BeFo

The Bolmen Tunnel Research Project

Final Report

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Stiftelsen Bergteknisk Forskning – BeFo
Swedish Rock Engineering Research Foundation

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PREFACE

The present report contains the results from research which was carried out at Staverhult in the northern part of the Bolmen tunnel during the years 1984 to 1986. The research was supported by research grants from the Swedish Rock Engineering Research Foundation (BeFo), Sydkraft's Research Foundation, Swedish Nuclear Fuel and Waste Management Co. (SKB) and the Swedish Environmental Protection Board (SNV).

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The multidisciplinary research group has had several meetings and discussions during the research period. Two research reports (Bjarnason et al 1986, Stanfors 1987) have been published so far. Two other reports, Olofsson (1988) and Gustafson & Wallman (1988) are under preparation. The research results have also been presented and discussed at a seminar in November 1986.

Bo Olofsson, M.Sc. has been editor and responsible for the present report. Prof. Gert Knutsson has been head of the whole research project.

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Dr. Tommy Olsson (planning of the project, hydrogeological discussions)
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Three meetings together with the reference group have given many valuable discussions.

It would not have been possible to complete this project without the assistance and support from the research reference group and from many contributors in the field as well as at the four departements involved in the project. The research group wishes to send our expressions of gratitude to them all.

SUMMARY

The Bolmen tunnel is an 80-km long tunnel extending from Lake Bolmen in southern Småland to Perstorp in Scania, southern Sweden. The purpose of the tunnel is to supply Scania with drinking water from Lake Bolmen. The construction of the tunnel began in 1975 and was completed in 1985.

A comprehensive site investigation programme has been carried out, including geological and tectonical studies as well as geophysical investigations such as magnetic, electric and seismic measurements. Core drilling has also been carried out in some areas. Groundwater levels and groundwater chemistry along the tunnel were studied by a monitoring system including around 400 wells.

In 1983, while the construction work was still in progress, a multi-disciplinary research group was founded with participants from four departments of technical universities in Sweden. The research objectives were to develop methods for the prognosis of water leakage into tunnels and to estimate the effects of underground work on groundwater in bedrock and soil. Another objective was to study the hydraulic conductivity in the rock mass and its dependence on the rock stresses.

The research project was concentrated to a short section along the tunnel routh, near the small village of Staverhult, where geophysical investigations had indicated at least three tectonic zones (the Staverhult line).

A comprehensive drilling and measurement programme was set up, including the drilling of two 250 m deep coreholes for rock stress measurements, five 50 m deep holes for hydraulic tests and the installation of fifteen tubes in the overburden and in the bedrock for groundwater level measurements. Measurement of water leakage into the tunnel was also carried out during tunnel excavation through the investigated area.

Geology

The investigation area is situated in the SW-Swedish gneiss region in which red and grey gneisses are predominant. A detailed geological/tectonical tunnel mapping was carried out in the Staverhult area and a Quaternary geological map was compiled, covering the research area.

The dominating rock type is a heterogeneous grey-red often banded gneiss, sometimes interbedded with red feldspar-rich layers and amphibolites. The central part of the Staverhult area was intensively faulted, often along shallow dipping amphibolite lenses. The fractures were often filled with chlorite and clay minerals, usually smectite. The main directions of the fractures were N60-70W and N40-50E.

The Quaternary deposits consist mostly of sandy-silty till, sometimes covered by sandy-silty sediments in depressions. Peat is frequently found in low areas.

Rock stress measurements

Rock stress measurements using the hydraulic fracturing and overcoring methods were carried out at two locations which represented different geological conditions. One of the two 250 m deep boreholes was located in the Staverhult line where the rock mass was heavily fractured. The other borehole was located outside the area in massive rock. The overcoring measurements were carried out in short boreholes in the tunnel at the same locations as the hydrofracturing measurements.

The rock stresses at the level of the tunnel (approximately 40 m) are relativily low compared to other areas in Sweden and fairly isotropic in the horizontal plane. The maximum horizontal stress within the Staverhult line is oriented parallel to the strike of the zone. The mean stress at the level of the tunnel varied between 2.0 and 2.8 MPa. The two methods, hydrofracturing and overcoring, showed good agreement in the mean stress magnitudes at the tunnel depth.

Hydraulic properties of the bedrock and the overburden

Recovery tests were carried out in five boreholes, six tubes and two dug wells in the area. Furthermore, short term pumping tests were carried out in three of the boreholes together with an injection test in one of them. Finally, an interference pumping test was also carried out. Evaluation of the hydraulic tests have shown hydraulic conductivity values in the range of 10^{-6} m/s in the overburden and 10^{-7} m/s in the bedrock. No distinct hydraulic anisotropy has been found in the bedrock. There was a fairly good agreement between the prognosis and the recordings of water leakage into the tunnel. However, the prognosis could not take into account individual leaking fracture zones. The heterogeneity of the rock mass gave local drawdowns and the overburden played an important role as a hydraulic conductor on top of the bedrock.

Changes in the groundwater conditions

Groundwater levels have been measured on a weekly basis from April 1984 to February 1987 in 48 boreholes, dug wells and tubes at Staverhult. The groundwater level situation in the bedrock has changed dramatically during the construction period. The lowering of the groundwater pressure in the bedrock indicates a heterogeneous hydraulic character of the rock mass. The drawdown in boreholes in the southern part of the area was less than 1 m but as much as 5-16 m in the central and northern parts. The tunnel influence on the soil aquifer exceeds 1 m only in topographical low depression areas. The most affected tubes and wells are situated in depressions filled with well sorted sand and silt in contact with a fractured superficial bedrock.

The drainage of the soil aquifer to the bedrock has also been indicated by water chemical analysis from boreholes in the area. The content of sulphate increases in some of the boreholes but the alkalinity and the pH-value decreases. This may be due to an inflow of water from swampy grounds and/or arable land in the surroundings.

The project has shown the necessity of taking into account the Quaternary deposits and also the hydraulic contact between rock and soil during planning and construction of rock caverns and tunnels.

Geophysical investigations

The project has shown that geophysical investigations, using VLF (Very Low Frequency), seismic refraction techniques and resistivity measurements are very useful for identifying and characterizing fracture zones. Geophysical logging in boreholes has shown to be a useful tool for the detection of water leaking fractures.

Final remarks

The research project has pointed out the advantages of combining different site investigation methods, such as rock stress measurements, hydraulic tests and geophysical and chemical investigations for the prediction of water leakage and stability problems in tunnels and rock caverns.

The methods can give a rough prognosis of the conditions in the bedrock and in the overburden. The applicability of each method depends on the type and design of construction, the geological and tectonical conditions and also the need for precision of the prognosis. Each method can be further developed but to provide more specific prognosis it is nessesary to carry out investigations continously during the construction period. This is one of the areas in which future development is urgent. The project has shown not only the advantages of using different methods but also some problems often related to unexpected geological and tectonical conditions. The present report contains therefore a chapter including recommendations for planning and construction of underground works and also a chapter including recommendations for further research (chapter 10).

SAMMANFATTNING

Bolmentunneln utgör en mer än 80 km lång bergtunnel från sjön Bolmen i södra Småland till Perstorp i Skåne. Tunneln byggdes under åren 1975-85 med syfte att försörja västra Skåne med dricksvatten från Bolmen.

Tunnelbyggandet föregicks av ett omfattande förundersökningsprogram med såväl geologiska och tektoniska studier som geofysiska undersökningar, främst magnetiska, elektriska och seismiska mätningar. Kärnborrning utfördes också i vissa områden. Ett miljökontrollprogram med mätningar av grundvattennivåer och grundvattenkemi har utförts i 400 brunnar utmed tunnelsträckningen.

År 1983, alltmedan tunnelarbetet pågick, bildades en brett sammansatt forskargrupp med deltagare från fyra högskolor i Sverige. Ett ramprogram uppställdes med målen att utveckla metoder för att prognosticera vattenläckage i bergtunnlar och att fastställa effekterna av undermarksbyggande på grundvattenförhållandena i jord och berg. Dessutom skulle den hydrauliska konduktiviteten i bergmassan studeras och dess relation till de rådande bergspänningarna.

Som undersökningsområde valdes ett tunnelavsnitt nära byn Staverhult, där geofysiska undersökningar givit indikationer på minst tre tektoniska zoner (Staverhultslinjen).

Ett omfattande borrnings- och mätprogram uppställdes, vilket innefattade två 250 m djupa kärnborrhål för bergspänningsmätningar, fem 50 m djupa brunnsborrhål för hydrauliska tester samt femton rör i jord och berg för grundvattennivåmätningar. Under utsprängningen av tunneln genom området utfördes mätningar av vatteninläckning.

Geologiska förhållanden

Staverhultsområdet är beläget inom det s k Sydvästsvenska gnejsområdet, där röd och grå gnejs dominerar. En detaljerad geologisk-/tektonisk tunnelkartering har utförts i undersökningsområdet liksom en yttäckande jordartskarta.

Den dominerande bergarten utgörs av en grå-röd, ofta bandad gnejs, ibland omväxlande med lager av röd fältspat och amfibolit. I den centrala delen av Staverhult är gnejsen kraftigt förkastad och krossad, ofta utmed svagt stupande amfibolitlinser. Sprickorna är ofta fyllda med klorit eller lermineral, vanligtvis smektit. Dominerande sprickrikningar är N60-70W och N40-50E.

Jordarterna består huvudsakligen av sandig-moig morän, i topografiska lågpunkter ibland täckt av sandiga-moiga sediment. Ytlager av torv är också vanligt förekommande i låglänta terrängavsnitt.

Bergspänningsmätningar

Bergspänningsmätningar med två olika metoder, hydraulisk uppspräckning och överborrning, utfördes i två punkter utmed tunnelsträckningen, vilka representerade skilda geologiska förhållanden. Ett av de 250 m djupa kärnborrhålen för hydraulisk uppspräckning borrades i Staverhultslinjen, där bergmassan var kraftigt uppsprucken. Det andra borrhålet lokaliserades norr om Staverhultsområdet i mer massivt berg. Bergspänningsmätningar med överborrningsmetoden utfördes i korta borrhål från tunneln inom samma tunnelavsnitt som mätningarna med hydraulisk uppspräckning.

Bergspänningarna i tunnelns nivå (ca 40 m under markytan) är i jämförelse med andra områden i Sverige relativt låga och tämligen isotropa i horisontalplanet. Den maximala horisontella spänningen i Staverhultslinjen är orienterad parallellt med zonens sträckning. Medelvärdet för bergspänningarna i tunnelns nivå varierade mellan

2.0 och 2.8 MPa. De två metoder som använts, hydraulisk uppspräckning samt överborrning, visade god överensstämmelse beträffande storleken på bergspänningarna i tunnelnivå.

Bergmassans och jordlagrens hydrauliska egenskaper

Återhämtningsförsök, dvs mätning av vattnets stigningshastighet efter tömning, utfördes i fem bergborrhål, sex rör och två grävda brunnar i Staverhultsområdet. Korttidsprovpumpning utfördes i tre av borrhålen samt en manchettmätning i ett av dessa. Dessutom har en interferensprovpumpning (långtidsprovpumpning) genomförts. Utvärdering av de hydrauliska testerna har givit värden på den hydrauliska konduktiviteten i storleksordning 10^{-6} m/s i jordlagren och 10^{-7} m/s i berggrunden. Ingen tydlig hydraulisk anisotropi märktes i berggrunden. Det finns en tämligen god överensstämmelse mellan det prognosticerade värdet för vatteninläckning i tunneln och de uppmätta flödena. Prognosen omfattade emellertid inte enskilda läckande sprickor och sprickzoner. Bergets heterogenitet medförde lokalt avsänkningar av grundvattnet och jordlagren spelade en viktig roll som hydraulisk ledare ovanpå berggrundsytan.

Förändringar i grundvattenförhållandena

Mätning av grundvattennivåer har utförts varje vecka från april 1984 till februari 1987 i 48 mätpunkter (borrhål, grävda brunnar och rör) i Staverhult. Grundvattnets nivå i berggrunden har kraftigt förändrats under byggnadstiden. Avsänkningen av grundvattentrycket i berget pekar på en heterogen hydraulisk karaktär på bergmassan. Avsänkningen i bergborrhål i södra delen av undersökningsområdet var mindre än 1 m medan den uppgick till 5-16 m i centrala och norra delen. Avsänkningen i jordlagren översteg 1 m endast i de topografiskt lägst belägna terrängavsnitten. De mest påverkade rören och brunnarna är belägna i sänkor fyllda med välsorterad sand och mo i kontakt med ett sprickrikt, ytligt berg.

Dräneringen av jordakviferen till berggrunden har också indikerats i vissa avsnitt genom vattenkemiska analyser från borrhål inom området. Sulfathalten har ökat i några borrhål, medan alkaliniteten och pH-värdet minskat.

De vattenkemiska förändringar som uppstått kan bero på ett inflöde av vatten från myrmark och/eller jordbruksmark i omgivningen. Projektet har visat på nödvändigheten av att, vid planering och byggande av bergrum och bergtunnlar, även ta hänsyn till de jordartsgeologiska förhållandena samt den hydrauliska kontakten mellan jord och berg.

Geofysiska undersökningar

Projektet har visat att geofysiska undersökningar med VLF (Very Low Frequency), refraktionseismik och resistivitetsmätningar är mycket användbara för att identifiera och karakterisera sprickzoner. Geofysisk loggning i borrhål har visats vara ett användbart verktyg för detektion av vattenläckande sprickor.

Slutkommentarer

Forskningsprojektet har pekat på fördelar med att kombinera skilda förundersökningsmetoder såsom bergspänningsmätningar, hydrauliska tester, geofysiska och kemiska undersökningar för att prognosticera vattenläckage och stabilitetsproblem i bergrum och bergtunnlar.

Metoderna ger en grov uppskattning av förhållandena i berg och jord. Applicerbarheten för varje enskild metod beror av berganläggningens utformning, de geologiska och tektoniska förhållandena samt behovet av prognosnoggrannhet. Varje enskild metod kan förbättras men för att erhålla mer noggranna prognoser är det nödvändigt att utföra undersökningar kontinuerligt under byggnadsperioden. Inom detta område är behovet av vidare forskning och utveckling angeläget. Projektet har inte bara visat på fördelarna med att använda olika prognosmetoder utan också på problem som kan uppstå, ofta i anslutning till oväntade geologiska och tektoniska förhållanden. Rapporten innehåller därför ett kapitel med rekommendationer vid planläggning och byggande av undermarksanläggningar samt även ett kapitel med förslag till fortsatt forskning (kap 10).

1 THE BOLMEN TUNNEL PROJECT

Scania, the southernmost region of Sweden, is one of the country's most densely populated areas. Up to the 1950s, the region's water supply was totally dependent on local sources. In spite of the incorporation of the Vombsjö and Ringsjö water catchments, an investigation set up by the government established that future water supplies must be based on catchments outside the region. An inter-local authority company, AB Sydvatten, was established with the objective of being responsible for future water supplies. At the time, Sydvatten had no staff of its own, but entered a co-operation agreement with Sydkraft AB, a company which was made responsible for the implementation of the construction project.

After detailed studies of various alternatives, a project was selected incorporating the main features shown in Figure 1.1.

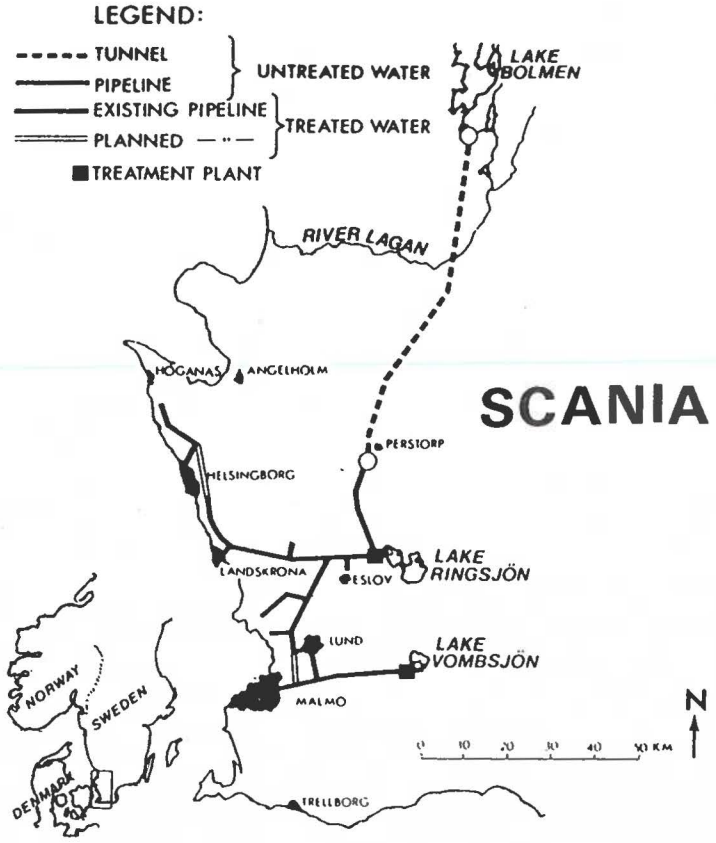


Figure 1.1 AB Sydvatten's water supply system (after Alestam 1986)

In short:

* Untreated water is taken from the southernmost part of Lake Bolmen at a maximum rate of 6 m^3/s.

* The water flows through an 80-km long tunnel with a cross-sectional area of 8 m^2, to Perstorp, where it enters a 25-km long pipeline to the existing water treatment plant at Lake Ringsjön. The depth to the tunnel varies between 30 and 90 m below the ground.

* After treatment, the water is distributed to consumers through the enlarged water supply network.

The work is now complete after ten years of rock tunnelling. The work was carried out under two contracts. The southern part, 56 km long, was constructed by a consortium consisting of the companies ABV, JCC and JM. Work was started in the summer of 1975 and completed during the summer of 1984.

After work on the main tunnel had been in progress some years, the contract was renegotiated and, because of the difficult rock conditions, technical modifications to the design were introduced. Together, the new unit prices and technical modifications resulted in a more than 100% increase in productivity. The weekly rate of advancement per face was increased from 20-25 m to 40-60 m.

The northern part extended a distance of 24 km and was started by Skanska AB in the autumn of 1981 and completed in the autumn of 1985. Skanska AB quickly reached weekly driving rates of 35-45 m per face.

The total cost of the Bolmen tunnel amounts to SEK 530 million at current monetary values.

Technical research and development has been carried out continuously during the course of construction. The production side has benefited from better methods of grouting and wet shotcreting,

optionally with reinforcement fibres, has been developed to a technically and financially viable method, even in small tunnels.

The scientific research has dealt with methods of prediction of water leakage as well as stability problems using geophysical data gained from resistivity, VLF and slingram measurements. Control of the quality of rock bolts was executed using a boltometer.

