation of effective environmental management systems. This standard was developed to define the rules of the delicate balance between preserving the viability and limiting their impact on the environment [26].

In 2003 the construction got the green light from government and in winter 2004 restarted the construction process. New design-build contractor started the works. Skanska with sufficient knowledge and experience of the area joined Vinci HB, leader in the construction of tunnels using tunnel boring machine, according to decision about method that must be used in such difficult ground conditions. The breakthrough of the East Tunnel has placed in August 2010 (Figure 18). In April 2012 TBM reached the Mid Adit where the maintenance had taken place and the cutterhead was changed for a new one. The end of project is expected on 2015 [26].
In April 2012 TBM reached the Mid Adit where the maintenance had place and the cutterhead was changed for a new one (Figure 19).
Without any big problems the 7940 meters of the West Tunnel is already build (Figure 20).

Figure 19. Breakthrough in Mid Adit in April 2012 [26]
In 2014 excavation of tunnel suppose to be done. For the last year application process regarding work connected with typical infrastructure will be finished. This will be work regarding laying tracks and installing signalization in accordance to safety rules (Figure 21 and 22). In its last stage of work all fire protection will be assembled. For protection of passengers special 19 cross passages are designed which will connect both tunnels and will be a runaway from the tunnel in case of dangerous accidents [26].

Figure 20. TBM progress in West Tunnel [26]
Figure 21. Planned cross passages [26]

Figure 22. Vertical cross section with safety systems [26]
4.2 Technology used in the project

The aim of the project is to construct two single-track tunnels (Figure 23). Total length of the tunnels are 8.7 kilometers and the outside diameter lining is 10.12 meters. The tunnels are constructed using a shield tunnel boring machine, ground freezing and drill and blast in cross-passages [26].

Figure 23. Double track line with comparison of today single track [26]

4.2.1 TBM

Specially constructed machine by Herrenknecht called Åsa is 240 meters long and has a cutterhead with 10.6 meters diameter (Figure 24).
The constructor of the machine had a few technical requirements to fulfill like [4]:
- difficult unstable ground conditions: hard and abrasive rock, zones of soft soil and mixed face conditions;
- high water inflow along of the tunnel and static water pressure about 10 bar
- environmental restriction.

According to these requirements the only solution was TBM with watertight segmental lining. The special lining is capable of withstanding 15 bars of water pressure. TBM Åsa has also a possibility to grout ahead and work in an open or closed mode dependant of conditions of the zones. TBM is consisting of some main parts like shield, cutterhead, mucking and dewatering system and segmental lining with backfilling [4].

Shield structure

Shield is specially designed to withstand a high water pressure up to 15 bars in static and difficult ground conditions. The main part consists of six sections which are equipped with bolted and sealed flanges, submerged wall, pressure bulkhead and erector support frame. All required installations and connection are foreseen. One of the most important part of shield is fixed double shell tailskin. Tailskin including all necessary grout lines, tail seal mastic and sampling lines (Figure 25). The structure of the shield also provides size and weight limits which are important underground [4].
1. 3 boomers for drilling through shield/cutterhead
2. 1 boomer for drilling through cutterhead center

Figure 25. Tailskin with special grout lines 1 and 2 [6]

Cutterhead

TBM cutterhead must fulfill five major requirements:
- strength and abrasive rock - according to such hard rock conditions it is important to have a strong structural design and proper cutters. Based on the Alpine tunnels experience on the design of the cutterhead was used 17 inches backloading disc cutter with face cutter spacing of 85 millimeters;
- zones of blocky rock - extort work as a rock crusher from the cutterhead according to experience at lotshberg tunnel;
- dual mode operation - possibilities of operating in open or closed mode depends on conditions;
- clogging in closed mode - size of the muck openings caused an arrangements of disc cutter more like “star type” which are not so good for this rock conditions.
According to this special requirements the cutterhead was designed with a hydraulic cutterhead drive system and cascade seal system. The final face of first cutterhead is presented on the Figure 26 [4].

![Cutterhead face with specific “star type” arrangement of cutters](image)

Figure 26. Cutterhead face with specific “star type” arrangement of cutters [6]

In connection with blocky rock conditions and overbreaks the maintenance routine was more common to control and reduce damages. Area of intense crushing of the material where the overbreaks taking place which are regarded as the most destructive (Figure 27).
Figure 27. Area of crushing of the material in front of cutterhead face [4]

The maintenance of the cutterhead from inside takes place each day and from the front of cutterhead each 500 meters. Obviously, except from the costs of maintenance there was also impact on the production. In 2006 decision was taken to design the new cutterhead. According to the experience of the underground conditions decisions was made to use 19 inches cutters. Heavier and more stiff structure of cutters increase the nominal load to 320 KN in comparison to 250 KN of 17 inches cutters that were used before. Some openings in cutterhead were eliminated because of the risk of clogging. The new cutterhead have been equipped with additional crucher tools in the most threat part and some new protections. The new cutterhead can stand more difficult ground conditions which makes closed mode less important. The second cutterhead have been changed in 2008 in Mid Adit (Figure 28) [4].
Working with new cutterhead decreased the damages of cutters for about 50% and also the daily maintenance of the cutterhead was reduced by 50%. In regard to effectiveness of the second cutterhead model this model is continued on the project \[6\].