2 A BRIEF OUTLINE OF THE INVESTIGATIONS ALONG THE BOLMEN TUNNEL

2.1 Site investigations

The Bolmen project has required 20 years of comprehensive work within the field of engineering geology. Site investigations were started in 1967 (Stanfors et al 1967) and the compilation of the geodata from the 80-km long tunnel between Lake Bolmen and the village of Perstorp (Figure 1:1) was completed during 1986 (see Sjöstrand & Stanfors 1975, Stanfors 1986).

Among all the site investigations that were done during the Bolmen project, the following can be mentioned:

* Air-photo analysis.
* Studies of geological maps and descriptions. However, the existing geological maps were all incomplete and insufficient for use in making any engineering geological assessments.
* Collection of information from Regional Highway departments, local authority engineers, power stations, construction companies and rock construction works.
* Collection of information from well drilling records, well drillers, etc.
* General geological mapping in a 10 km wide area between Bolmen and Perstorp, including collection of information from the general public about wells and other matters of interest.
* Detailed geological mapping in a 2 km wide corridor along two main tunnel routes that were chosen after the initial study.
* Airborne magnetic measurements.
* Ground-level magnetic measurements. The aim was to locate, in detail, a great number of dolerite dykes that had been observed in the southern part of the tunnel and also to study predicted tectonic zones along the tunnel route.
* Basic tectonic assessments.

* Seismic measurements over a total length of 200 km. The measurements covered the entire length of the tunnel and many suspected tectonic zones were located using this method.
* Core drilling was carried out on a relatively limited scale, mostly to check the quality of the rock in zones in which indications of fractured rock had been obtained using geological or geophysical methods. Core drilling totalling ca. 3000 m was completed.
* Measurements of groundwater levels and groundwater chemistry in a monitoring system of around 400 wells along the tunnel.

2.2 Results

Analysis of all site investigations that were executed indicated a number of tectonic zones running mainly in the directions NNE and WNW. From the Bolmen end, the most serious tectonic zones were regarded as being adjacent to the valley of the Torpaän stream (I) and the Exen-Staverhult (II) area, the valley of the River Lagan (III), the Markaryd-Kraxasjön (IV) lake area, the extension of the border zones of the Hallandsås uplift (the Slättsjö (V) area) and the valleys of Perstorpsbäcken (VI) and Ybbarbsän (VII) (The numbers refer to figure 2.1).

The aim of the geological site investigations was naturally primarily to establish basic information in order to determine a suitable route for the tunnel. All the geological information along the tunnel line that had been obtained during the investigation period was presented in a longitudinal tunnel profile, where each drawing covered five kilometers of the tunnel path. The profile also contained information on rock quality and where the need for shotcrete support work was expected.

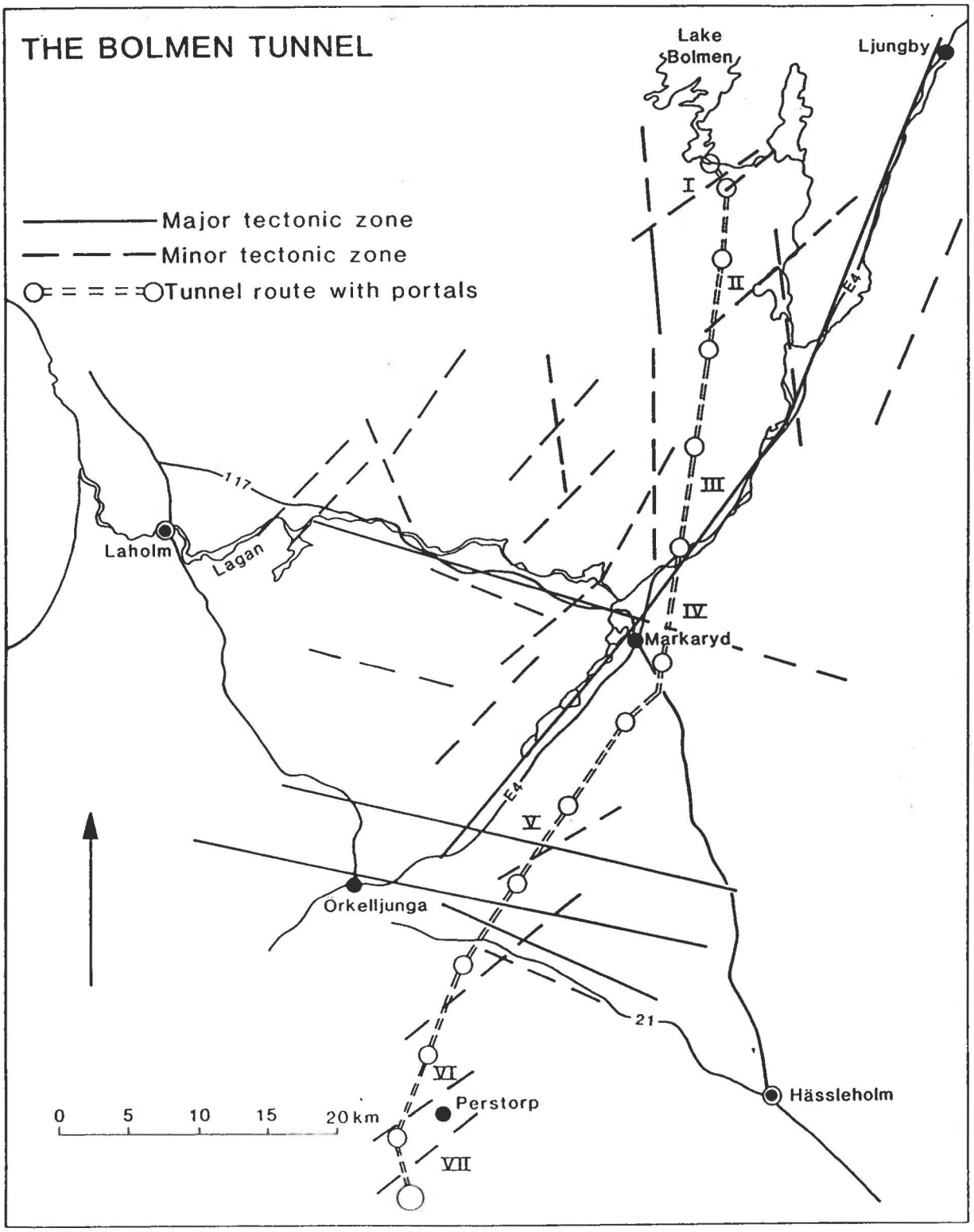


Figure 2.1 Predicted tectonic zones in the Bolmen tunnel area (Stanfors 1987)

2.3 Supplementary investigations

During the entire tunnelling stage, complementary seismic and electrical measurements were carried out around many of the major tectonic zones that had been indicated during previous investigations. The later investigations resulted in a total of about ten local changes in the original tunnel route and considerably shorter passages through tectonic zones requiring support work. In all cases, the cost of this work paid for itself several times over by the reduction in rock support work required. In this context, the resistivity measurements provided especially valuable basic information for a description of the clay-filled and often water-bearing zones of fractured rock. An excellent example of a local change in the line of the tunnel was the approximately 75-m lateral move introduced prior to the passage through the Staverhult line. This change in the tunnel line permitted tunnelling to be carried out in the most fractured part of the tectonic zone from the most advantageous angle, thus reducing the need for rock support measures (Bäckblom & Stanfors 1986).

Geological mapping was carried out continuously from the start of blasting for the Bolmen Tunnel in 1975 up to the time of its completion in 1985. The aim of the geological mapping was primarily to describe the engineering geological conditions in detail in and immediately adjacent to the sections that required some form of permanent support.

All information from the geological mapping was presented on drawings with a scale of 1:1000, together with information on rock support work carried out.

3 GEOLOGICAL AND HYDROLOGICAL CONDITIONS IN THE BOLMEN TUNNEL - A BRIEF OVERVIEW

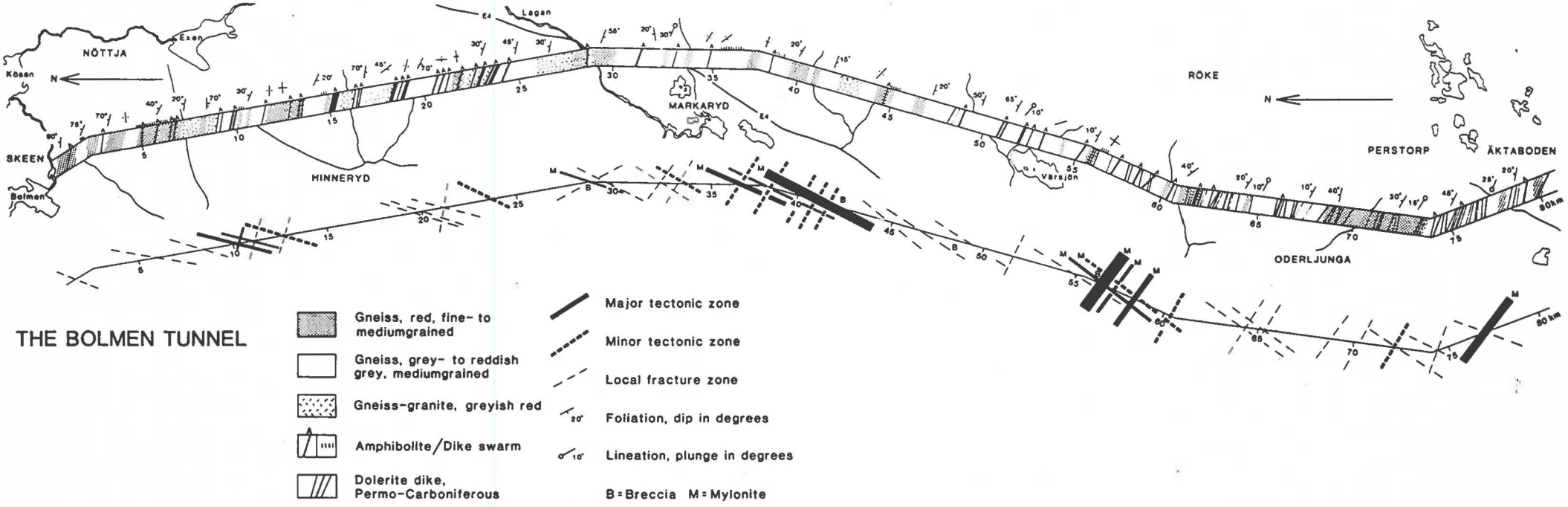
The main purpose of the geomapping in the Bolmen tunnel was to document parameters of engineering-geological interest. The rock divisions and descriptions from the tunnel were therefore primarily based on engineering-geological aspects. No petrographic report was made on the basis of microscopic or chemical analyses.

3.1 Geology

An overview of the geological conditions in the tunnel is shown in Figure 3.1.

Different variants of gneisses are the types of rock which totally dominate. This rock has been diveded into variants from an engineering-geological point of view. The predominant type of gneiss is grey to reddish, usually medium-grained with distinct schistosity. This gneiss is often migmatized with veins of red potassium feldspar.

Another type of gneiss is the red gneiss, which is much less common than the greyish-red variant. The red gneiss is fine to medium-grained and the schistosity is significantly less conspicuous than in the greyish-red variant. Migmatization is often absent.



THE BOLMEN TUNNEL

Figure 3.1 Generalized geological map (Stanfors 1987)

A banded gneiss was also encountered, especially between stations 13+000 and 16+000. This variant is fine-grained throughout and characterized by flat-lying bands which consist of thin parallel layers of grey and red gneisses and some distinct bands of black amphibolite.

The gneiss-granite is one of the most homogeneous types of rock found in the tunnel. The gneiss-granite is medium-grained and grey-red in colour, often with centimetre-large porphyroblasts of potassium feldspar.

For practical reasons in the geological mapping, all basic rocks showing schistosity were put in the same group - amphibolite. About 5% of the tunnel bedrock consists of amphibolite. The distribution along the length of the tunnel, however, varies a great deal from about 20% between stations 20+000 and 25+000 to only a few per cent in the southern part of the tunnel. The basic rocks seem to constitute a genetically very heterogeneous group with very varying forms - from small lenses and bands to thick bodies several hundred metres wide in the tunnel.

Amphibolite occurs as fragments and inclusions in all granitic rocks, except in the banded gneisses, where it forms layers and bands parallel to the schistosity. Several dykes cut through the gneiss structures and especially interesting are the swarms of metre-wide, steep dykes that intersect the northern part of the tunnel. The often strongly schistose and clay-altered contact zones of the amphibolites are of great significance from a engineering-geological point of view.

In the southern part of the tunnel 118 Permo-Carboniferous dolerite dykes have been found, varying in thickness from 1 to 80 m. Thirty-five of them are more than 20 m wide. Altogether, this type of dolerite amounts to 1 800 m of the tunnel length.

Most of the dykes are trending roughly N65^{o} - 75^{o}W. About 10% of the dykes have a strike running NW. The dip is usually steep or moderately steep towards SSW.

3.2 Tectonic features

Most of the rock types in the Bolmen tunnel have been involved in folding along flat-lying axes mostly trending WNW. The fold type is mostly open and characterized by large folds with a WNW plunging fold axis. Locally, especially in the northern part of the tunnel, more isoclinal folds along N or NW trending axes were observed.

The northern part of the tunnel, from 0 to 45 km, is dominated by fractures and fault zones trending NNE, whereas the southern part is characterized by the NW-WNW fault system.

From Lake Bolmen, the tunnel passes through a number of tectonic zones of regional character, i.e. the Staverhult line, the valley of the River Lagan, the Slättsjö zone and the Ybbarp zone. The regional tectonic zones are often 200-600 m wide and composed of several heavily crushed and mylonitized zones, often clay-altered.

In addition to the major regional tectonic zones, there is also a number of minor tectonic zones and a large number of local fracture zones. The predominant directions of these zones and of the fracturing in general is WNW in the southern part and NNE in the northern part. It is interesting to note that movements and faults in the NNE direction often seem to overprint structures trending WNW. Faults trending NNE have in several cases been observed cross-cutting Permo-Carboniferous dolerites.

A measure of the tectonic influence to which the dolerite dykes have been subjected may be obtained by studying the amount of rock support required in the dykes. It was found that about 30% of the dykes required some support (in addition to rock bolting). Only 3 of the 118 dykes exhibit traces of more intense tectonization. About 15% of the dykes required some kind of support in the contact zone between the dyke and the country-rock.

This lends support to the opinion that younger movements in the bedrock were mostly triggered off along the major regional tectonic zones.

3.3 Hydrogeological aspects

Due to water leakage more or less extensive pre-grouting was required along some 25% of the Bolmen tunnel length. Water leakage into the tunnel may primarily be related to the regional tectonic zones between stations 35+000 - 45+000 and 55+000 - 60+000. There is also a good correlation between minor regional and local fracture zones and water inflow in many other sections of the tunnel. Leakage was especially widespread in conjunction with the regional tectonic zones adjacent to deeply eroded depressions in the rock surface filled with glacio-fluvial material. No general correlation has been found between inflow of water and sections of tunnel that pass under peat lands.

Even if most of the water inflow into the tunnel can be related to major tectonic zones, there are many examples of inflows in conjunction with single open fractures or very narrow fracture zones in otherwise solid rock. Just over 25% of the inflow occurred in such areas.

Five typical examples on correlation between water leakage and rock structures are presented in Figure 3.2.

The composition and nature of fillings in fractures is another parameter that naturally affects water flow in the bedrock. The Bolmen tunnel contains fractures sealed mainly with epidote, quartz and feldspar and fractures coated with chlorite, calcite and clay minerals. The direction and magnitude of rock stresses are probably also of great influence on the water flow.

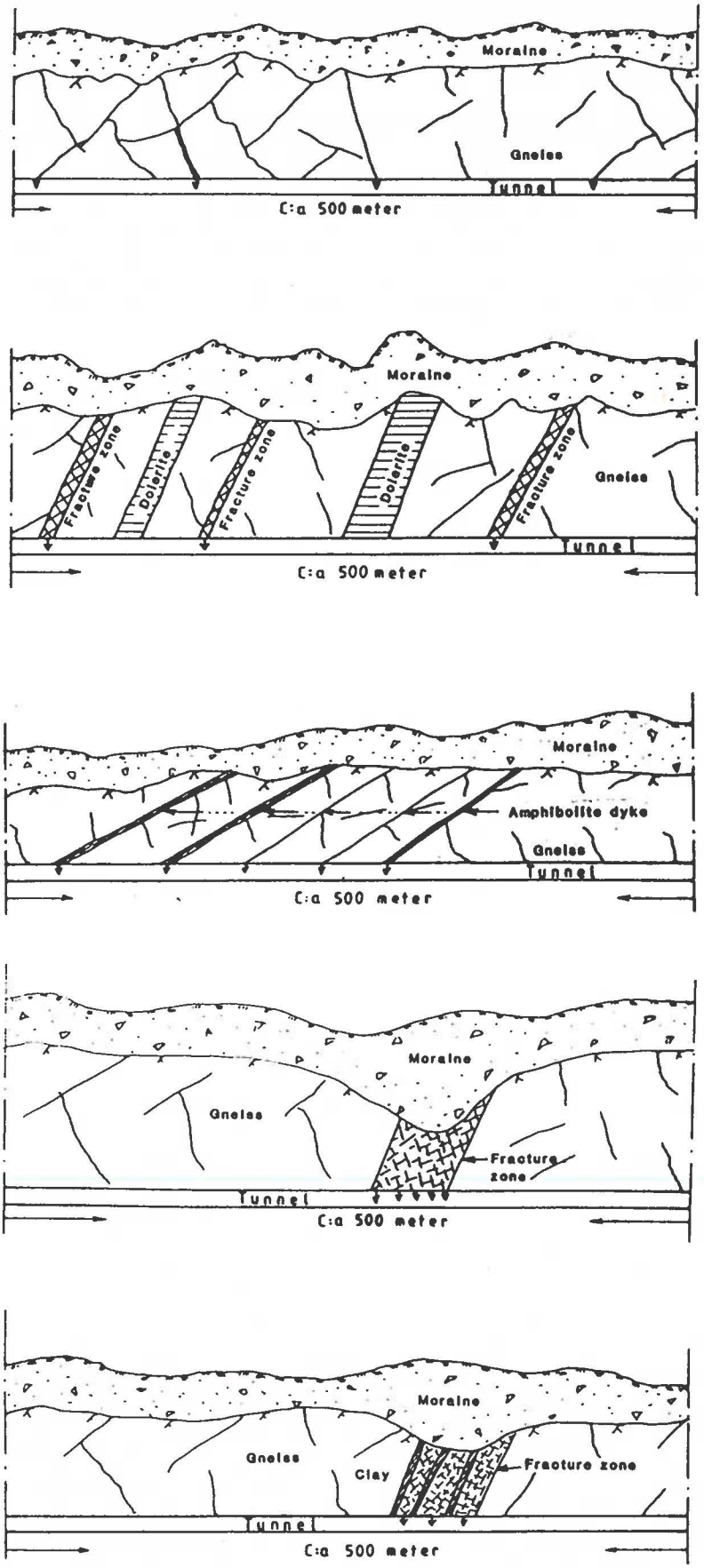


Figure 3.2 Five different examples of geological and tectonical conditions in the Bolmen tunnel connected to water inflow (Stanfors 1984).