Mucking system

TBM had installed mucking system for both open and closed mode. For the open mode special belt conveyor was installed with capacity of the 1000 ton/h. The rock material is moving from muck hopper placed in central part of cutterhead to belt extension area from where to tunnel belt conveyor is moving (Figure 29). The size of material depends on deflectors and grain size limiters which are installed in the openings in the cutterhead.
Open mode is more efficient and quicker. TBM working in open mode can excavate more parts of tunnels. About 80% of the tunnel is excavated in an open mode with maximum progress speed of 8 cm/min.

TBM has also a possibility to operate in a closed mode thanks to submerged walls which can enclose machine body. In such conditions above 20% of the tunnel can be excavated with maximum progress about 4 cm/min. TBM in closed mode can operate in pressure of 8 bar without problems. Once the TBM is operated in closed mode it is impossible to use belt conveyor in which a special hydraulic muck system (slurry) was installed (Figure 30). The slurry circuit must fulfill pressure requirements and grain size of the material which is distributed along. The most important part of a slurry circuit is the combination of crusher jaws which are called suction grill. This part of slurry circuit is determined the time consumption needed for excavating in closed mode. The crusher jaw crumbles the rock material to allowed grain size of 150 millimeters. In the most unfavorable conditions speed of the excavation is really low or sometimes work must be stopped [4].
Dewatering system

According with the limitations of groundwater inflow special water management system was installed. Progress of excavation of tunnel mainly depends on ground water inflow conditions. Dewatering circuit was essential when involving flushing and pumping. The slurry circuit transport of the ground water to the slurry treatment plant which is capable of treating about 400 l/s. From treatment plant water is moved to natural waterways. To control water inflow in the project is used as a technique of pre-grouting and also construction of barriers. The main point of building barriers is reducing the water inflow long ways along the segmental lining. This technique consist of the main stage [4]:

- excavation of 6 rings with backfilling or 4 without;
- pressurization in order to stop flow of water;
- backfilling with using of mortar the last 4 rings;
- grouting of the pea-gravel matrix;
- making de-pressurization.

The barrier construction system is presented on the Figure 31.
Backfilling of segmental lining

Backfilling is a technique of filling the spacing between excavated wall and segmental lining. This space about 25 centimeters must be filled by a special material to reduce the water circulation. Backfilling is made in the open mode only and is dependant from injections of the material like pea-gravel, mortar or SH cement ratio. The technique is showed on the Figure 32 where there are indicated three phases of backfilling.
Figure 32. Backfilling technique in 3 phases [6]

Segmental lining

TBM Åsa is adjusted to lay the watertight pipe behind the machine body after excavate the tube. This special pipe is called lining and it is build to prevent leaking of the groundwater to the tunnel. The lining consists of concrete rings which are assembled from special segments. The segments are 2.2 meters long average and were produced in 3 types. Each ring consists of 5 standard, 2 counter key and 1 key segments which give 8 segments per ring. One segment weights 12 tons and have a special constructed reinforcement cages (Figure 33) [13].
The segment was produced in specially opened segment factory in Ästorp about 30 km from the construction site (Figure 34).
The segments after their production and stage of usefulness to use are transported by train straight to the construction site where they are storaged. The segments which are needed on the TBM to construct the lining are also transported by special small train. Segments are formed into rings with special key to protect the leaking and deflection. In Ästorp factory 40468 segments were produced. The total cost of the segments is 465 734 000 SEK what gives 11 508 SEK per segment. The factory is already closed after manufacturing all needed segments [13].

4.2.2 Ground freezing

The worst rock conditions are located in the Möllback zone (MBZ) where TBM has a really big problem to excavate. This area is about 300 meters long and consists of varied and poor quality rock. Because of that TBM cannot go through without help and the decision was made to freeze some parts of the rock. The aim of the method is to drill horizontal pipes over 260 meters in the central part, freeze the northernmost part and pre-grout the southernmost part (Figure 35). In order to have a good connection with the
beginning of the MBZ an access tunnel from the northern side of the West Tunnel and the drilling chamber was excavated [11].

Figure 35. Drilling chamber with freezing circuit

On the first stage in a 8 meters diameter circle the 100m long holes were drilled. To the drilled holes all essential equipment and pipes were installed. In first 6-12 months the pipe was frozen to the temperature of 40°C below 0°C. After first stage the tunnel inside freezing circle was excavated and then the second stage had began. 40 meters long holes were excavated and pipes were installed. Second part of MBZ was frozen to the arrival of TBM. TBM carried out MBZ without any problems. According to the successful drive along Möllback zone decision was made to use freezing technique also in West Tunnel [11].
4.3 Financing and organization of the project

The two construction leaders met together to join forces to take part in a very difficult and demanding project of Hallandsås Tunnel which was built over 20 years. The project is in 60% owned by Skanska and in 40% of Vinci HB. Around 300 people are employed on the project, not only from Sweden and France but also from Poland, Ireland, Germany or England. Such multicultural work environment can cause misunderstanding and conflicts during the work. Management system makes the work much easier and the conflicts are rare. Organization chart is made in a clear and easy way to understand for everyone involved in the project. The main organization diagram (Appendix 2) is divided into the key departments like: technical department, financial and logistic department, quality, health and safety department, the biggest production department. The organization chart shows connections and responsibilities of each person. Besides of main organization chart the work on TBM and on the Yard (construction site) is also showed in a special chart. The workers on the TBM and on the Yard are divided into 5 shifts, where each worker has 3 days of work and 3 nights of work and then 9 days off. Such a organization gives an easy way for personnel management and coordination of action in construction site (Appendix 3).