4 THE BOLMEN TUNNEL RESEARCH PROJECT

4.1 Background

The leakage of water into tunnels and rock caverns generally causes difficulties such as increasing costs depending on the necessity of pumping the water out of the tunnel and also for increase of support requirements. A considerable part of the costs for rock support in Swedish tunnelling is related to inflow of water. A large inflow of water can also endanger the labour force. The lowering of the groundwater table often causes environmental problems, especially in populated areas where ground subsidence may cause damage to buildings, sewers and roads. Dug and drilled wells may dry up, which leads to claims for compensation or expensive drilling of deeper wells. Lowering of the groundwater table is sometimes related to changes in groundwater chemistry which might be irreversible.

Water inflow during the construction of a tunnel for water transportation purposes can sometimes cause an outflow of water when the tunnel is in operation. Outflow of water implies a rise in the groundwater table and may imply water-logging of the ground level. Water inflow into road-tunnels may be dangerous to the traffic due to slippery or ice-covered roads.

Problems related to water inflow during tunnelling have been described in many reports from other projects in Sweden, e.g. the power plant in Juktan (Carlsson & Olsson 1978) and from several tunnels in Stockholm and Gothenburg (Sund et al 1977, Ahlberg & Lundgren 1977).

In crystalline rocks the inflow of water in the tunnel is generally associated with fractures or fracture zones, while the porosity of the rock-matrix in crystalline rocks is more or less zero. Large fractured zones, at least if they are steep enough, can usually be detected by geophysical methods and can therefore be avoided. By applying pre-grouting when passing fracture zones, water inflow

can be minimized. The amount of water that can be drained by the tunnel is not limited by the theoretical storage capacity of the surrounding rock. The connection between different sets of fractures is thought to be very important and where there is a good hydraulic contact between the open fractures in the rock and a big water reservoir in the overburden, or a lake, the inflow of water can be very dramatic.

All these potential problems related to groundwater highlight the necessity of qualified hydrogeological evaluations during the design and construction of underground works.

4.2 Objectives

During the whole period of planning, design and construction of the Bolmen tunnel a number of different investigations were made as described in Chapter 2. Some of the data collected are unique. Therefore, in 1983, when the construction work was still in progress, a multidisciplinary research group was formed with participants from four scientific departments of technical universities in Sweden. After discussions a frame work research programme was propounded. The overall objectives for the complete research program were as follows:

* To develop methods for the prognosis of water leakage into tunnels and to study the consequences of water-leakage on tunnel progress and the working environment

* To make quantitative analysis of the geological and hydrological surroundings, hence estimating the effects of underground work on groundwater in the bedrock and overburden as well as on the environment.

* To study the role of in situ rock stresses on the hydraulic conductivity of the rock mass, the water leakage and the stability of the tunnel.

The research project area concentrated around the small village of Staverhult, southwest of the town of Ljungby, where geophysical investigations and core drillings had indicated at least three significant tectonic zones. At the time when the research project started, the tunnel had not yet been driven through the research area but two tunnel faces (from north and south) were planned to meet right under the central part of Staverhult. Hence, it was a good opportunity to test a method for prognosis of water leakage and analyse the geological/hydrogeological and rock stress conditions and how these affect the tunnel construction, in an area where the tunnel intersected one of the most distinct tectonic zones.

4.3 Organization of the research project

The four scientific departments involved in the research project and their field of research were as follows:

Division of Rock Mechanics, Luleå University of Technology

Research project: The role of in situ rock stresses on water leakage and stability problems in the tunnel. The objective was also to compare the rock stress situation within the specific tectonic zone at Staverhult to a more massive rock sequence area. By using two different methods at both localities - hydraulic fracturing and overcoring - they could be compared in different geological situations.

The Department of Geology, Chalmers University of Technology and University of Gothenburg

Research project: The hydraulic properties of the rock mass. The principal object of this project was to carry out different hydraulic tests which, combined with geological and tectonical site investigations, could result in a prognosis of the water leakage into the tunnel.

Department of Land Improvement and Drainage, Royal Institute of Technology, Stockholm

Research project: Water leakage and water chemistry in relation to different geological and hydrological situations. The object was to study and verify how different soil and rock aquifers reacted to the construction of the Bolmen tunnel, in and around the Staverhult line area.

The Department of Geology, University of Lund

Research project: A comparison between the results of site investigations that had been carried out and the actual conditions encountered in the tunnel. This project discusses observations made from the whole tunnel line. The project has been reported to Sydkraft AB and is presented in Stanfors (1986 and 1987)

The research programme was supported by research grants from the Swedish Rock Engineering Research Foundation (BeFo), Sydkraft's Research Foundation and the Swedish Environmental Protection Board (SNV). Each research group is responsible for its own investigations and research results. However, a drilling and measurement program common to all research groups was also set up. A research reference group was established with participants from the granting foundations and authorities, the owner of the tunnel and the contractor.

4.4 Drilling and measurement programme in the Staverhult area

4.4.1 Drilling programme

The field investigations in the Staverhult area required a rather comprehensive drilling and measurement programme. The aim was to improve and co-ordinate the basic data for the multidisciplinary research group.

The following drillings were carried out according to the object of each research group. The exact location of each borehole and the specitic investigations carried out are presented in Table 4.1 and Figure 4.1.

Rock stress measurements:

Rock stress measurements were carried out at two locations, each representing different geological conditions. One of the locations was within the Staverhult tectonic zone and the other one was about 1.5 km north of the zone in a more massive rock. Two different measuring methods, hydraulic fracturing and overcoring, were employed at each location. Location 1 is situated close to the position 8+640 m and location 2 at the position 10+312 m (the figures refer to the tunnel extension).

Two 250 m deep boreholes for hydrofracturing measurements were core-drilled with a diameter of 56 mm at each location together with two short holes, drilled into the tunnel roof for overcoring measurements. The four boreholes have all been mapped in respect to fractures and rock types.

The hydraulic properties of the rock mass:

Five boreholes each with a diameter of 115 mm were drilled down to the tunnel floor level. In order to achieve the best possible evaluation results from the hydraulic tests, the location of each borehole was specified by conclusions made from the geophysical-geological site investigations and tectonic lineaments from an air photo interpretation. During the percussion drilling, the drilling rate, rock type, fractures and water leakage were noted, and an elementary recovery test was carried out.

Furthermore, three single hole test pumpings, one interference test pumping and one injection test were successfully completed.

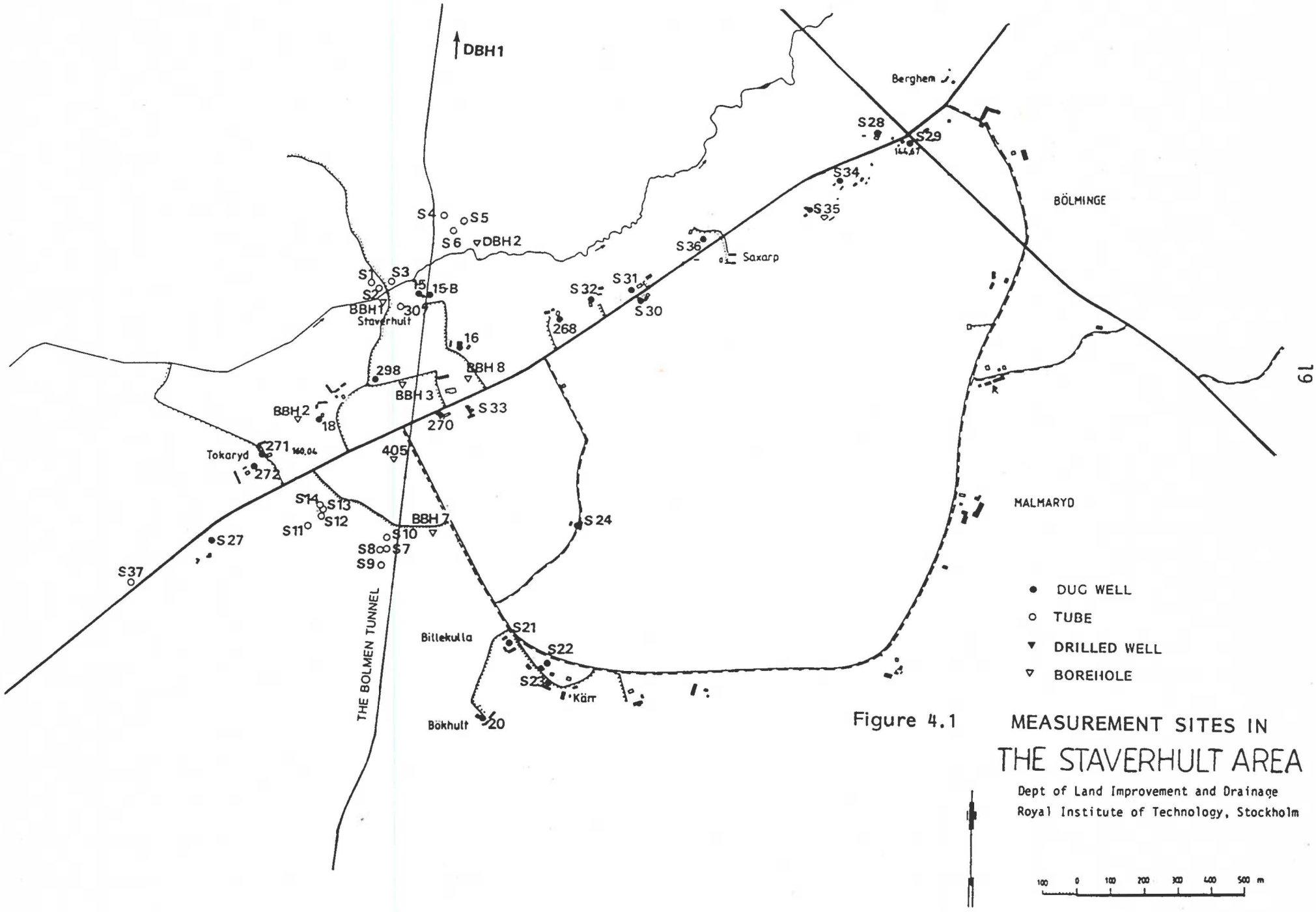


Figure 4.1 MEASUREMENT SITES IN THE STAVERHULT AREA

Dept of Land Improvement and Drainage
Royal Institute of Technology, Stockholm

Table 4.1 Measurements in the Staverhult area

Site No	Geo-logy	Depth (metres)	Type of well	Water chem. 1-6 times	Geophys. logging	Recovery tests	Pumptest single hole	Pumptest inter-ferrence test	Injection test	Rock stress measur.	Ground water level measur.	Since	Soil or rock type analysis	Approx dist to the tunnel line (metres)	
Wells			cement lined (ce) stone lined (st) drilled (dr)												
15	till	4.25	ce	x**							x	69**		70	new drilled well inside the dug well
158	till	2.30	st								x	84		40	
16	till	4.88	st	x**							x	71**		100	
17	till	3.81	st	x**							x**	71**		240	
18	till	5.23	ce	x**							x	71**		280	
20	till		st	x**							x	69**		330	
S21	till	4.00	st								x	84		350	
S22	till	5.05	ce								x	84		470	
S23	till	4.10	st								x	84		480	
S24	till	3.20	ce								x	84		530	
S27	till	4.66	ce								x	84		550	
S28	till	5.00	ce								x	84		1 370	
S29	till	3.18	ce								x	84		1 470	
S30	till	4.03	ce								x	84		650	
S31	till	6.00	ce								x	84		620	
S32	till	4.45	ce	x							x	84		500	
S33	rock	20.00	dr								x	84		170	
S34	till	5.33	ce								x	84		1 250	
S35	till	7.00	ce								x	84		1 150	
S36	till	5.85	ce								x	84		820	
268	till		ce	x**							x	72**		410	
270	till		ce	x**							x	72**		105	new drilled well, 88 m deep
271	till		st	x**							x	72**		440	
272	till		ce	x**		x					x	72**		490	
298	till		ce	x**		x					x	75**		100	

* = Overcoring carried out from the tunnel

** = Made by Sydvatten AB

Table 4.1 (continued)

Site No	Geo-logy	Depth (metres)	Type	Water chem. 1-6 times	Geophys. logging	Recovery tests	Pumptest single hole	Pumptest inter-ferrence test	Injection test	Rock stress measur.	Ground water level measur.	Since	Soil or rock type analysis	Approx dist to the tunnel line (metres)	
Bore hole			drilled (dh) core drilled (cdh)												
BBH1	rock	50	dh	x	x	x	x		x		x	84		120	
BBH2	rock	50	dh	x	x	x					x	84		340	
BBH3	rock	50	dh	x	x	x	x	x	x		x	84		40	
BBH7	rock	50	dh	x	x	x					x	84		100	
BBH8	rock	50	dh	x	x	x	x				x	84		150	
DBH1	rock	250*	cdh							x				200	situated north of the Staverhult area
DBH2	rock	250*	cdh	x						x	x	84		130	crushed rock below 150 m
405	rock	13	dh	x							x	71**		40	
Tubes			plastic (pl) or iron (ir) tube												
S1	rock	7.50	pl	x		x					x	84		160	
S2	till	4.10	pl	x		x					x	84		150	
S3	till	2.60	pl	x		x					x	84	x	120	
S4	rock	9.10	pl	x		x					x	84		30	crushed rock below 6.70 m
S5	till	3.14	pl	x		x					x	84		80	
S6	rock	4.50	pl	x		x					x	84	x	70	
S7	till/ rock	9.00	pl	x							x	84	x	50	bore crown in the ground below 3.40 m
S8	rock	9.10	pl	x							x	84		50	
S9	peat	2.12	pl	x							x	84		50	
S10	till	6.00	pl	x							x	84		50	
S11	peat	2.55	pl	x							x	84		270	
S12	rock	12.60	pl	x							x	84		230	crushed rock below 11.20 m
S13	sand, till	5.60	pl	x							x	84	x	230	
S14	peat	2.50	pl	x							x	84		230	
S37	till	3.95	ir	x							x	84		800	
307	till	4.24	ir	x							x	71**		70	

* = Overcoring carried out from the tunnel

** = Made by Sydvatten AB

Water leakage and water chemistry in relation to different geological and hydrological situations:

Drilling and tube-pressing were carried out at five sites in the Staverhult area. Totally, 15 tubes, divided into four groups and one reference tube were completed.

The location of the five tube groups was based on the results of:

- The geophysical-geological site investigations
- The indicated tectonic zones
- The distance from the tunnel line
- The different soil types
- The topographic position.

Boreholes were drilled and the tubes were pressed down to different levels in peat, till and superficial bedrock. Drilling rate, frequency of large boulders etc were noted and a sampling programme was carried out. This programme included analysis of soil types as well as water chemistry.

Furthermore, the tubes have been used in an extensive programme for groundwater level measurements, in conjunction with data from other available wells, boreholes and tubes in the investigation area. A number of hydraulic tests and geophysical loggings have also been completed in some suitable boreholes.

4.4.2 Measurement of water leakage into the Bolmen tunnel

The measurement of water leakage into the tunnel was one of the fundamental prerequisites for the accomplishment of the multidisciplinary research programme. Hence, it was important that measurements were carried out with the utmost accuracy.

Water quantity measurements were originally carried out by the contractor at one site at the access station Balkö, about 3 km north of the Staverhult area. This was unfortunately not sufficient for the research programme, because of water inflow from two directions, i.e. not only from the investigation area.

Hence, three more or less equivalent measurement methods were suggested in the programme frame:

1. Pump pit. The cavity is blasted out close to the investigation area. A water pump with a flow meter is installed in the cavity.

2. Thompson weir. A barrier is built in the tunnel with a wedge-shaped outflow. The water level in this wedge gives a fair approximation of the flow.

3. A basin with a flow meter. Instead of the Thompson weir in number 2, the barrier/basin will have its outflow through a pipe with a flow meter.

After discussions with the contractor and considering the working routines, a mixture between the methods was suggested. A cavity was excavated, in which a large open box, approximately 3x2x1.5 m, was placed. The water was pumped from a small pump cavity to the box. It then passed a V-shaped Thompson weir at one side of the box and was transported through a 15 m long pipe northward to prevent water circulation. Water flow measurements were supposed to be carried out regularly by the contractor.

4.4.3 Geological and tectonical mapping in the Bolmen tunnel

A detailed mapping of geology, fractures and water leakage has been completed along a section of 1.5 km through the Staverhult area. Two reference sections north of the Staverhult line, together approximately 200 m long, were also mapped in detail.

The detailed map sections were as follows: (the figures refer to the tunnel extension)

9+800 - 11+300	The Staverhult area
8+570 - 8+670	Reference mapping around a core drilled borehole (DBH1) which was made for rock stress measurements.
6+680 - 6+780	Reference mapping.

During the geological and tectonical mapping, orientation of the fractures were measured together with rock types, fracture lengths, water leakage, mineral fillings, sliding planes etc.

The fracture data has been statistically and graphically analysed using a microcomputer. The fracture data programme complex "SPRICK1.BAC" has been developed by Olofsson(1986).

5 THE STAVERHULT AREA

5.1 Description of the area

The research area is situated 30 km southwest of the town Ljungby in the southern part of the district of Småland. The area was chosen because of the major tectonic zone, the Staverhult line, indicated by the seismic survey and electric resistivity measurements. The tectonic zone included at least three significant zones of disturbance, hence, water leakage and stability problems in the tunnel were expected in the Staverhult area.

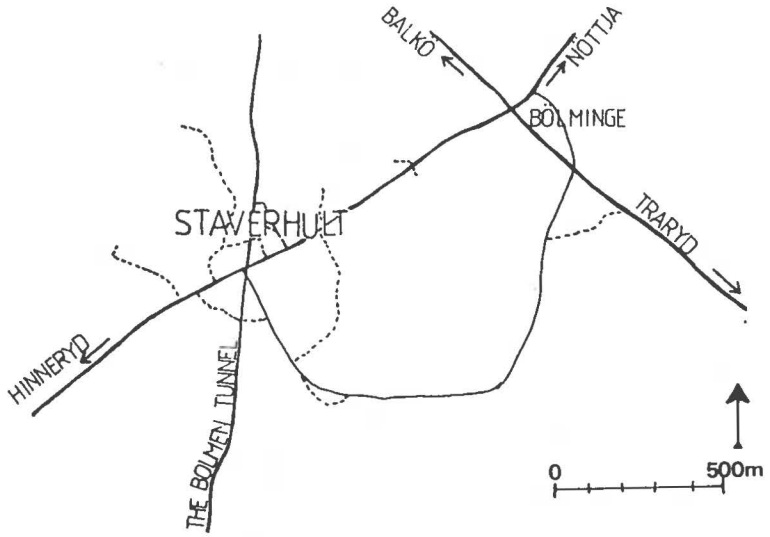


Figure 5.1 The Staverhult area

5.2 Geology

Bedrock

There are very few outcrops in the Staverhult area and the thickness of the overburden is usually 4-10 m rarely exceeding 15 m. The hills and depressions in the area are usually caused by

topographic variations in the underlying bedrock, hence, the thickest overburden is normally found in depressions.

The dominating rock type is a heterogeneous grey-red, often banded gneiss. The darker layers, including more mafic minerals, are interbedded with red feldspar-rich layers and sometimes penetrated by veins of potassium-feldspar or pegmatite. A minor part of the gneiss is more basic and may be characterized as an amphibolitic gneiss. The banded gneiss is sometimes cut by amphibolite dikes, usually 0.1-1 m wide. A more massive, coarse grained and homogeneous gneiss-granite is also found in the area. The layering and foliation usually trend east-west and the dip is relatively flat towards the south.

Quaternary deposits

The geological site investigations that were carried out during the planning of the Bolmen tunnel included studies of tectonics and rock types, without attention to Quaternary deposits, except in regard to thickness of the overburden. Hence, a detailed Quaternary map, covering the Staverhult area (scale 1:10 000) has been compiled, Figure 5.2.

The area is located in the southern Swedish Uplands, where hummocky moraine is predominant, alternating with wide-spread peatland. Glaciofluvial deposits can be found all over and glaciolacustrine sediments are frequently found in depressions.

In the mapped area around Staverhult, several different soil types are found. Till is the predominant deposit north of the road Hinneryd-Bölminge and in the central part of the area south of the road. The predominant till is usually a sandy-silty type, relatively homogeneous all over the area. The ground surface has a normal or in some parts low frequency of boulders.



Figure 5.2 QUATERNARY MAP OF

THE STAVERHULT AREA

Dept of Land Improvement and Drainage
Royal Institute of Technology, Stockholm

P. Edmark 1984

The southeastern part of the Staverhult area forms a valley trending NE-SW. The altitude in most of the valley is below 145 m a s l and glaciolacustrine sediments are found in the lowermost parts. Along the western slope of the valley glaciofluvial sand and gravel can be traced appoximately 2.5 km in the NE-SW direction. The southern part of this esker is flat and often difficult to recognize. Northward, the esker rises to a 6-8 m high ridge, about 15 m wide.

In the southeastern part of the valley, below 145 m a s l, reworking of the glaciofluvial deposit and the till by waves and winds has produced a vast distribution of sandy material.

In the southwestern part of the Staverhult area the areal distribution of peat soils is considerable. Peat bogs are the prevalent type of peatland in the district, mainly depending on high annual precipitation. Fen areas can be seen along the rivulet in the north. Fairly thin layers of peat covering till and sand have an extensive distribution in the area and are generally cultivated, at least in central part of Staverhult.

5.3 Precipitation

Situated on the west side of the southern Swedish Uplands, the Staverhult area has an annual precipitation of about 800 mm. Precipitation data from two adjacent precipitation stations, Långhult and Bolmen, and one climatological station, Ljungby, has been collected from SMHI (Swedish Meteorological and Hydrological Institute).

Långhult, situated 20 km SW of Staverhult, has the highest annual precipitation of the three stations. Since the station is situated in a very rainy area, the precipitation graph from Bolmen, 17 km N of Staverhult, probably matches the Staverhult area better. The annual precipitation at the three stations since 1961 is presented in Figure 5.3. It shows that 1975 and 1976 were very dry years in this area.

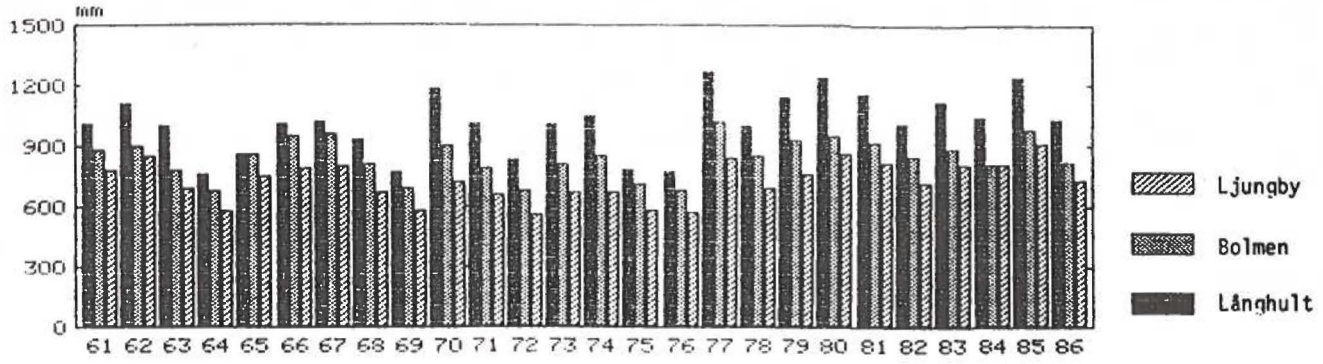


Figure 5.3 Yearly amount of precipitation at Bolmen, Ljungby and Långhult 1961-1986 (Source: SMHI)

The precipitation in 1984 and 1986 was close to the average annual precipitation for 25 years (1961-1985). However, in 1985 the precipitation was 15-25% higher compared to the average precipitation (Table 5.1). The average precipitation at Ljungby is usually much lower than at Bolmen and Långhult. The precipitation values presented in Figure 5.3 and Table 5.1 have not been corrected for measuring errors such as wind deficit and evaporation from the precipitation gauge. The revised precipitation is often 15-25% higher than the measured one.

Table 5.1 Precipitation at three stations during the research period and the average annual precipitation (mm) for 25 years (1961-85)

Station	Precipitation (mm)			
	1984	1985	1986	Average 61-85
Bolmen	805	979	822	846
Långhult	1041	1240	1031	1012
Ljungby	810	906	731	726

6 ROCK STRESS MEASUREMENTS

6.1 Introduction

This chapter presents the results from rock stress measurements conducted within the Bolmen research project. The objectives of the rock stress measurements were:

* To determine the far-field stress conditions in the research area. This included determination of the change of stress state with depth.

* To determine the state of stress close to the tunnel, i.e. within a zone where the stress conditions are affected by the presence of the tunnel.

* To investigate possible stress anomalies associated with the Staverhult line.

The results are applied to study the role of in-situ rock stresses in relation to the hydraulic conductivity of the rock mass and the leakage and stability problems in the tunnel.

The field work was carried out during Spring 1985. A detailed report on the measurements including field data, stress calculations, interpretation and conclusions has been published by BeFo, (Bjarnason et al. 1986).

The stress measurements were made at two test locations which represented different tectonical conditions. Location 1 was in a relatively competent rock about 1.5 km north of the Staverhult research area, (see Figure 6.1). Location 2 was within the Staverhult line. These two different test areas were chosen to investigate possible stress anomalies associated with the Staverhult line.

Two principally different measuring methods, hydraulic fracturing and overcoring, were applied at each test location. The hydraulic fracturing measurements were conducted in vertical, 250 m deep boreholes core-drilled from the ground surface. One borehole was drilled near the stretch of tunnel at each location. It was intended that the measurements obtained by the hydrofracturing method would determine the far-field stress conditions in the areas considered. The overcoring method was used in short boreholes drilled into the tunnel roof. These measurements were conducted to determine the local stress field close to the tunnel.

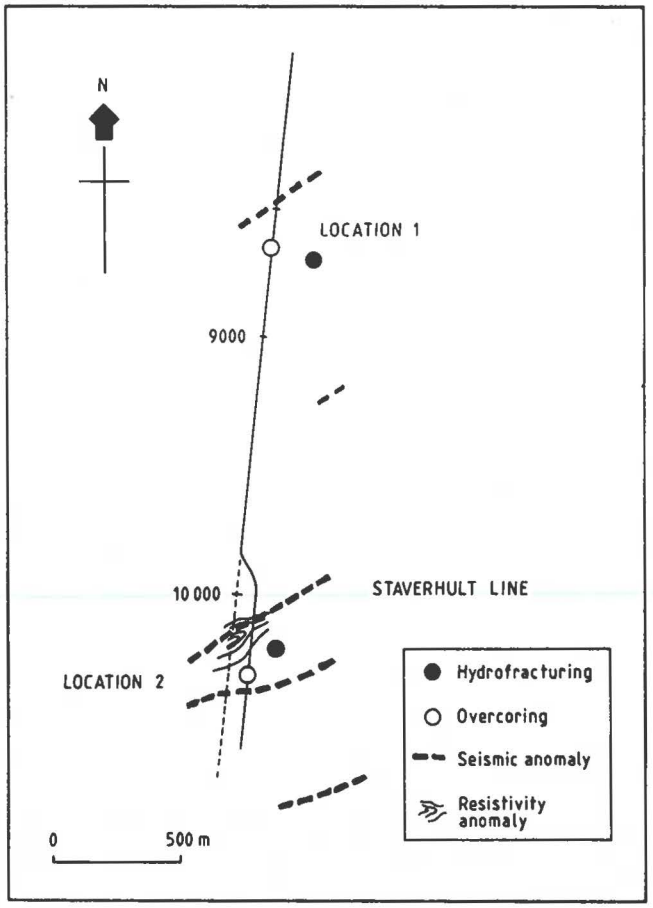


Figure 6.1 Stress measurement locations along the tunnel (Bjarnason et al 1986)

6.2 Methods

6.2.1 Hydraulic fracturing

In its classical application, the hydrofracturing method is two-dimensional, measuring stresses in a plane perpendicular to the borehole axis. It is usually applied in vertical water-filled boreholes drilled from the ground surface. A short section of the borehole, free from natural fractures, is sealed off from the rest of the borehole by means of two inflatable high pressure packers, Figure 6.2. The sealed-off test section is pressurized by water and the pressure line is increased at a steady rate until a fracture is initiated in the borehole wall. The water injection is then stopped and the pressure line to the test section is shut down. The water pressure in the test section falls steeply down to a nearly constant level, called the shut-in pressure. The shut-in pressure is a direct measure of the mechanical stress acting perpendicular to the fracture plane. In an isotropic rock volume, free from natural fractures, the orientation of the induced hydrofracture is controlled by the stress field in the rock. Thus, in a vertical borehole, the fracture will run in a vertical plane, perpendicular to the minimum horizontal stress, σ_h. The maximum horizontal stress, σ_H is calculated analytically from information obtained from the pressure-time curves recorded during the test. When the fracturing process is completed, the orientation of the hydrofracture is recorded by an impression packer and a borehole compass, Figure 6.2. As the fracture forms perpendicular to the minimum horizontal stress, the fracture orientation will give the true orientation of the maximum and minimum stresses in the horizontal plane at the test depth.

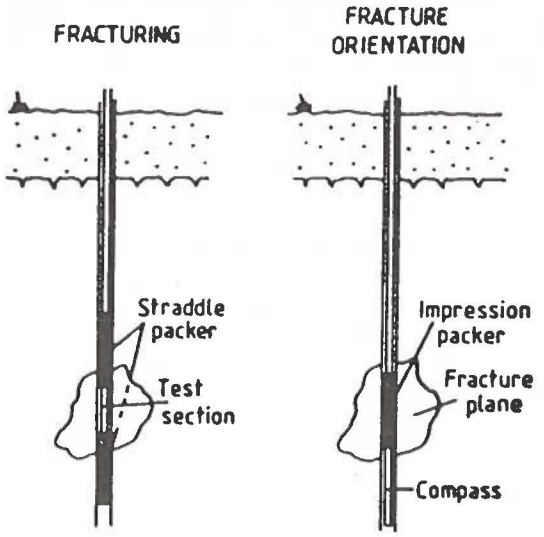


Figure 6.2 Test configuration in the borehole during hydro-fracturing stress measurements (Bjarnason et al 1986)

6.2.2 Overcoring

The overcoring stress measurements were conducted with the LUT-Gauge, which is a modification and further development of the well known Leeman-Gauge. The method is three-dimensional and the complete stress tensor is determined from measurements in a single borehole. The principles utilized by the method are illustrated in Figure 6.3.

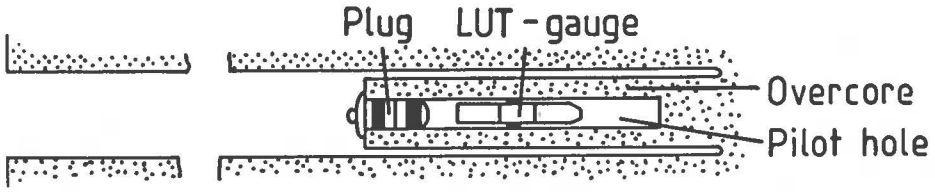


Figure 6.3 The LUT-Gauge installed in the overcored rock volume (Bjarnason & Leijon 1986)

The LUT-gauge serves to carry a set of 12 strain gauges that can be glued to the walls of a small diameter pilot borehole. Strain readings are recorded after installation. The pilot borehole is then overcored with a drill of larger diameter whereby the rock volume containing the pilot borehole is relieved from external stresses. Strain readings are recorded again after overcoring, revealing strains caused by the stress relief. If the elastic parameters of the rock are known, the magnitudes and orientations of the principal stresses can be calculated from the test data.

The overcoring method was applied in two short boreholes drilled from the tunnel. The locations of the boreholes corresponded to the surface boreholes made for hydraulic fracturing. The objectives of the overcoring tests were:

* To determine the secondary stress field in the immediate vicinity of the tunnel

* To determine spatial orientation of the stress field

* To verify the results obtained from the hydrofracturing measurements.

6.3 Field conditions

The two boreholes for hydrofracturing measurements were located according to information from earlier geophysical measurements conducted along the extension of the tunnel (Bäckblom & Stanfors 1985). Both holes were 250 m deep, 56 mm in diameter and core drilled down to bottom. Fracture logs from the drillcore revealed that the rock at location 1 (north of the tectonic zone at Staverhult) was heavily fractured from the surface down to an approximate depth of 60 m. Below 60 m depth the rock was of relatively good quality. The core from the borehole at location 2 (within the tectonic zone at Staverhult) was generally of lower quality than the

core from location 1. Between the depth of 150 m and 160 m the rock was crushed, resulting in core losses and borehole instability. This precluded measurements below 150 m depth in this borehole.

The short boreholes for the overcoring stress measurements showed an unexpected fracture frequency close to the tunnel. This, together with water inflow in the boreholes, rendered the measurements difficult to conduct.

6.4 Results

6.4.1 Location 1 (north of the Staverhult line)

Hydraulic fracturing:

Measurements were carried out at 28 points from a depth of 24.5 m down to 248 m. The results are given in Figure 6.4. The shut-in pressure increases rapidly from surface down to approximately 70 m depth where it reaches a magnitude of 5 to 6 MPa. Between 70 m and 230 m depth the shut-in pressure is nearly constant around 5 MPa. Between 230 m and 250 m the shut-in pressure increases again. The sound lines in the figure show linear regression of measuring points between 0-60 m and 70-250 m respectively.

Due to difficult field conditions (high fracture frequency) between 0-60 m depth, the maximum and minimum horizontal stresses cannot be calculated in the depth interval. Instead, the shut-in pressures recorded should be taken as an estimate of the mean stress level in the rock. Below 70 m the shut-in pressure is assumed to represent the minimum horizontal stress.

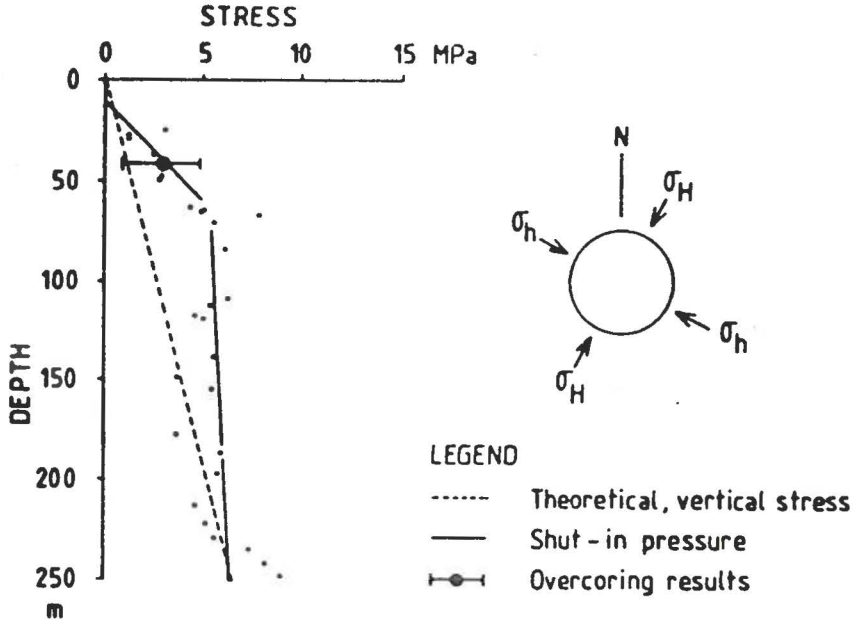


Figure 6.4 Test area north of the Staverhult line. Summary of stress measurement results (Bjarnason & Leijon 1986)

Directions of the maximum and minimum horizontal stresses, as determined from the hydrofracturing measurements, are shown to the right in Figure 6.4. The maximum horizontal stress, σ_H, is oriented NNE-SSV, 30^o from north. The consistency of orientations between test points is very good.

Overcoring:

The hole was drilled nearly vertically up into the tunnel roof. A total of 7 measurements were conducted at depths between 2.6 and 6.1 m. High fracture frequency precluded measurements at shorter hole lengths than 2.6 m. Hence, the results are only representative for the primary stresses in the rock mass and do not show the secondary stress field around the tunnel. Test results are shown in Table 6.1 and in Figure 6.4. The relative scatter of the magnitudes is considerable but the mean value of all three principal stresses should give a good estimate of the stress level at the tunnel depth.

Table 6.1 Results from overcoring stress measurements at the test area north of the Staverhult line.