Construction site is divided into 3 parts: north, middle and south. On the North Adit work is based on building the cross passages and freezing on the Möllback zone (Figure 36). On the Mid Adit is an access tunnel where the maintenance of cutterhead is possible. On the South Adit the rest of the work is taking place (Figure 37). On the south site the production office, warehouse and storage area are placed. On this construction site is also slurry treatment plant present. Next to South Adit is placed the main office where the management employers are working.
The Hallandsås Project is fully financing from the government. The client that accounted the Skanska-Vinci HB is Trafikverket. The total cost of the project for year 2008 was 10.5 billion SEK [26].
5. Technologies used in the tunnel

5.1 General

Grouting is used to seal the tunnel in Hallandsås. In both pre- and post-grouting method it is important to use proper grout material which is water-tight and penetrates all kinds fissures properly. While constructed a tunnel such a Hallandsås where the conditions and requirements about sealing the tunnel are stiff the amount of grouting is huge. It is necessary then to chose the material which fulfill the requirements and also which will be effective. The grout material used in Hallandsås is a grout based on cement. The pre-grouting treatment being done on the Hallandsås Project is performed with grout mixes based on micro-fine cement Rheocem 650. These mixes are thin and penetrate in small cracks. Because of these good flowing properties of the Rheocem grouts, high amount of grout is injected in highly fractured ground encountered in water bearing zone before the required stop pressure is reached. Description of the Rheocem 650 is evaluated in chapter 5.2.

To decrease the amount of material that must be pumped into one hole and decrease the pressure the new grout materials are tested in the tunnel. One of the grout mixes that was tested is based on MF20 with high content of additives, present higher viscosity and yield stress than the Rheocem grouts used. However, by using a different grouting procedure which consists in maintaining pressure in the injected holes, this thicker grout should be able to penetrate small cracks. The main assumption concerning that procedure is that smaller quantities of MF20 grout could be used with a similar sealing effect than pre-grouting with Rheocem 650. The properties of tested MF 20 are presented in chapter 5.3.

A full scale test, consisting of a fan treatment, had already been performed at the end of the East tunnel drive (2009). However, the conclusions of this first test in terms of efficiency were poor because of the good ground conditions (low water flow) at the chosen position (ring 2448). The main test, similar to the first one, was done in a water bearing zone (Flynta Lycke) around ring 630 (West tunnel) where flows up to 4 l/s per ring was expected. It is possible to compare grouting results from the East Tunnel done with Rheocem 650 and from the West Tunnel done with MF20 since they both were used in the Flynta Lycke area.
5.2 Rheocem 650

5.2.1 Description of the material

Rheocem micro-cements are micro-fined Portland cements with a fast setting time made especially for rock and soil injections. One of these cements used in Hallandsås is Rheocem 650 which is also milled from a Portland cement clinker with a blain value of 650m²/kg. It is designed in order to penetrate tight joints (mainly measured in micrones) and voids to provide grouted rock which is water resistant and can increase significantly progress rate while tunneling. All around the world it is used for pre-excavation and post-excavation grouting in order to seal tunnels or mines properly. It has a short setting time, which at about 20°C and w/c ratio 1.0 equals $2\frac{3}{2}$ hours. Rheocem 650 should always be used with a water reducing admixture called Rheobuild 1000 or Rheocem 2000 PF (containing in total from 1.0% to 2.0% of cement weight) and w/c ratio between 0.5 and 1.0. On Hallandsås only Rheocem 1000 admixture was used. According to its producer BASF its injection grout properties when a mix contains 1.5% Rheobuild 1000 are:

- Mud balance: 1.48-1.50 kg/l
- Water/cement ratio: 1.0
- Flow cone: 32-34 s
- Bleeding maximum 1%.

Firstly, in order to prepare a mix a mixer should be filled with water and then added cement. Secondly, this should be mixed for about 2 minutes and then added Rheobuild 1000 and mixed for another minute. When this is done the whole mixture should be transferred to a colloidal mixer and not kept in it for more than 30-40 minutes [15].