Test No.	Dist. from tunnel roof (m)	Stresses (MPa)								Angle
		σ_1	σ_2	σ_3	σ_{pa}	σ_{pe}	σ_v	σ_H	σ_h	*
1	2.60	5.5	4.4	2.0	3.0	4.5	4.3	4.8	2.8	112
2	3.15	5.2	3.4	0.5	3.1	3.0	3.1	4.0	2.1	45
3	3.55	6.4	3.5	3.2	3.2	3.7	6.2	3.7	3.2	96
4	4.65	7.5	3.2	2.5	3.3	7.3	2.5	7.5	3.1	81
5	5.05	2.8	0.5	-1.7	-0.8	2.8	-0.3	2.8	-0.8	85
6	5.76	4.2	1.1	0.4	2.0	3.2	0.4	4.2	1.0	56
7	6.10	2.8	0.9	-1.0	0.8	0.2	1.6	1.0	0.1	25
Mean value		4.9	2.4	0.8	2.1	3.5	2.5	4.0	1.6	71
Std.dev.		1.8	1.5	1.8	1.6	2.1	2.2	2.0	1.6	31

σ_1 = Maximum principal stress
σ_2 = Intermediate principal stress
σ_3 = Minimum principal stress
σ_{pa} = Horizontal normal stress parallel to tunnel axis
σ_{pe} = Horizontal normal stress perpendicular to tunnel axis
σ_v = Vertical stress
σ_H = Maximum horizontal stress
σ_h = Minimum horizontal stress
* = Direction of σ_H measured clockwise from north

The scatter is large for the orientations of the principal stresses. However, the results show a tendency for σ_1 and σ_2 to be horizontally oriented, Figure 6.5.

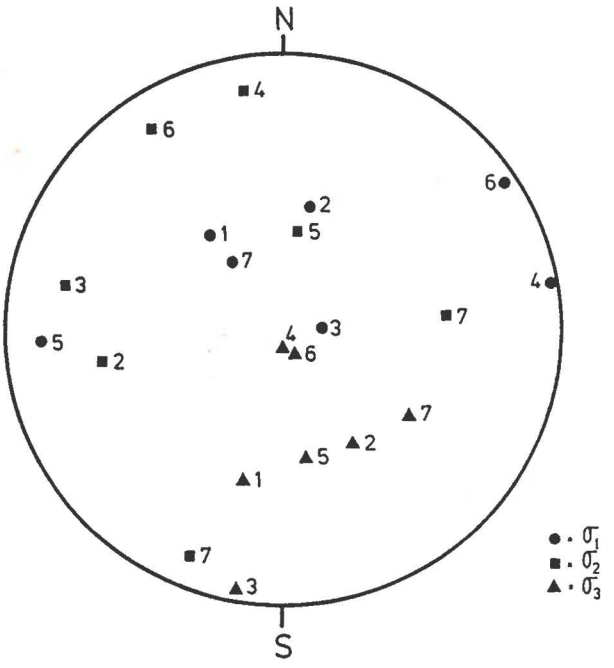


Figure 6.5 Stereographic representation of principal stress directions, Location 1, section 8640. Identification numbers are given for each test (Wulff net, lower hemisphere).

6.4.2 Location 2 (Staverhult line)

Hydraulic fracturing:

Stresses were measured at 16 points between 20 m and 147 m depth. The results are shown in Figure 6.6. The shut-in pressure increases with depth, reaching a value of about 5 MPa between 100 m and 150 m depth but the scatter is large. The regression line for all test points is almost parallel to the theoretical vertical stress. Due to high fracture frequency the shut-in pressure is again assumed to show the average stress level in the rock mass.

The maximum horizontal stress, σ_H is oriented ENE-WSW, about 70^o from north. This orientation coincides with the strike of the Staverhult line as determined from seismic refraction profiles.

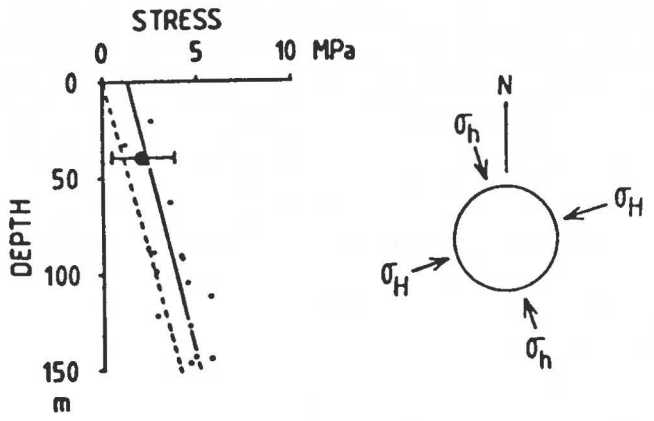


Figure 6.6 Test area within the Staverhult line. Summary of test results (Bjarnason & Leijon 1986)

Overcoring:

Four experimentally valid measurements were carried out between 2.2 and 4.2 m hole length. Also in this case, the results represent the primary stress field in the rock mass. The results are shown in Table 6.2 and in Figure 6.6. Again the stresses are low and the scatter in measured values is large. A stereographic plot of the overcoring results is shown in Figure 6.7.

Table 6.2 Results from overcoring stress measurements at the test area within the Staverhult line.

Test No.	Dist. from tunnel roof (m)	Stresses (MPa)								Angle
		σ_1	σ_2	σ_3	σ_{pa}	σ_{pe}	σ_v	σ_H	σ_h	*
1	2.18	4.4	2.6	0.8	2.8	2.8	2.2	3.2	2.4	45
2	2.71	5.3	2.3	1.2	3.8	3.6	1.4	5.3	2.1	43
3	3.71	2.2	1.7	-0.1	1.8	1.4	0.7	2.2	1.0	144
4	4.20	2.7	1.2	-0.5	1.3	2.6	-0.5	2.7	1.2	77
Mean value		3.7	2.0	0.4	2.4	2.6	1.0	3.4	1.7	77
Std.dev.		1.4	0.6	0.8	1.1	0.9	1.1	1.4	0.7	

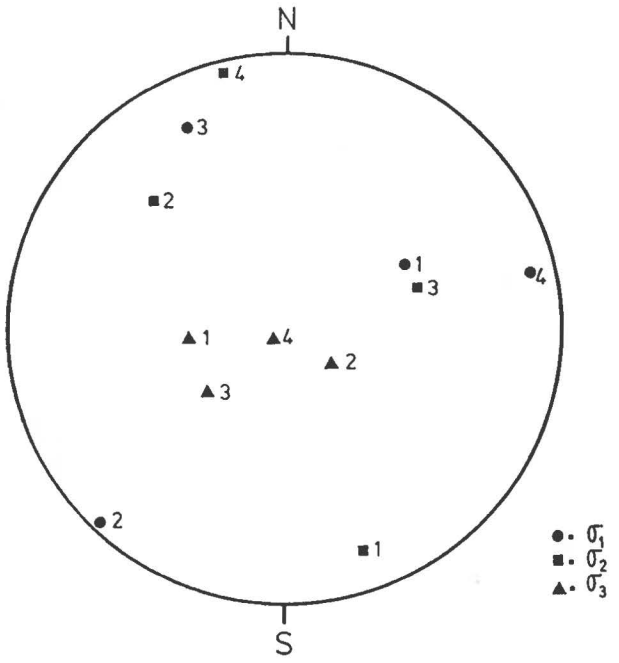


Figure 6.7 Stereographic representation of principal stress directions, Location 2, section 10312. Identification numbers are given for each test (Wulff net, lower hemisphere)

6.5 Discussion

Compared to the bulk of rock stress measurements conducted in Fennoscandian bedrock, (Stephansson et al. 1986), the results from the measurements in Bolmen show low stress magnitudes in the research area. However, similar low rock stresses have been recorded using the hydrofracturing method at Stidsvig, some 60 km south-west of Staverhult.

Experimental uncertainty is attached to both the hydraulic fracturing data and the overcoring data. This is due to the fact that the stress magnitudes in the research area are low, in fact of the same order of magnitude as the accuracy inherent in the measuring techniques. A further reason was technical difficulties due to the relatively fractured rock mass. In the case of hydraulic fracturing, this implied that the magnitude of the maximum horizontal stress could not be determined at shallow depths. In the case of overcoring, these difficult test conditions precluded determination of the

secondary state of stress around the tunnel. Another consequence was that directions of the principal stresses could not be satisfactorily evaluated from the data.

In spite of the uncertainties mentioned above, the two methods agree quite well on the mean stress level in the rock mass measured at the tunnel depth.

6.6 Summary of results

In summary, the results of the stress measurements are as follows:

* A marked stress relief is found within the fractured interval from surface down to 60-70 m depth.

* Stresses at the level of the tunnel (40 m) are below the average of those previously measured in Precambrian terrains and fairly isotropic in the horizontal plane.
* Results from the hydrofracturing and the overcoring methods show good agreement in regard to the mean stresses at tunnel depth.

	Hydraulic fracturing	Overcoring
Location 1	2,8 MPa	2,7 MPa
Location 2	2,3 MP	2,0 MPa

(location 1 = outside the Staverhult line)
(location 2 = Staverhult line)

* The hydrofracturing results show that the orientation of the maximum horizontal stress differs by approximately 40^{o} between the two test locations. Within the Staverhult line the maximum horizontal stress is oriented parallel to the strike of the tectonic zone.

* The magnitude of the maximum horizontal stress in the test area at Staverhult is not well defined, and hence the same applies to the ratio of the maximum to the minimum horizontal stress, σ_H / σ_h. Therefore, statements about the influence from rock stress anisotropy on the hydraulic conductivity of the rock mass must be made with great care.

7. THE HYDRAULIC PROPERTIES OF THE ROCK MASS

7.1 Introduction

The present chapter gives a short account of the results from the research project: The hydraulic properties of the rock mass within the Bolmen research project. The sub-project was planned by the Department of Geology in Gothenburg.

The complete report (Gustafson & Wallman 1988) will be published in the Swedish Rock Engineering Research Foundation (BeFo) publication series.

The report constitutes a subproject to the BeFo 84 project, - Geohydrological investigation methods.

The principal objectives of the subproject were:

* To characterize the hydraulic properties of the rock mass.

* To exploit and assess available modern geohydrological measuring and evaluation techniques.

* To investigate the correlation between rock stress, fractures and hydraulic conductivity.

* To investigate the relationship between water leakage and hydraulic conductivity.

* To predict the inflow of groundwater to the tunnel.

* To supply basic data for the calculation of environmental effects.

* To supply basic data for modelling of the investigation area.

From a hydraulic point of view, the rock mass is usually anisotropic. In order to obtain a correct prognosis, the permeability of entering fractures and their mutual relationship must be known.

The two perhaps most important factors, which affect the groundwater flow in the rock mass are:

* The principal hydraulic drainage directions, i.e. the internal communication of the fissure system.

* The in situ stress situation in the aquifer.

By means of a combination of fracture mapping, geophysical investigations, rock stress measurements and hydrogeological tests, it is possible to obtain a tectonic-hydraulic model. This can then be utilized to establish a prognosis of the leakage into a section of the tunnel. In order to control the accuracy of the predicted prognosis, a systematic recording of water leakage and groundwater level variations was carried out in co-operation with the other projects.

The investigation programme contained the following items (see Figure 7.1):

* Geological and tectonic mapping along a 1,5 km section through the Staverhult area, partly carried out together with the Department of Land Improvement and Drainage, KTH. The purpose was to study the distribution of fractures and water inflow in relation to the hydrogeological situation. The results are to a great extent presented in chapter 8.

* Five percussion drilled holes with a length of approximately 50 meters, down to the tunnel base level.

* Discharge capacity measurements in the five boreholes for the estimation of specific capacity.

* A statistical analysis of discharge capacities from the well archives at SGU, (The Swedish Geological Survey) in order to obtain an approximate value of the specitic capacity on a regional basis.

* Three short term single borehole pumping tests for an estimation of hydraulic conductivity, transmissivity and storage coefficient values and for an assessment of the water balance situation.

* One interference pumping test which enables an evaluation of the hydraulic heterogenity of the aquifer, i e the main direction of the flow. Two methods are used, a distance- drawdown analysis and a graphical solution of the cone of depression (drawdown).

* Injection tests (Lugeon test) in one borehole, to get an idea of the properties of the fractures and their hydraulic conductivity values.

* Prognosis of water leakage by using an analytical method with an image tunnel and an infinitesimally narrow well line source solution.

The investigation was for the greater part concentrated to the Staverhult area (Figure 7.1).

The pumping wells were located in the assumed principal fracture zones, so that their hydraulic properties may be determined and their interdependence elucidated.

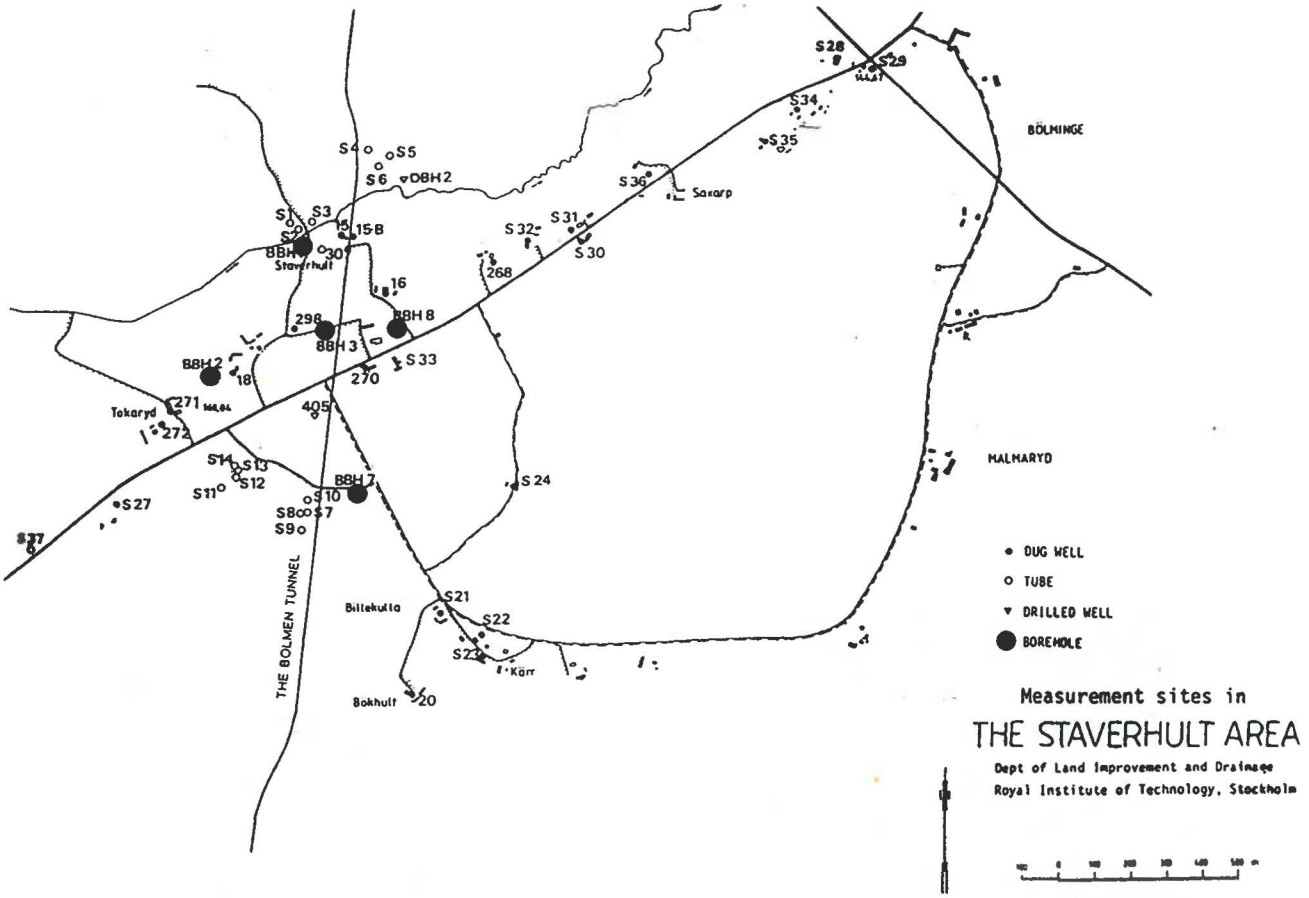


Figure 7.1 Geohydrological test sites in the Staverhult area

7.2 Methods

7.2.1 Geological and tectonic mapping

The first stage of the geohydrological survey was to produce a geological-tectonic model of the area. This was carried out by using the results from the geophysical-geological site investigations, (Bäckblom & Stanfors 1985), and an interpretation with the aid of aerial photographs.

An outline of the conclusions from these points are presented in Figure 7.2. This tectonic model constitutes the main basis for the siting of the five test locations.

7.2.2 Well drilling

One of the fundamental ways of obtaining sufficient geohydrological information about an investigation area is through well drillings. As a rule these drillings should be sited in such a way that they penetrate a representative rock volume and the major fracture zones in the area. The drillings should also be sited in configuration, so that the boreholes interdependence can be determined.

Totally, five percussion boreholes were completed, each with a diameter of 115 mm, and drilled down to the tunnel base level. The location, dip and direction of each borehole was specified by utilizing data from the tectonic model, (Figure 7.2).

During the percussion drilling, the drilling rate (sec/20 cm), rock colour, fractures and water yield were noted, and after completion of drilling operations, discharge capacity measurements were carried out. The positions of the boreholes were surveyed and levelled and regular groundwater level measurements commenced.

The following is a short description of data from each borehole. An example of the drilling information obtained from the borehole contractor is shown in Figure 7.6.

BBH 1: Depth 47 m Casing 3 m
Highly fractured with distinct zones encountered at several levels down to 45 m. Water was found at about 17 m and 26 m. The well capacity is estimated to approximately 240 l/h.

BBH 2: Depth 50 m Casing 12 m
Medium fractured with distinct fracture zones between 15 m and 27 m. No water was found in this borehole.

BBH 3: Depth 52 m Casing 9 m
Medium to low fractured with six distinct zones between 10 and 22 m. Water was encountered at 35 m together with a minor fracture. The total capacity is estimated to about 500 l/h.

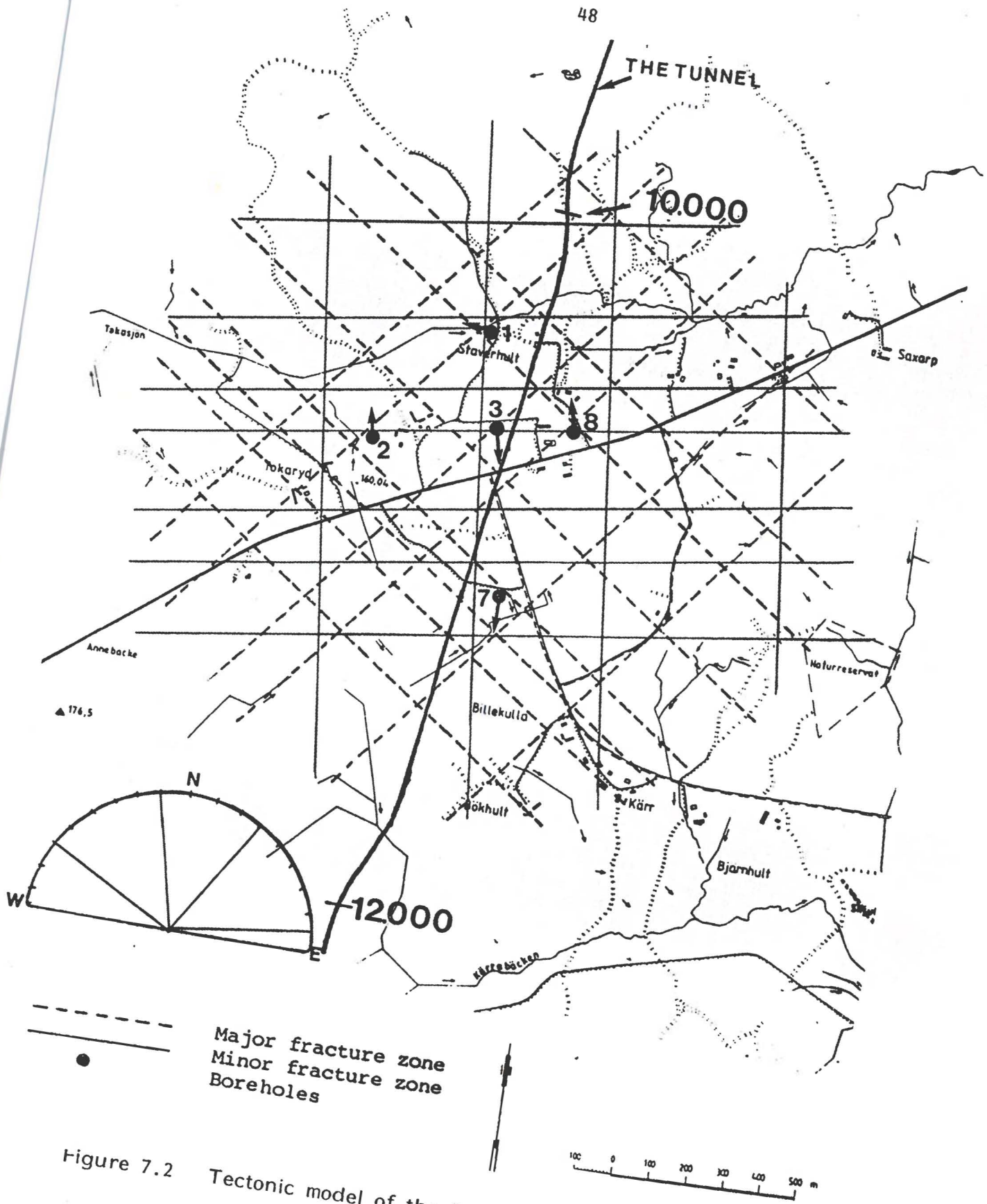


Figure 7.2 Tectonic model of the Staverhult area

BBH 7: Depth 52 m Casing 9 m
Medium to low fractured with some distinct zones just below the rock surface at 9 m to 20 m. A minor water leakage was noted at 10 m. The capacity is about 50 l/h.

BBH 8: Depth 50 m Casing 12 m
Highly fractured with distinct zones at several levels down to about 40 m. Water was found after about 27 m of drilling together with a major fracture. The total capacity is estimated to appoximately 250 l/h.

Generally the drillings show a medium to highly fractured rock with a drilling rate constantly faster than 50 sec/20 cm. From the obtained data there is no obvious concentration of fractures at specific levels in the boreholes. A comparison between the estimated well capacities indicates that the fracture characteristic is of greater importance than fracture intensity for bedrock permeability, i.e. a high fracture frequency does not necessarily indicate high permeability.

7.2.3 Elementary recovery test and specific capacity

The elementary recovery test is one way to estimate the permeability in the rock mass. This method constitutes a complement to the test pumping methods and gives a fairly good idea of the hydraulic conductivity span in an investigation area.

The borehole is emptied using air-lift pumping and then the rate of water level rise is recorded. The obtained recovery curve plot corresponds to the total hydraulic conductivity of the entire sequence of fractures intersecting the well. An evaluation of the curve gives a value for the transmissivity (T) according to the definition:

$$T = \int_b K(z)dz$$

K = hydraulic conductivity, (m/s)
b = thickness of the aquifer, (m) i.e. the borehole depth

The evaluation procedure is the one described by Ramey (1975), using a curve matching technique. An example is shown in Figure 7.3.

The discharge capacity (Q) obtained from the emptying of the borehole, the borehole depth (d_w) and the static groundwater level (d_o) constitute the basis for deriving the specific capacity from

$$Q/s_w = \frac{Q}{(d_w - d_o)} \quad \text{where } s_w = \text{drawdown}$$

The specific capacity is a function of transmissivity as well as permeability and can be used for a approximate calculation of transmissivity.

If the skin effects (clogging of the well faces) are neglected, a generalized value for the transmissivity is $T \approx 1.4 \cdot (Q/s_w)$; (Gustafson & Åberg 1985).

The results from the five boreholes are presented in Table 7.1.

Table 7.1 Results of recovery tests at the five test locations

	Transmissivity (T) (m^2/s)	Specific capacity (Q/s_w) (m^2/s)
BBH1	$27 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
BBH2	-	$0.017 \cdot 10^{-6}$
BBH3	$30 \cdot 10^{-6}$	$3 \cdot 10^{-6}$
BBH7	$27 \cdot 10^{-6}$	$0.33 \cdot 10^{-6}$
BBH8	$27 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$

An evaluation of the transmissivity in borehole BBH2 is not possible with the curve matching method because the quantity of water is too small. The borehole is regarded as dry and is excluded from further discussion.

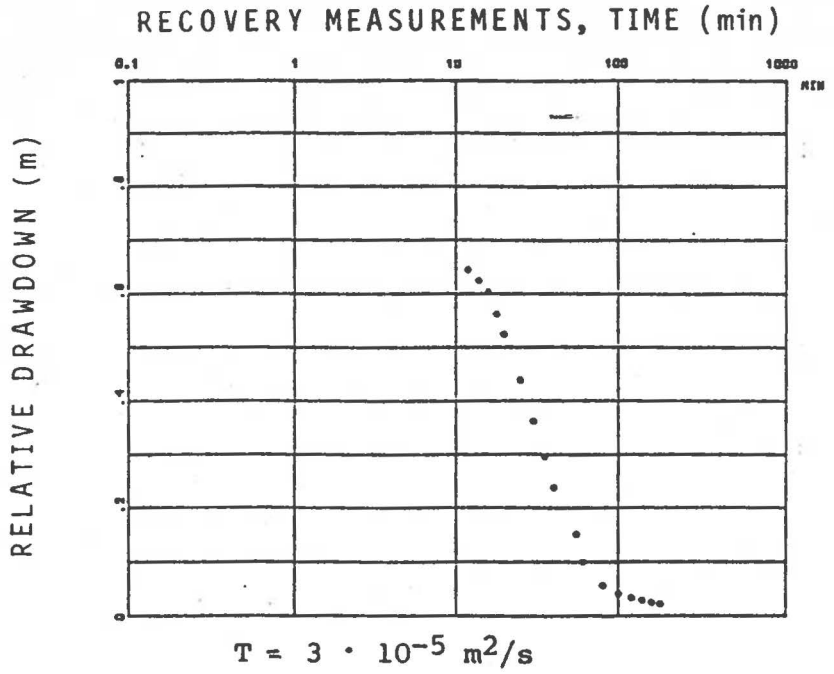


Figure 7.3 Evaluation of transmissivity by curve matching. Borehole BBH3, Staverhult.

7.2.4 Specific capacity from SGU Well archives

From the well archives of SGU (The Geological Survey of Sweden), the following values have been used in a regional analysis of the specific capacity in the investigation area.

Discharge capacity: 1 080 l/h ($0.3 \cdot 10^{-3}$ m^3/s)
Borehole depth: 56 m
Soil depth: 5 m

The values are median values and are based on 1 073 wells in the county of Kronoberg. A calculation of the specitic capacity (see 7.2.3) gives:

$$\frac{Q}{s_w} = \frac{0,3 \cdot 10^{-3}}{51} = 5.9 \cdot 10^{-6} \ m^2/s$$

The drawdown, s_w, is assumed to be equal to the borehole length minus the soil depth, i.e. normally the casing length.

The advantage of using the archives data is the large amount of values which can be statistically treated while not being dependant on the accuracy of the single well estimated value. The obtained data are consequently well suited for prognosis calculations on a regional basis.

7.2.5 Single borehole tests

For this project three single hole test pumpings have been carried out, BBH1, 3 and 8 (see Figure 7.1).

Specific wells were selected on the basis of estimated well capacities having the highest values. The reason for this is partly because pumping is always easier if the well has reserve capacity, and also a higher rate of abstraction causes a larger drawdown, so that the largest possible area is affected by the pumping.

The pumping procedure includes approximately 12 hours of pumping and 12 hours of recovery measurements. During this time, pressure in the borehole is measured with a pressure sensor and is recorded automatically on magnetic tape. The pumping capacity is kept constant during the pumping phase. The recovery measurements are used to check the drawdown data and can be evaluated and compared according to chapter 7.2.3.

The single hole pumping test provides data for the calculation of transmissivity (T), storage coefficient (S), skin factor (ζ) and the effective radius of the well (r_{wf}). The results from these tests, together with data from other wells and observation holes, can also provide data for a regional analysis of the transmissivity and hydraulic conductivity and its distribution in the rock mass. The evaluation procedure is described in Gustafson (1986).

The results from the three single borehole tests are presented in Table 7.2.

Table 7.2 Results from three single hole pumping tests

	Transmissivity T (m^2/s)	Storage coefficient (nondimen.)	Skin factor ζ (nondimen.)	Effective radius, r_{wf} (m)
BBH1	$4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	+ 9	$7 \cdot 10^{-6}$
BBH3	$1.4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	- 4	3.1
BBH8	$1.4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	+ 6	$1.4 \cdot 10^{-4}$

The obtained T-values from the single hole pumping tests are rather high and indicate higher permeabilities than "normal" in crystalline rocks. The values are also very similar in magnitude, $1.4 - 4.0 \cdot 10^{-5}$ m^2/s, and correspond extremely well to the values obtained from the elementary recovery tests, $2.7 - 3.0 \cdot 10^{-5}$ m^2/s. The homogeneity and high magnitude character of the achieved values make it reasonable to suggest a probable impact from the soil aquifer.

7.2.6 Interference long term pumping test

The interference pumping test involves recording levels in surrounding boreholes and in the test well itself.

The measurements obtained often give valuable and useful information about the rock mass aquifer. Firstly, information about the test hole can be evaluated using the above described methods. Secondly, information about hydraulic properties of the observation holes and their interdependence are obtained.

The long term pumping test allows the hydraulic heterogenity of the aquifer to be evaluated. Two methods have been applied, a distance-drawdown analysis and a graphical solution of the cone of depression (drawdown).

The interference test was carried out in borehole BBH3, because of its high capacity and strategic location in the area. A high capacity of the test well is specially important so that the largest possible area is affected by the pumping. The pumping test started 1984-06-27 and continued to 1984-08-09. The pumping capacity was approximately 0.15 l/s up to 1984-07-31 when it was increased to approximately 0.28 l/s, in order to provide a greater drawdown.

The drawdown in the observation holes was between 0 and 0.90 m and shows a rather low reaction. BBH2 did not react at all. For another borehole, BBH7, the drawdown can be a result of the natural groundwater fluctuation. The generally low reaction could be expressed by the soil aquifer influence.

The distance-drawdown analysis is carried out in order to achieve a control of the transmissivity. The evaluation procedure is described in Cooper & Jacob (1946).

The evaluation gives $T = 1.4 \cdot 10^{-5}$ m^2/s, ($Q = 0.15$ l/s) and is in very good agreement with the other analysis. The drawdown in the observation holes is more or less of the same magnitude, which indicates an isotropic groundwater aquifer.

It must be pointed out that the reaction to the pumping in borehole BBH3 is surprisingly low. As has been stressed before, this could be a result of the soil aquifer influence and the result should be treated carefully.

The other method applied to show isotropic or anisotropic properties of a rock aquifer is to analyze the cone of depression (drawdown). In a homogeneous, isotropic rock aquifer, a circular cone of depression will have developed by the end of a long term pumping test. On the other hand, the cone will be ellipse-shaped in a anisotropic medium, i.e. the cone will be extended along the main direction of the flow, (the direction of highest hydraulic conductivity).

The cone of depression is graphically constructed using logarithmic interpolation according to Figure 7.4. The method is described in Gustafson (1986).

A semilogarithmic diagram with the drawdown as a function of the distance to the well, is a useful tool in determining the interpolation lines graphically. One interpretation is presented in Figure 7.5.

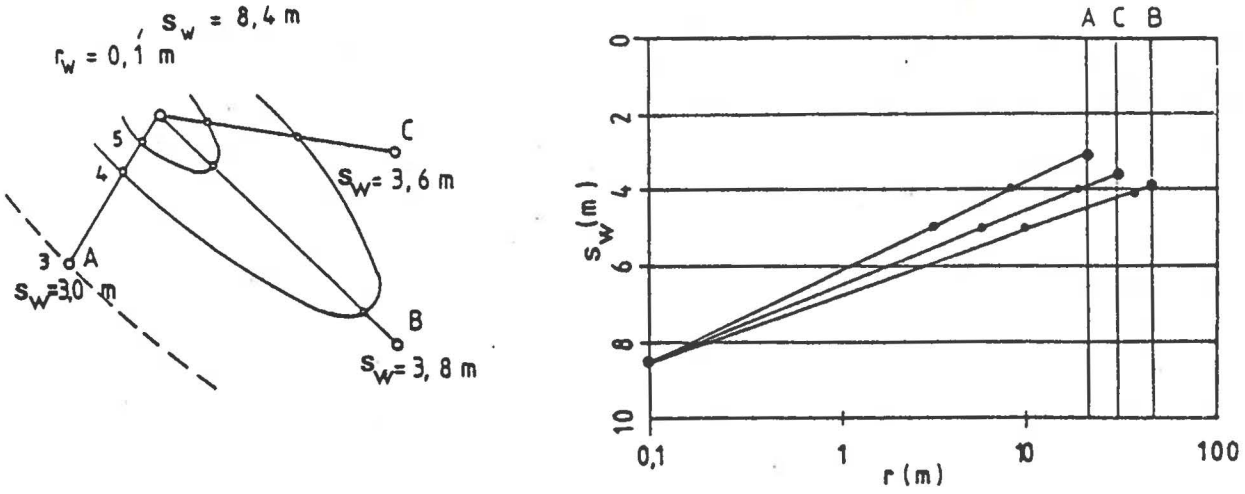


Figure 7.4 Logarithmic interpolation of a cone of depression (principal sketch)

It is remarkable that the depression cone caused by the long-term pumping test is not as irregular as would be expected in crystalline rocks. One explanation for this can be that the soil aquifer has an important impact on the conducted hydraulic tests. However, this fact may also be a result of the borehole configuration as well as only three of the five boreholes reacting significantly.

An important observation that could help to explain the unexpected results is the low stress values from the rock stress measurements. The horizontal stress field is fairly isotropic within the depth interval for the hydraulic tests and the orientation of the maximum horizontal stress is uncertain.

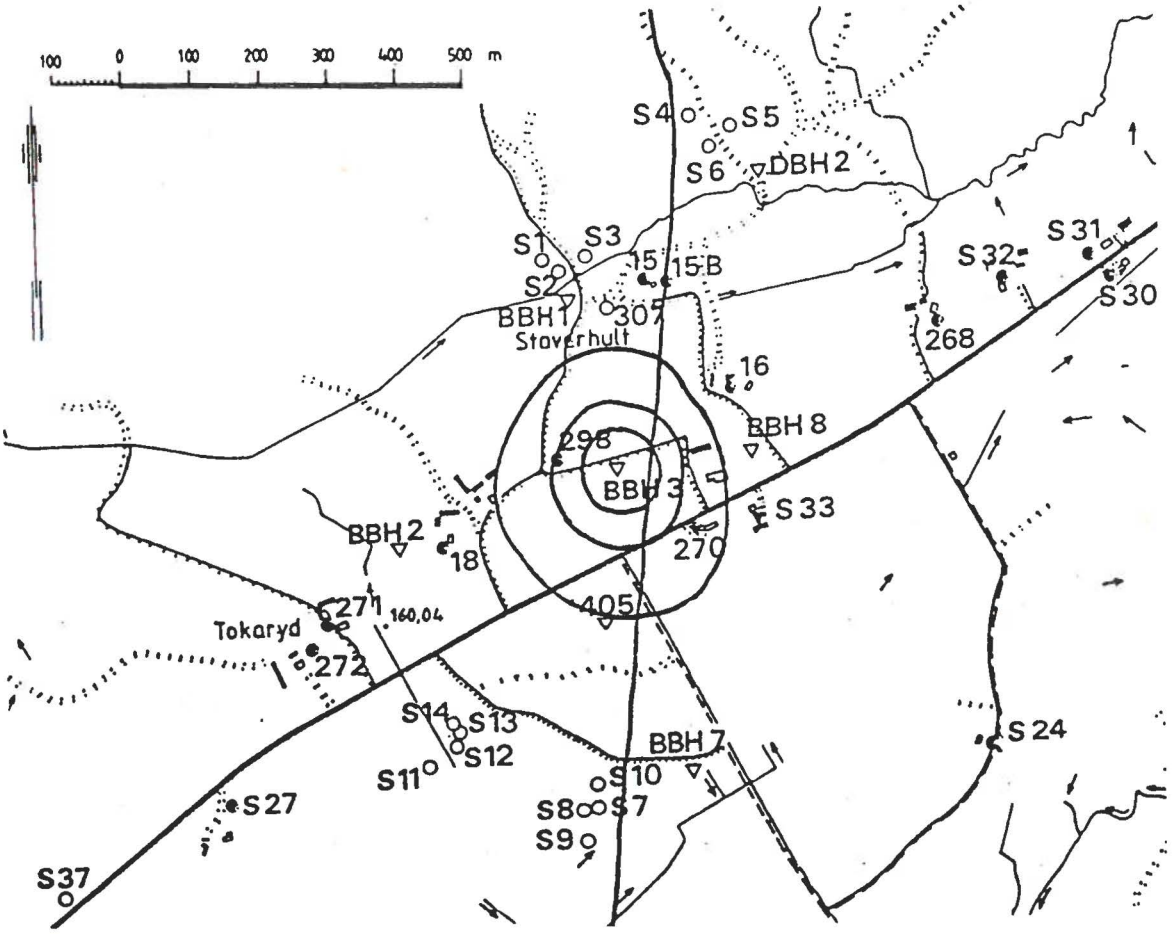


Figure 7.5 One possible interpretation of the appearance of the cone of depression at borehole BBH3

7.2.7 Injection test

Water loss measurements were used as a method for the localization of permeable zones penetrated by the borehole. The water injection test (Lugeon test) was carried out using a double packer equipment with a two meter test section. The injection pressure was approximately 10 bars. The water loss and pressure were continuously measured in each section during the test.