5.2.2 Experience of use on Hallandsås

Rheocem 650 was used as a grouting cement for pre-extraction grouting on the whole length of the East Tunnel and it is still used in the West Tunnel. The grout mixes is obtained from Rheocem 650, water and additives. The Portland cement which is a part of Rheocem 650 has a big amount of gypsum which gives the compound better hardening properties. The additive compound in this case is Rheobuild 1000 which has special properties. The main purpose of using this kind of additive is to stabilize grout properties and improve w/c ratio. The grout mix is made directly in the TBM because of rapid aging
of the mixture. Grout mix which is older than 45 minutes is useless. On the TBM the special equipment manufactured by Häny for mixing and handling the grout mix is placed. The Rheocem 650 is transported on the boxes directly to TBM and then placed to the colloidal mixer. In this stage Rheocem 650 is mixed with water and Rheobuild 1000. This mixer is not a standard type of mills but the mixing process consists of a pumping pressured water what makes the “cyclone effect” inside (Figure 38). In this special way the material is mixed but during the process gypsum in huge pressure causes releasing of big amount of energy what makes the compound unstable. From the mixer the ready mix is transported to the agitator where the mix is handled (Figure 39). It is possible due to the unstable properties of compound that mix can harden really quick. This is the reason why the ready compound is suppose to be used as soon as possible. From agitator mix is transported to the pumps which are pumping the material through pipe lines and hoses to the drilled holes. The holes are made by 3 drill rigs in long arm configuration in order to penetrate the ground in all positions. These rigs are equipped with 76mm and 103 mm drill bits (only used for radial injections) and steering rod for RD holes (holes made with a certain angle). Then there is placed a re-usable inflatable packer in each hole. The thing that must be remembered is to put the tailskin grease at the end of the packer in order to make it easier to remove. In order to start grouting there must be used 12m (6 x 2m) long 1” grouting pipes.

Figure 38. HÄNY HCM High Shear mixers (colloidal mixers) [23]
Figure 39. The HRW agitators are used as holding tanks between the HCM batch mixers and the pump [23]

There is no specific procedure of using Rheocem 650 in the project. In consideration of that the Rheocem 650 is a type of grout material which has a big area of spread (penetrates even really small cracks), during the pumping of the material is a special “umbrella” made. The grouting is made in sequence of 30 fans with certain angle of 10˚ and 13˚ due to control the grout spread and then 32 fans ahead. Such procedure made grouting process much effective and grouts only the needed area without any unnecessary migration of grout material.

It was observed that Rheocem 650 has a good flow properties and a good setting time. Unfortunately, Rheocem 650 has also some disadvantages that where affecting progress rate and project budget. The main problem was that large volumes of the mix had to be consumed before the rock was grouted. Secondly, grouting was considered to be too much time consuming. These were the general reasons to experiment with application of other micro-fine cements.
5.3 Microfine 20 (MF 20)

5.3.1 Description of the material

MF 20 is a cement based material which is produced by Cementa AB. This type of grout material is based on Portland cement which gives MF 20 a good penetration volume especially in hard injection conditions. Portland cement which is used to produce the mixture MF 20 have reduced particle of chromate which is highly allergic. MF 20 consist of 4.5% by weight of sulfur trioxide and about 0.1% by weight of chlorides. The particle size of this kind of grout material is $d_{95} = 20 \mu m$. The specific surface area determine by Blaine method is $810 m^2/kg$. That composed mixture have a great setting time of about 135 min which makes good injection properties. Short setting time is provided by good flowing properties independently from water content ratio. The main advantages of MF 20 is stability, flow and filtering characteristics [16].

5.3.2 Procedure of use MF 20 in Hallandsås

The work which is done through the cutterhead is divided into three types of work (drilling, injecting and testing). For each of the works different material and equipment ought to be used which does not differ from the one used when grouting with Rheocem 650 apart from the material used and that only 2 boomers inject the grouting material. Material which must be present on the TBM in order to perform grouting is microfine cement MF20 and additives such as SetControl II and GroutAid (used only when injecting grout type 2).

The grouting procedure is designed to use two different grout mixes. The mixes will be produced with the two stationary Häny mixing units on the TBM. The composition and expected properties of the mixes are different in both types. Both mixes have only the same w/c ratio and the cement type used in them. Technical parameters of the first mix are lower than type 2. It has lower parameters like density (from 1450-1500 kg/m$^3$), yield stress (2-4 Pa) and viscosity (30-38 mPas). Whereas type 2 density is 1520 kg/m$^3$, yield stress 8-12 Pa and viscosity from 44-52 mPas. Type 1 has no GroutAid added to him but only SetControl II which is 2% of the whole mix weight. Type 2 consists of a significant admixture of GroutAid of about 15% of the whole mix weight and a bigger amount of SetControl II of about 4% of the cement weight. [14]
These parameters state that Type 2 mixes should be used when the rock is more fractured with bigger fissures and a higher water inflow coming from them. Type 1 should be used for low water ingress coming from the drilled holes and more stable rock conditions.

The fan treatment includes 3 stages. Each stage contains three different steps which include drilling, flow test which is done on every hole and grouting with MF20. During the first stage 6 holes are set to be grouted and the head turns into a position called number 1. In result holes marked in green (Figure 40) called D33, D36, D3, D43, D40 and D10 are grouted.

Figure 40. Head position number 1 [14]
On stage 2 the next 5 peripheral holes at the position of 13 degrees are drilled and grouted through the shield and 4 horizontal face holes are drilled through the cutter head. Horizontal drillings are done in order to evaluate the effect of the first round of grouting done in stage 1. The 5 peripheral holes are marked in red (Figure 41) and are called RD30, RD6, RD10, RD20 and RD24. The 4 horizontal holes are marked in green and are called : D31, D1, D6 and D9. Since this drilling pattern, head of the TBM has to turn to position number 4.