The results obtained from these measurements were used to calculate the gross hydraulic conductivity (K_g) in each section. The evaluation procedure is described by Gustafson (1986).

Two tests (in BBH1 and BBH3) were planned within the project. These boreholes were selected according to the drilling information. Owing to technical problems with the equipment, only one injection test (BBH3) was fulfilled.

The groundwater level in borehole BBH3 was approximately 18.80 m below the surface when the test started. The first test section was consequently 19-21 m and the borehole was then continuously tested in 2 m sections down to 51 meters. Due to experimental difficulties, seven K_g-values are missing in the results presented in Table 7.3.

Table 7.3 Results from the injection tests in borehole BBH3.

Section (m)	Q (m^3/s) ($\cdot 10^{-6}$)	K_g (m/s) ($\cdot 10^{-9}$)	K^* (m/s) ($\cdot 10^{-9}$)
19-21	-0.7	-	4.0
21-23	0.5	1.4	
23-25	33.8	94.5	
25-27	-	-	4.0
27-29	-	-	4.4
29-31	12.1	33.8	
31-33	1.25	3.5	
33-35	-0.75	-	7.0
35-37	-1.2	-	4.6
37-39	1.92	5.4	
39-41	2.83	7.9	
41-43	7.67	21.4	
43-45	-1.0	-	36.0
45-47	7.67	21.4	
47-49	2.67	7.5	
49-51	-0.08	-	14.0

* = estimated from cross-plot using recovery data

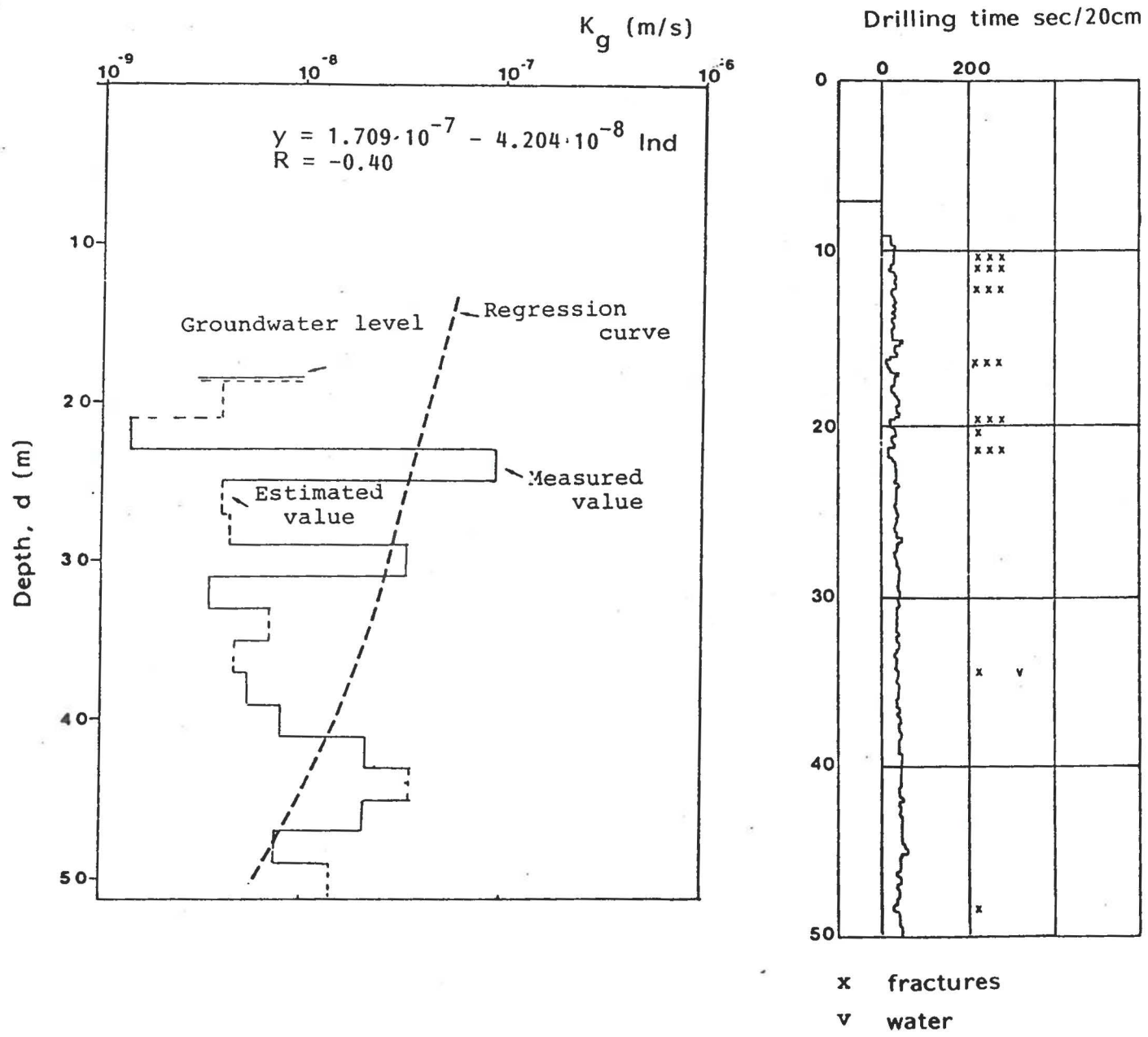


Figure 7.6 Results from the injection tests and the drilling information in borehole BBH3.

In order to achieve an estimation of the magnitude of the missing K_g-values, a cross-plotting was carried out using the recovery data from the injection test. The result from the injection test is presented in Figure 7.6 together with a regression curve, i.e. the best fitting regression of hydraulic conductivity towards depth. For a comparison, the result from the drilling is shown in Figure 7.6.

The calculation from the regression curve gives Kg = $1.71 \cdot 10^{-7}$ - $4.2 \cdot 10^{-8}$ Ind.

$K_{gm} = 2.7 \cdot 10^{-8}$ m/s (mean value)
$T = 1.2 \cdot 10^{-6}$ m^2/s

7.2.8 Summary of results from the hydraulic tests

The results from the hydraulic tests are presented in Table 7.4. The geometric mean value from the four boreholes is also calculated for each of the different methods. The advantage of using the geometric mean value for estimating the gross hydraulic conductivity has been shown by Dagan (1979,1981).

The different hydraulic tests used in the project and described above are valuable for the estimation of different parameters and together they constitute the basis for hydrogeological prognosis.

7.4 Leakage predictions

The porous homogeneous media that most test-formulae are developed for is rather different from a fractured crystalline rock. However, processing of data from hydraulic tests in fractured aquifers shows that it is possible to some extent to apply the principles of flow in a porous continuum if the studied rock volume is large enough (Carlsson & Carlstedt 1976, Carlsson & Gustafson 1984, Blomquist et al 1985). For the analysis of the hydraulic properties, the flow is treated analytically. It is often more important to critically examine the evaluated parameters from the hydraulic tests than use a complicated mathematical model for the prognosis.

Table 7.4 Hydraulic tests in wells at Staverhult

Bore hole	Bore hole length (m) casing = ( )	Elementary recovery test $T\ (m^2/s)$	Specific capacity $Q/sw\ (m^2/s)$	Pumping test (short term) $T\ (m^2/s)$	S	$K\ (m/s)$	ξ	$r_{wf}\ (m)$	Injection test $T\ (m^2/s)$	Long term pumping test $T\ (m^2/s)$
BBH1	47 (3)	$2.7 \cdot 10^{-5}$	$4 \cdot 10^{-6}$	$4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	$2.1\ 10^{-7}$	9	$7 \cdot 10^{-6}$	-	
BBH3	52 (9)	$3 \cdot 10^{-5}$	$3 \cdot 10^{-6}$	$1.4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	-	-4	3.1	$1.2 \cdot 10^{-6}$	$1.4 \cdot 10^{-5}$
BBH7	52 (9)	$2.7 \cdot 10^{-5}$	$3.3 \cdot 10^{-7}$	-	-	-	-	-	-	-
BBH8	50 (12)	$2.7 \cdot 10^{-5}$	$1.5 \cdot 10^{-6}$	$1.4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	$1.2\ 10^{-7}$	6	$1.4 \cdot 10^{-4}$	-	-
Geom. mean value		$2.8\ 10^{-5}$	$1.6\ 10^{-6}$	$2\ 10^{-5}$						

Prognosis of water leakage (q) has been calculated using an analytical method with an image tunnel and an infinitesimally narrow well line source solution. The methods are described in Gustafson (1986).

The obtained results give values for the leakage to the tunnel per length unit (km) and do not indicate specific water leaking zones. The leakage predictions are valid for a non-grouted situation.

The infinitesimally narrow well line source solution

By using the geometric mean value of specific capacity from Table 7.4 (elementary recovery test) we can calculate the leakage to:

$q = 1.1$ l/s·km

For a more reliable estimation of the leakage, we can use the specific capacity values from the SGU Well archives. The advantage of using this regional parameter has been stressed before. From Chapter 7.2.4 we have:
$Q/S_w = 5.9 \cdot 10^{-6}$ m^2/s.

According to Gustafson (1986) this gives:
$q = 4.2$ l/s·km

The image well method

An often used procedure for groundwater prognosis is the image well method. The principle aim is to fultill the boundary conditions for the hydraulic system. One of these boundary conditions in the case with a tunnel construction is the groundwater level. The drawdown of groundwater level at surface is assumed to be small. The boundary conditions are fultilled using an image tunnel at the same distance above the groundwater level, where the identical amount of water is supplied as has been abstracted from the tunnel.

From the injection test (Chapter 7.2.7) we have:
$K_{gm} = 2.7 \cdot 10^{-8}$ m/s
A calculation using the image well method (Gustafson 1986) gives:
$q = 2.2$ l/s·km.

Using the mean hydraulic conductivity value estimated from the short term test pumping at BBH1 and BBH8, $K_g = 1.6 \cdot 10^{-7}$ m/s, the leakage can be calculated to:
q = 12.8 l/s km.
This value is probably too high because of the influence of the soil aquifer on the test pumpings.

The two different methods give a range between 1.1 - 12.8 l/s km and a comparison with the recordings of water leakage to the tunnel shows a fairly good accordance. From the measuring of water flow at the access station 3 km north of the Staverhult area, the leakage can be estimated to 6-6.5 l/s km. The measuring in a pump pit within the Staverhult area gives 6-9 l/s km during the investigation period.

7.5 Conclusions

The results from the hydraulic tests in the Staverhult area show that it is possible to some extent to predict the water leakage to an underground construction.

A direct comparison between the predicted prognosis and the recordings of the leakage into the tunnel is not possible as the tunnel is partly pregrouted. However, the obtained results give a regional value for the water leakage to the tunnel per length unit and do not reveal the specific water leaking zones.

The results from the investigations also show that the influence from the soil aquifers and the specific rock mechanical conditions in the area, must be taken into consideration during evaluation of the hydraulic tests.

8. WATER LEAKAGE AND GROUNDWATER CHEMISTRY IN RELATION TO DIFFERENT GEOLOGICAL AND HYDROLOGICAL SITUATIONS

8.1 Objectives

The overall objectives for the research project carried out by the Royal Institute of Technology, Stockholm were:

- To identify and quantify possible changes in the surface water and the groundwater conditions (environmental effects) caused by construction of the Bolmen tunnel.

- To relate the changes to the prevailing hydrological, geological and hydrogeological conditions in the tunnel and its surroundings, especially the consequences for different types of peatlands and coarse sand aquifers in contact with the bedrock.

- To compare the results with observations from other underground constructions in order to find out the environmental effects of tunnelling from a general point of view.

The research project is subdivided into two parts; a study of the environmental effects along the whole 80 km extension of the Bolmen tunnel and a detailed study in the Staverhult area, where the tunnel intersects a tectonic zone (the Staverhult line).

The present summary includes only the results from the field investigations that were carried out in the Staverhult area 1984-1986. The tunnel influence on the groundwater condition along the whole Bolmen tunnel will be presented in a separate report. For more detailed information and results from the investigations in the Staverhult area, the reader is referred to Olofsson (1988).

8.2 Methods of investigation

The investigation, data collection and experimental field work that was carried out within this project in the Staverhult area were as follows:

1. Inventory of existing wells in the Staverhult area and its surroundings.

2. Collection and processing of precipitation data from SMHI.

3. Drilling and tube-pressing at 5 sites in the Staverhult area in April 1984. 15 tubes, divided into four groups and one reference tube were pressed down to different levels in peat, till and superficial bedrock, se Chapter 4.4.

4. Studies of soil types and soil profiles including soil sampling and analyzing of grain size distribution.

5. Compilation of a base map (1:10 000) covering the Staverhult area.

6. Compilation of a Quaternary geology map (1:10 000) in the Staverhult area. The map was based on identification of soil-types on infra-red air photos controlled by field observations.

7. Manual measurement of groundwater levels on a weekly basis in 48 dug wells, drilled wells, boreholes and tubes in the Staverhult area during 1984. The number of measuring points was reduced to 31 in 1985 and 1986.

8. Automatically recorded measurements of groundwater levels at 3 points in 1984.

9. Geological and tectonical studies in the Bolmen tunnel.

10. Study of water flow in fractures using tracers. Two tracer experiments were conducted, using a metal complex (Cr-EDTA) and bromide ions (Br^-).

11. Geophysical logging in 5, 50 m deep boreholes. Temperature, borehole diameter, electric conductivity and self-potential (SP) were recorded.

12. Pumping and recovery tests in 6 tubes and 2 dug wells in the Staverhult area.

13. Water sampling in tubes and boreholes. Water chemistry was analyzed regularly from 5 boreholes and 8 tubes in the Staverhult area.

14. Water sampling and water chemistry analyzing of leakage water from the Bolmen tunnel.

15. Measurements of radon content in groundwater from the Bolmen tunnel.

8.3 Groundwater level fluctuations 1984-1986

8.3.1 Type of aquiters

Groundwater in the Staverhult area occurs both in pore aquifers in the overburden and in fracture aquifers in the bedrock. The pore aquifers are characterized mainly by storage and circulation of water in pores in till and in the well graded sandy sediments. In the fracture aquifers, the storage and water circulation are restricted to fractures, whereas no primary pososity exists.

Groundwater level observations have been carried out both in boreholes in the rock mass and in tubes and dug wells in the overburden.

8.3.2 Sites of measurement

Groundwater levels have been measured at 48 sites at Staverhult, at a distance of up to 1.5 km from the tunnel line. Among the measured sites are 24 dug wells, 16 tubes, 7 boreholes and 1 drilled well. The groundwater level has been measured on a monthly basis or at least quarterly since 1971 in 12 points (10 dug wells, 1 tube and 1 borehole). These measurements were included in a defined control programme around the Bolmen tunnel. Most of the 24 dug wells are lined with cement rings but 6 of them are stone lined. Their depth varies between 2.5 and 7 m.

15 plastic tubes (Ø = 4 cm) were pressed down into peat soils and inserted in drilled holes in till and superficial bedrock using a small drilling machine.

The tubes were placed in four groups in or near fracture zones in the Staverhult area, where influence on the groundwater level by the tunnel could be expected. All groups consisted of tubes representing different levels in peat, till and hard rock enabling the study of groundwater level fluctuations at different depths and in different aquifers. A reference tube in till was also placed outside the Staverhult area. Measurements have also been carried out in five 50 m deep inclined boreholes (Ø = 11.5 cm) and one 250 m deep core drilled hole (Ø = 5.6 cm), that were drilled within the scope of the other research projects in the same area. Finally, there is also one old drilled well, 20 m deep and one borehole, 13 m deep. The sites of measurement are presented in Table 4.1 and their geographical position can be seen in Figure 4.1 (Chapter 4).

8.3.3 Groundwater fluctuations in boreholes

One of the eight boreholes (S33) shows no distinct change in groundwater level caused by the tunnelling. A slight lowering of the groundwater level in BBH2 and in BBH7 in 1986 compared to 1984 might indicate tunnel influence. The greatest lowering of the groundwater level has been measured in borehole BBH3, a 50 m

deep borehole situated approximately 50 m from the tunnel route. The water level started to sink in September 1984, when the tunnel face was about 200 m from the borehole and the drainage continued until Januari 1985. The sinking rate in October 1984 was as high as 34 cm per day and the maximum lowering of the groundwater level has been about 15 m.

Two other boreholes, BBH1 and BBH8, reacted similarly to the tunnelling and the groundwater levels started to sink in August 1984, when the tunnel face was approximately 200-230 m from each borehole. The maximum drawdown in BBH1 and BBH8 has been between 5 and 7 m.

Finally, borehole no 405, which has been regularly monitored since 1971 indicates a clear but rather small lowering to the groundwater level, approximately 1.3 m.

Groundwater level measurements on a weekly basis in two of the boreholes during the research period are presented in Figure 8.1.

A comparison using a simple linear interpolation between the reactions of the five, 50 m deep, boreholes when the tunnel was excavated through the Staverhult area is presented in Figure 8.2. The groundwater pressure levels in the rock aquifer under natural conditions appear to be a function of topography in the Staverhult area. Hence BBH3, situated at the summit of the hill had originally the highest groundwater level and the difference of about 7 m to the lowest level in borehole BBH1 before tunnelling through the area began. When the northern tunnel face approached the central zone in the research area, first BBH1 and later BBH3 started to sink. No such dramatic influence could be seen at the southern tunnel face, although the tunnel was very close to BBH7.

The groundwater level in BBH3 continued to sink during the winter 1984/85, even though the northern face had passed by and a distinct cone of depression was developed in BBH3 in relation to the other boreholes.