![Figure 41. Head position number 4](image)

Peripheral holes can be already drilled during stage 1 setting time because they do not affect the horizontal holes. In this case the 4 horizontal holes can only be drilled when the packers from stage 1 are removed.
In the third stage 3, 4 holes in a peripheral positions are drilled in order to evaluate stage 2 results and if needed to grout. These holes are marked in red (Figure 42) and are drilled in a 10 degrees angle and are called RD3, RD 23, RD27 and RD 9. As in the previous stage, when the packers from radial positions from stage 2 are removed holes for stage 3 can be drilled.

Figure 42. Drilling pattern for stage 3 [14]

When the packers from stage 2 radial holes are removed, the holes for stage 3 can be drilled using two boomers (RD3 and RD 23, RD27 and RD 9). For the same reasons than previous stages, a 12 meters long reusable packer is placed and inflated in each hole once it is drilled. Packers used for pre-grouting divided in two ones that can be used several time or just once. When the packers are used only once the stay inside the sealed rock mass whereas others can be removed. Sometimes it is not possible to remove one so
in the end it also stays inside the sealed rock mass. When grouting with MF 20 it is obliged to keep the pressure for 30 - 40 minutes when already reached stop pressure even with grout injected in order to enhance the properties sealed rock mass, which is different from Rheocem 650.

What must be remembered while these activities take place also investigation tests measuring water inflows and pressure are occurring. These actions state weather to chose grouting with type 1 or type 2 mix. They are measured by a special equipment show on Figure 43.

Figure 43. System measuring the water inflow and water pressure [14]
6. Comparison of injection technologies

The aim of trying to test new micro-cement (in this case MF 20) was to minimize the amount of grout injected with the same or even better effect and control. Testing of a new micro-cement was an idea of Trafikverket later introduced and encouraged for Skanska-Vinci to evaluate.

According to Appendix 4 it is possible to see how often the grouting was made in the East Tunnel using Rheocem 650 and in the West Tunnel using MF 20. The testing zone was from ring 650 to ring 687 for Rheocem 650 and from ring 637 to ring 659 for MF 20. These numbers of rings in the East Tunnel accord to the ones that are in the West Tunnel. Below the ring number the measured water inflow from the face of TBM is showed in liters per second. Depending on this number the grouting was done. In the tables the length of penetration and amount of grout material used is shown. When high water inflows occurred it was decided to pre-grout again even though the grout material overlapped but it meant that it was not sealed enough.

It was observed that the biggest water inflows occurred in the section between West ring 647 to 658. This is one of the reasons why at ring 658 it was decided to grout again. The largest water ingress in the East section of the Flynta Lycke zone happened at ring 661 what caused earlier grouting at ring 663 and the same situation occurred from 669 to 679 where it was needed to grout three times. The overall amount of grout injected in the same zone in the East part was equal to 176.2 m$^3$ whereas in the West Tunnel apart from unknown value at ring 658 it is calculated to be 90 m$^3$. As the results show in the Appendix 4 Rheocem 650 achieved slightly better effects in the Flynta Lycke zone with smaller water inflows coming from already pre-grouted rock mass. Unfortunately, it cannot be said that it was more efficient then MF 20 because bigger amount of grout was injected inside the rock mass. In this case looking from a financial point of view where the cost for one square meters for both cements does not differ (for testing MF 20 the company recommending it has set up the same price as for Rheocem 650) both mixes achieved almost the same efficiency.

In the tables from Appendix 5 and 6 the test results are shown which are divided into stages. In the table from Appendix 5 the grouting procedure is shown for first grouting in ring 637 where there were injected 29 m$^3$ of grout on the length of 33m. Such penetration length is suppose to be sufficient for 15 rings but the new injection was needed
at ring 651 because of increasing water inflow. In the table the possible type of rock mass is shown and the worst cases are marked in grey. The important information are the inflows in every drilled hole. Dependant on the conditions that are in each hole the grouting type is chosen. In most cases type 2 of grout mix was used because of hard conditions in rock mass but in some cases type 1 was chosen like in hole D9 where the conditions give a possibility to inject in the most part type 1 grout. Definitely the biggest amount of grout was injected in hole RD8 where a soft rock mass with big water inflow up to 10 l/s is present. The rock was so weak that even with 22 bars the 5000 l of grout was pumped which is a huge value with such a low pressure. The same situation is in Appendix 6 where the table shows second grout injection which had taken place at ring 651, where 61 m$^3$ of grout was pumped on the length of 30 m. This penetration length is suppose to be effective for almost 14 rings but after the grouting, the amount of water inflow increased to 270 l/s. Such situation provides necessity of grouting after 7 rings. The procedure was the same as in Appendix 5. Even if after the first grouting MF 20 has good effectiveness the later behavior of the grout shows that the properties are not good enough for this type of conditions. After second grouting test injection of MF20 was stopped because of poor sealing properties. As it is shown in the Graph 1 and 2 it is possible to compare the water inflow in both cases. When using Rheocem 650 on this area the average water inflow is about 149 l/s and when using MF 20 is about 191 l/s. It is also due to the fact that East section was grouted more often and with the overall bigger amount whereas MF 20 was only pre-grouted twice.
Graph 1. Water inflow per ring in the East section using Rheocem 650

Graph 2. Water inflow per ring in the West section using MF 20
Injecting of MF 20 was a concept created for geological conditions containing solid rock with minor fractures. In order to test how MF 20 behaves when grouted it was firstly tested on the end of the East Tunnel but the rock conditions at that time were very good, containing a lot of solid rock material and with a small water ingress whereas, the geological conditions on Hallandsås vary a lot in different zones. Unfortunately, the Flynta Lycke area on which it was mainly tested on contained large amounts of water and highly weathered rock mass judging from a big amount of collapsing rock which can be seen on Appendix 3. Rheocem 650 which was used on this zone also had not sealed the rock mass as expected so usage of MF 20 was hard to achieve better sealing efficiency.

From a technical point of view MF 20 should be tested again on another area where geological conditions can be more suitable for this type of the mix. Taking into consideration the properties of rock mass present on Hallandsås MF 20 is not a universal mix for all of them. MF 20 as a grout material with less gypsum is more stable and the penetration of the grout is more stable then Rheocem 650. That makes MF 20 good prepared cement for high pressure in comparison to Rheocem 650 which reacts unstable.

The search for a grout with good sealing properties in varied rock mass is a concept which is worth fighting for. Even though usage of MF 20 seems to be abandoned a new micro-cement is being tested currently which is called INJ30. These efforts can bring a lot of advantages when used on other tunneling projects.
7. Conclusions

Taking into consideration the whole project and the construction time it is easy to say that is one of the longest construction project but it is important to know how difficult it is. During these 20 years there were many problems that the project had to face. After the contamination problems there was a long period of time in order to improve the decontamination progress. The new contractor Skanska-Vinci HB has brought a new light to finish the two tunnels. In order to do so they are implementing sufficient and effective techniques through which the progress rate has improved. To achieve so they are organizing community meetings on which they are explaining all necessary information and what kind of an impact do their decisions and implementations have on the area they are living in. Even though the zone seems to be decontaminated from the previous usage of RhocaGil they are still testing the local wells for any signs of water pollutions. When blasting occurs inside the tunnel Skanska-Vinci HB installs detectors on the local houses which state it the ground quakes were too big or too dangerous for the local community. On such a huge project with so many employees (Hallandsås project employees nearly 300 people) it is really hard to implement sufficient organization system and chart in order to make sure that everyone is informed about the projects and changes happening in it and controlling the work of every person. In order for everyone to be informed every week a new number of the project newspaper is made and sent to every employee and printed out so that everyone can see on what works the project is currently focusing on. To do so a very wide and simple organization chart was used with the workers on the North and South yard and TBM divided into shifts.

The project had to face a complicated rock structure with high water ingress and the area belonging to Nature 2000 because of which has to work according to Swedish Environmental Courts regulations and limitations when pumping out water from the tunnel. In order to do this in the project there must be used a special sealing method and construction technologies. The main construction technology that is used to excavate the tunnels is TBM using segmental lining system. This specially constructed machine besides excavation also arranges the segmental concrete lining behind the shield. To seal the tunnel the voids between lining and excavated hole are backfilled with sufficient material. To avoid high water inflow the pre-grouting technique is normally used from the face of the TBM. In very difficult area called Molleback zone also freezing is implemented.
Pre-grouting ahead of the TBM is done using Rheocem 650 but a new micro-cement called MF 20 has been tested. It was used in order to stabilize the sealed rock mass and consume less grout achieving the same or better sealing efficiency. It contained less gypsum so it was more stable with a little bigger setting time. Even though it setting time was three and a half hours where setting time of Rheocem 650 was two and a half hours it was more predictable. Unfortunately, MF 20 was tested on highly weathered area of Flynta Lycka containing a lot of ground water to which MF 20 was not designed for. Concluding the implementation of MF 20 instead of Rheocem 650 was declined because the results stated that after sealing the tunnel with it higher water inflows from the face of the TBM occurred. Nowadays a new micro-cement is tested on another area called INJ30. Testing and comparing the results of micro-fines cements are very important for future tunneling projects. They can significantly fasten the progress rate of their construction and seal the ground more efficiently.
List of references

9. PN-EN 197-1. Cement - Part 1: Composition, specifications and conformity criteria for common cements
12. Skanska-Vinci HB data base
15. Technical data sheet Rheocem 650, BASF
16. Technical data sheet MF20, Cementa AB
20. www.acpasion.net (date of download: 22.03.2012)
23. www.haeny.com (date of download: 05.05.2012)
24. www.markinfo.slu.se/eng/soildes/berggr.html (date of download: 01.05.2012)
26. www.trafikverket.se (date of download: 22.03.2012)
List of figures

1. One of many examples of grouting classification ............................................. 8
2. Additional requirements divided into three group ............................................ 10
3. Probe and pre-excavation grouting positions ................................................... 16
4. Post grouting on Hallandsås ............................................................................. 17
5. Localization of Scandinavia in the Jurassic on the Baltica southern coast ............ 19
6. Geology of Denmark and south of Sweden taking into consideration geological periods ....................................................................................................................................................................................... 21
7. History of geology of the Hallandsås Project ..................................................... 22
8. Scheme of horst definition .................................................................................. 23
9. Opening the rail station in Båstad ...................................................................... 28
10. West coast Line .................................................................................................... 29
11. Amount of trains that will run after building a tunnel in comparison with current situation .................................................................................................................................................................................................................................................. 30
12. Infrastructure lines in Skåne ............................................................................ 31
13. Traffic on the major roads in Skåne ................................................................... 32
14. Percentage of the total number of goods transports via Skåne ........................... 33
15. Transport from Helsingborg ............................................................................... 33
16. Type of vehicles used for transport goods in Skåne ......................................... 34
17. Kraftbyggrna starting the Project ..................................................................... 35
18. The breakthrough of the East Tunnel in 2010 ................................................... 37
19. Breakthrough in Mid Adit in April 2012 ............................................................. 38
20. TBM progress in West Tunnel .......................................................................... 39
21. Planned cross passages ..................................................................................... 40
22. Vertical cross section with safety systems ......................................................... 40
23. Double track line with comparison of today single track ................................... 41
24. Shield body in construction site before first drive ............................................. 42
25. Tailskin with special grout lines 1 and 2 ........................................................... 43
26. Cutterhead face with specific “star type” arrangement of cutters ..................... 44
27. Area of crushing of the material in front of cutterhead face ............................... 45
28. Second cuterhead face ..................................................................................... 46
29. In yellow belt conveyor is marked to show how the material is going in open mode .................................................................................................................................................................................................................................................. 47
30. In blue the slurry circuit is marked to show how the rock material is going ..........48
31. Barrier construction system .............................................................................49
32. Backfilling technique in 3 phases .................................................................50
33. Casting of the segment ..................................................................................51
34. Storage area in factory ..................................................................................52
35. Drilling chamber with freezing circuit ..........................................................53
36. North Adit .........................................................................................................55
37. South Adit .........................................................................................................55
38. HÄNY HCM High Shear mixers (colloidal mixers) .......................................58
39. The HRW agitators are used as holding tanks between the HCM batch mixers
    and the pump .......................................................................................................59
40. Head position number 1 ..................................................................................61
41. Head position number 4 ..................................................................................62
42. Drilling pattern for stage 3 ...............................................................................63
43. System measuring the water inflow and water pressure ....................................63
List of graphs and tables

1. The graph shows the importance when using apparatuses for different joint sizes
   ........................................................................................................................................9

2. Water inflow per ring in the East section using Rheocem 650 ........................................67

3. Water inflow per ring in the West section using MF 20 ..................................................67
Appendices

1. Geological map of Flynta Lycke zone
2. Organization chart of Skanska-Vinci HB - departments
3. Organization chart of Skanska-Vinci HB – shifts
4. Grouting injections table in East and West Tunnel
5. First injection of MF20
6. Second injection of MF20
| Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # | Ring # |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| # 650 | # 657 | # 658 | # 659 | # 660 | # 661 | # 662 | # 663 | # 664 | # 665 | # 666 | # 667 | # 668 | # 669 | # 670 | # 671 | # 672 | # 673 | # 674 | # 675 | # 676 | # 677 | # 678 |
| 62 L/s | 77 L/s | 90 L/s | 113 L/s | 136 L/s | 158 L/s | 181 L/s | 204 L/s | 227 L/s | 250 L/s | 273 L/s | 296 L/s | 319 L/s | 342 L/s | 365 L/s | 388 L/s | 411 L/s | 434 L/s | 457 L/s | 480 L/s | 503 L/s | 526 L/s |

**EAST**

<table>
<thead>
<tr>
<th>Length:</th>
<th>33 m</th>
<th>36 m</th>
<th>39 m</th>
<th>42 m</th>
<th>21 m³</th>
<th>9.2 m³</th>
<th>15 m³</th>
</tr>
</thead>
</table>

**Rheocem**

Length: 33 m

**Grouting:**

29 m³

<table>
<thead>
<tr>
<th>Length:</th>
<th>15 m</th>
<th>18 m</th>
<th>21 m</th>
<th>24 m</th>
<th>27 m</th>
<th>30 m</th>
<th>33 m</th>
<th>36 m</th>
<th>39 m</th>
<th>42 m</th>
</tr>
</thead>
</table>

**Common:***

- Water coming from D3, D33 which have not been properly grouted.
- Connection between the amphibolite and gneiss (200 cm overbreak).

**Leak behind shield:**

150 L/s
<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D10</strong></td>
<td>Medium - Medium - Soft</td>
<td>Soft - very Soft - Medium - Hard</td>
</tr>
<tr>
<td><strong>D40</strong></td>
<td>Medium - Medium - Soft</td>
<td>Soft - Medium - Hard</td>
</tr>
<tr>
<td><strong>D33</strong></td>
<td>Medium - Medium - Soft</td>
<td>Soft - Medium - Hard</td>
</tr>
<tr>
<td><strong>D43</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Hard</td>
</tr>
<tr>
<td><strong>D36</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft - Medium - Hard</td>
</tr>
<tr>
<td><strong>D3</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Hard</td>
</tr>
<tr>
<td><strong>D22</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Hard</td>
</tr>
<tr>
<td><strong>D24</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Hard</td>
</tr>
<tr>
<td><strong>D9</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Very Soft - Soft</td>
</tr>
<tr>
<td><strong>D31</strong></td>
<td>Medium - Medium - Soft</td>
<td>Very Soft - Very Soft - Medium - Soft</td>
</tr>
<tr>
<td><strong>D28</strong></td>
<td>Medium - Medium - Soft</td>
<td>Very Soft - Medium - Hard</td>
</tr>
<tr>
<td><strong>D6</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D1</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D8</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D6</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D25</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D27</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D9</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td><strong>D3</strong></td>
<td>Medium - Medium - Soft</td>
<td>Medium - Medium - Soft</td>
</tr>
<tr>
<td>STAGE 1</td>
<td>STAGE 2</td>
<td>STAGE 3</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td><strong>D1</strong></td>
<td><strong>D2</strong></td>
<td><strong>D3</strong></td>
</tr>
<tr>
<td><strong>D33</strong></td>
<td><strong>D34</strong></td>
<td><strong>D35</strong></td>
</tr>
<tr>
<td><strong>D36</strong></td>
<td><strong>D37</strong></td>
<td><strong>D38</strong></td>
</tr>
<tr>
<td><strong>D39</strong></td>
<td><strong>D40</strong></td>
<td><strong>D41</strong></td>
</tr>
</tbody>
</table>

**COMMENTS**

- **GROUTING**

- **STAGE 1**

<table>
<thead>
<tr>
<th>D10</th>
<th>Medium - Soft</th>
<th>Soft</th>
<th>Medium - Soft</th>
<th>40 bar</th>
<th>1511 l</th>
<th>OK</th>
</tr>
</thead>
<tbody>
<tr>
<td>D33</td>
<td>Soft</td>
<td>very Soft</td>
<td>Soft</td>
<td>41 bar</td>
<td>2381 l</td>
<td>OK</td>
</tr>
<tr>
<td>D36</td>
<td>Medium</td>
<td>Hard</td>
<td>Medium - Soft</td>
<td>40 bar</td>
<td>1132 l</td>
<td>OK</td>
</tr>
<tr>
<td>D2</td>
<td>Medium</td>
<td>Soft</td>
<td>Medium - Soft</td>
<td>37 bar</td>
<td>4900 l</td>
<td>OK</td>
</tr>
<tr>
<td>D20</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium - Soft</td>
<td>38 bar</td>
<td>5822 l</td>
<td>OK</td>
</tr>
<tr>
<td>D9</td>
<td>Medium</td>
<td>Soft</td>
<td>Medium - Hard</td>
<td>39 bar</td>
<td>4849 l</td>
<td>OK</td>
</tr>
<tr>
<td>D25</td>
<td>Medium</td>
<td>Soft</td>
<td>Medium - Soft</td>
<td>15 bar</td>
<td>1108 l</td>
<td>OK</td>
</tr>
<tr>
<td>D31</td>
<td>Medium - Hard</td>
<td>Medium - Soft</td>
<td>Soft</td>
<td>4 bar</td>
<td>700 l</td>
<td>OK</td>
</tr>
<tr>
<td>D1</td>
<td>Soft</td>
<td>Medium - Soft</td>
<td>Soft</td>
<td>6 bar</td>
<td>1908 l</td>
<td>OK</td>
</tr>
<tr>
<td>D6</td>
<td>Medium - Soft</td>
<td>Soft</td>
<td>Medium</td>
<td>19 bar</td>
<td>5460 l</td>
<td>OK</td>
</tr>
<tr>
<td>D10</td>
<td>Medium - Soft</td>
<td>Soft</td>
<td>Collapsing rock – could not continue</td>
<td>40 bar</td>
<td>0 l</td>
<td>Blocked</td>
</tr>
<tr>
<td>D1</td>
<td>Medium - Soft</td>
<td>Soft</td>
<td>Too much water to continue</td>
<td>12 bar</td>
<td>2143 l</td>
<td>OK</td>
</tr>
<tr>
<td>D6</td>
<td>Medium - hard</td>
<td>Medium - Soft</td>
<td>very Soft</td>
<td>20 bar</td>
<td>5012 l</td>
<td>OK</td>
</tr>
<tr>
<td>D23</td>
<td>Medium</td>
<td>Soft</td>
<td>Clocking rock as stopped</td>
<td>20 bar</td>
<td>3369 l</td>
<td>OK</td>
</tr>
<tr>
<td>D3</td>
<td>Medium</td>
<td>Soft</td>
<td>Medium - Soft</td>
<td>42 bar</td>
<td>1720 l</td>
<td>OK</td>
</tr>
<tr>
<td>D27</td>
<td>Medium</td>
<td>Soft</td>
<td>Soft</td>
<td>-</td>
<td>603 l</td>
<td>OK</td>
</tr>
<tr>
<td>D3</td>
<td>Medium - Soft</td>
<td>Soft</td>
<td>Medium - Hard</td>
<td>14 bar</td>
<td>5176 l</td>
<td>OK</td>
</tr>
</tbody>
</table>

**APPENDIX 6**