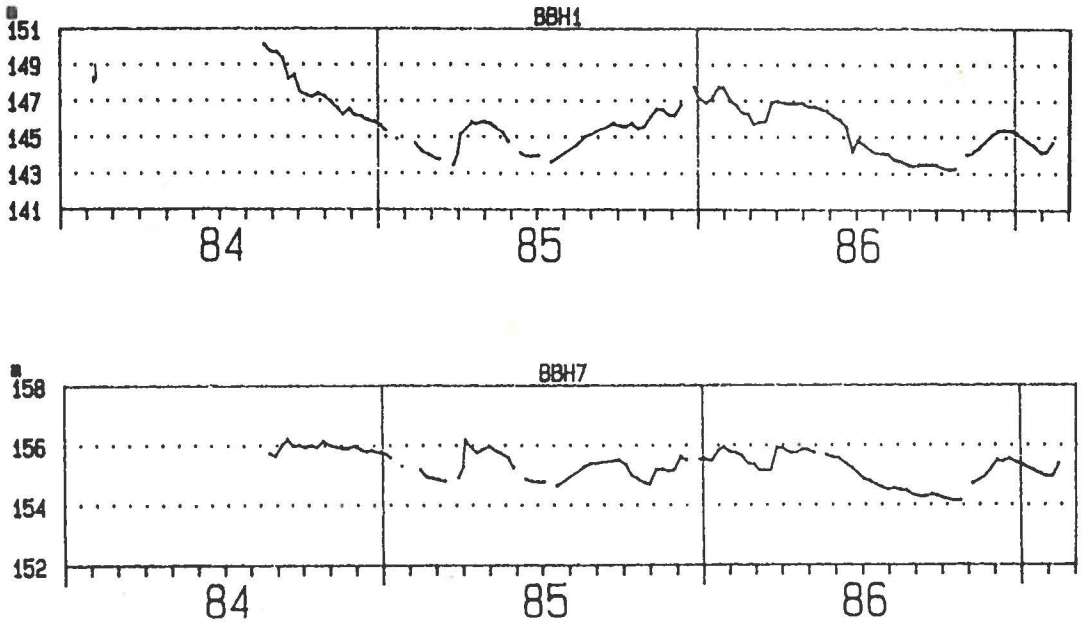


Figure 8.1 Groundwater levels measured on a weekly basis in two boreholes from August 1984 to Februari 1987

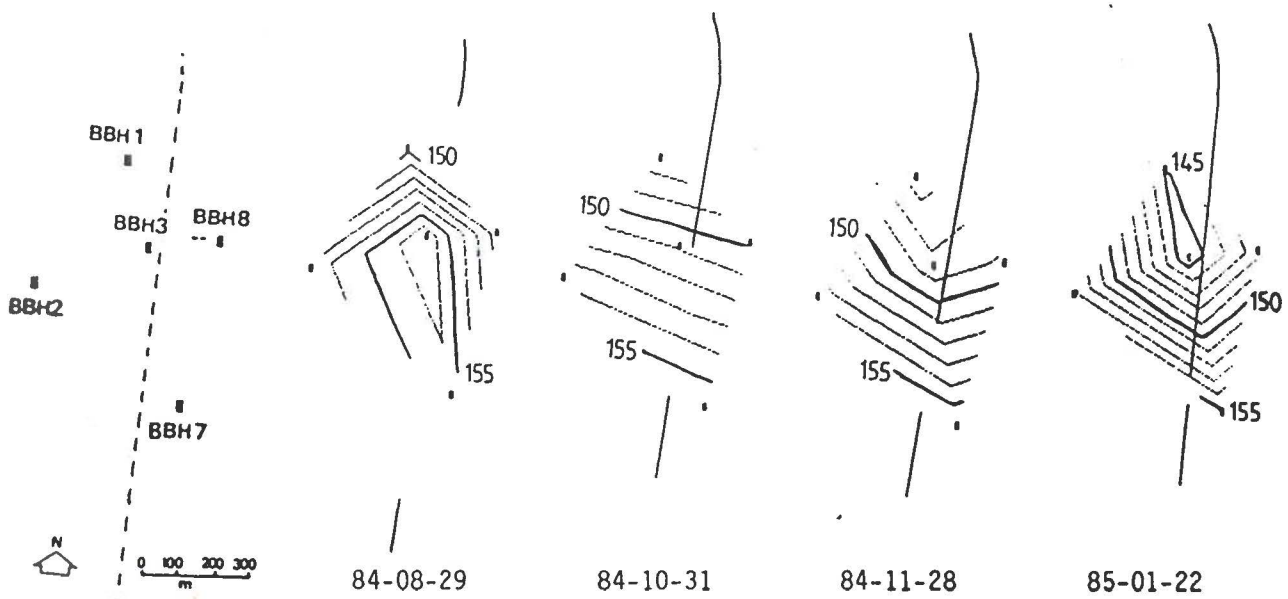


Figure 8.2 Groundwater pressure changes in five boreholes 1984-1985. Equidistance 1 m. The tunnel route is presented in the figures.

8.3.3 Fluctuations in dug wells and tubes

The Bolmen tunnel influence on the overburden in the Staverhult area is not as distinct as for the bedrock except at a very few sites of measurements. Groundwater level lowering of more than 1 m is obvious only in 3 of 40 sites; the dug wells no 15, 15B and the tube 307. All these sites are situated in the northern part of the area.

A study of the groundwater level fluctuations in the soil aquifer and its dependence on the tunnelling through the area is presented in figure 8.4. Since the fluctuations in the soil aquifer usually are less than 1 m, a detailed study of the northern part of the area is presented in figure 8.5.

A clear similarity between the groundwater fluctuations in the bedrock and the overburden can be seen in both the northern and southern part of the area (Figure 8.3). No such connection can be seen in the central part, which is made up of a till-covered hill, where the dug well no 298 and the borehole BBH3 reacted remarkably differently. The groundwater fluctuations between different kind of tubes, wells and boreholes were compared using a linear regression method in order to distinguish between different soil and rock aquifers in the area.

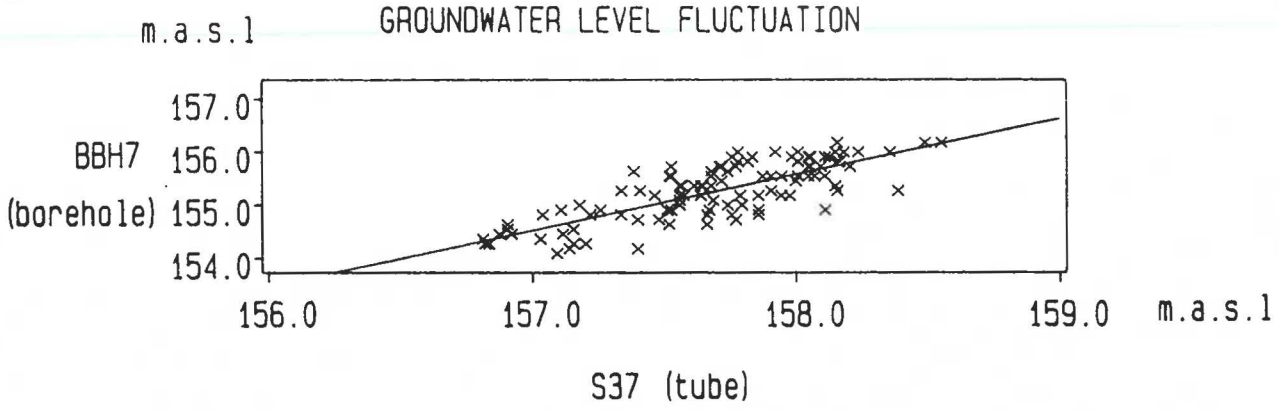


Figure 8.3 Linear regression analysis between groundwater level measurements in a borehole (BBH7) in the Southern part of Staverhult and a tube in till (S37) located outside the area.

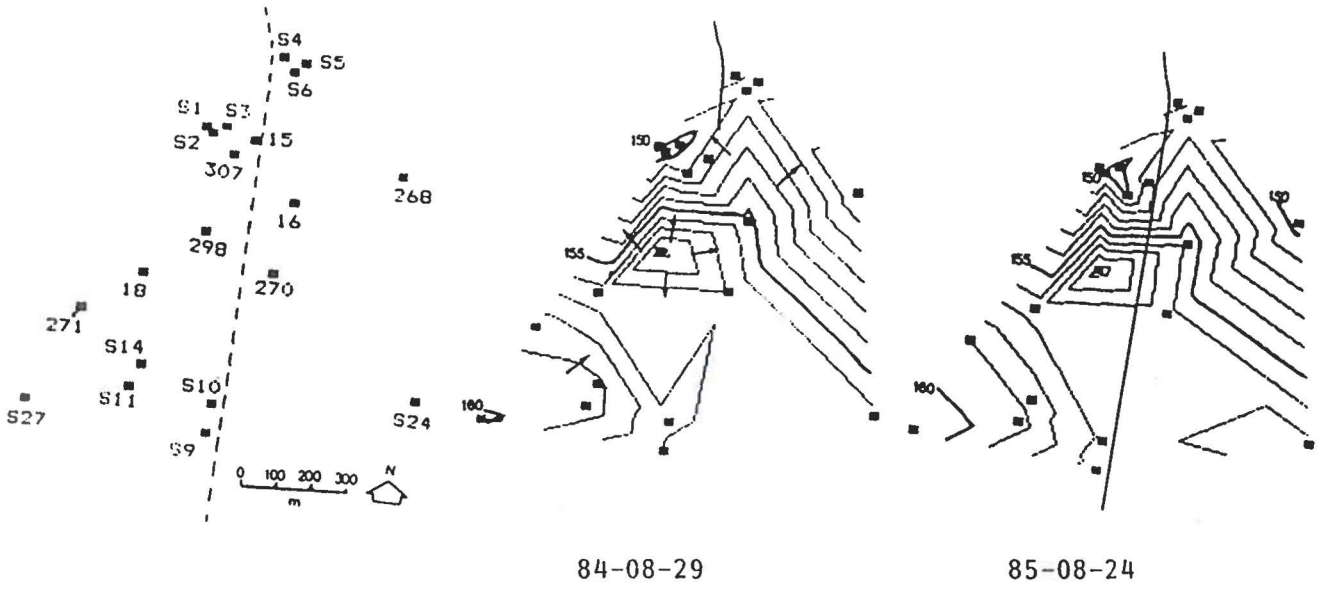


Figure 8.4 Groundwater level changes in tubes and wells in the Staverhult area due to tunnelling through the area. Equidistance = 1 m . The tunnel route is presented in the figures.

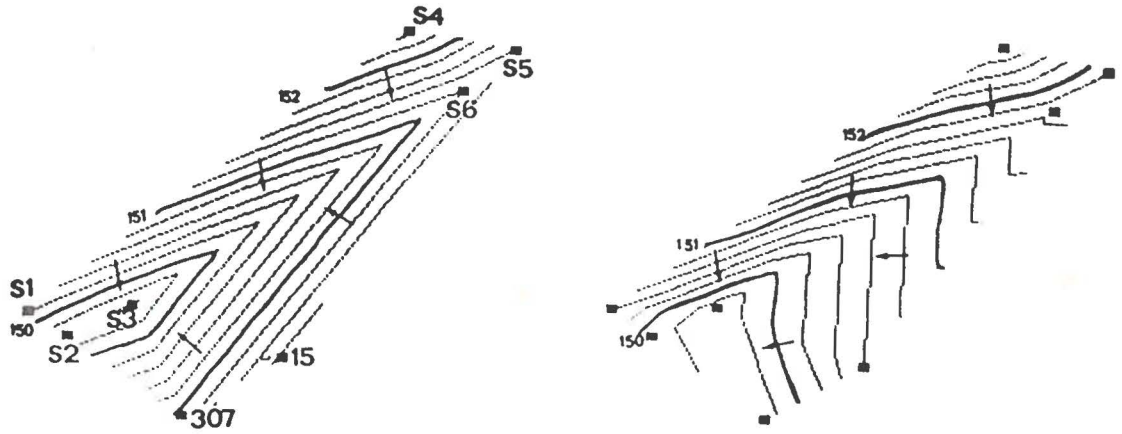


Figure 8.5. Detailed study of idealized groundwater level contour lines at the northern part of Staverhult. Equidistance = 0.2 m.

The linear regression analysis curves for tubes and wells at Staverhult in relation to a reference well, no S29, situated outside the presumed influence-area, has indicated lowering of the order of 0.1 - 0.9 m for many of the tubes in the northern and southern parts of the area.

8.3.4 Summary of results

The groundwater level situation in the bedrock at Staverhult has changed dramatically during the tunnel construction period. This is indicated by a distinct lowering of the levels in three of the five 50 m deep boreholes, the core drilled hole and the 13 m deep borehole. The highest groundwater level in BBH3 has at the end of the research period, changed to the lowest level. The maximum lowering of the groundwater level from August 1984 to September 1986 was 15 m.

The drawdown in the bedrock indicates a heterogenous hydraulic character of the rock mass with a slight influence by the tunnel in the southern part of Staverhult and with a distinct lowering of the groundwater level in the northern part.

The influence from the tunnelling on the soil aquifer has been of a local character except along the tectonic zones in the area and exceeds 1 m only in topographical depressions. It is presumed that the most affected tubes and wells are situated in depressions filled with well sorted sand and silt. Dug wells penetrating till in topographical high positions show none or very slight influence from the tunnel. Only a few dug wells in the area are significantly affected by the tunnel. A small fen, situated directly above the tunnel route, has been much drier according to the local farmer's observations. The total lowering of the groundwater levels in the overburden at Staverhult ranged from 0.1 m to more than 3 m. A drawdown in the overburden was observed as far as 800 m from the tunnel line along one of the distinct tectonic zones in the area.

The variation of soils in the area plays an important role in the groundwater level changes. The discharge areas (usually depressions), probably connected with well sorted sediments, seem to be the most affected areas.

8.4 Fractures and water leakage

A detailed geological and tectonical mapping in the Bolmen tunnel has been carried out along a sequence of 1.5 km through the Staverhult area and in two short reference sequences north of the area (see Chapter 4). Fracture orientations were measured together with rock types, fracture length, water leakage, mineral fillings, sliding planes etc. The fracture data have been statistically and graphically computed in a microcomputer programme developed at the Department of Land Improvement and Drainage, Royal Institute of Technology and treated in a hydrogeological/tectonical manner in order to study water leakage into the tunnel in relation to the hydrogeological situation. The evaluation is presented in Olofsson (1988) and a short summary of the results is as follows:

* The dominating rock type between 9+800 and 11+300 is a grey-red banded gneiss (62%) often including veins of red potassium-feldspar. Minor parts of the mapped sequence consist of amphibolite and amphibolite-gneiss (13%) and a homogenous gneiss-granite (2%). 23% were covered by shotcrete.

* The layering and foliation in the area are predominantly in an E-W direction, often flat dipping towards north.

* The total number of fractures increases in the Staverhult line but the percentage of leaking fractures decreases, perhaps due to a successful pre-grouting.

* The predominant fracture directions in the area are N60-70W and N40-50E.

* The main fracture directions have probably been created during different rock stress situations and neither rock type, schistocity or foliation seems to control the direction of fractures.

* The distribution of different kinds of leakage were as follows:

	percentage of the total number of leaking fractures	
	all leaking types	pouring
from small fracture zones	11.8%	26.2%
from single fractures	73.5%	57.0%
parallel to the foliation	0.6%	0.8%
from intersection between two fractures	14.0%	16.0%
from rock contacts	0.1%	0.0%

* The most frequent water inflow is observed in single, steeply dipping fractures predominantly striking N60-70W and N40-50E (Figure 8.6).

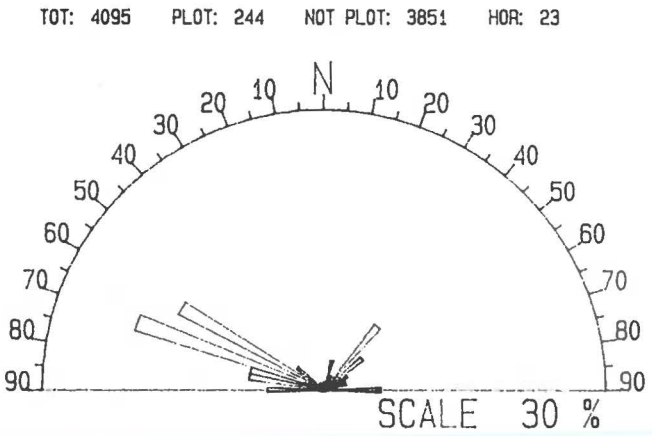


Figure 8.6 Strikes of fractures showing pouring water leakage in the Staverhult area

* The main volume of the leakage water is probably due to small fracture zones striking N60-70W, filled with clay and rock fragments.

* The water leakage in the tunnel has an unambigious anisotropic character, where a few percent of the fractures serve as major drainage channels in the rock mass.

8.5 . Recovery tests

8.5.1 Methods and results

In order to study the hydraulic properties of the soils, recovery tests were conducted in 6 plastic tubes and 2 dug wells in the Staverhult area. The recovery tests in the tubes were carried out using a small petrol-powered pump and the groundwater discharge was constant for about 10 minutes until the groundwater drawdown was more or less stabilized. The discharge of water was small compared to the aquifer and the adjacent tubes did not react to the pumping. After pump stop, the drawdown was measured manually. Hence, it was very difficult to get reliable values in the beginning of the recovery period because of the rapid recovery rate. The evaluation was made using a simple method according to Theis (1935). The calculated coefficients of transmissivity are presented in Table 8.1. For tubes no S2, S3 and S5, which are pressed down in till, inflow of water may occur only through the bottom filter section (1 m). For the other tubes S1, S4 and S6, which are drilled and pressed down in superficial bedrock, the inflow is supposed to occur from the end of the tube down to the bottom of the drilled hole.

Table 8.1 Recovery tests in tubes at Staverhult

No	Type	Depth(m)	inflow sequence(m)	Transmissivity (m^2/s)
S1	till/bedrock	7.0	1.9	$3.0 \cdot 10^{-6}$
S2	till	4.1	1	$2.2 \cdot 10^{-5}$
S3	till	2.6	1	$9.7 \cdot 10^{-5}$
S4	till/bedrock	9.1	1.7	$2.3 \cdot 10^{-6}$
S5	till	3.1	1	$9.3 \cdot 10^{-6}$
S6	till/bedrock	4.5	3.8	$3.2 \cdot 10^{-6}$

Recovery tests have also been carried out in two of the dug wells in the area. The objective was originally to measure and compare values of the hydraulic conductivity obtained from the wells which obviously were affected by the tunnel, to those wells which were uninfluenced. However, the field work was carried out in August 1986 and, due to extreme low groundwater levels during this period, the most influenced wells, no 15, 15B and 270, had more or less dried out. Hence, values could only be obtained from two unaffected wells, no 298 situated within a distance of 100 m from the tunnel line and no 271, situated in the outermost part of the area.

The drawdown was measured manually at the beginning of the recovery period but after one hour, a water level recorder was set up.

The evaluation was made by a simple method developed and described by Engqvist & Olsson(1974) and derived from Muskat(1937). The method is used for evaluation of recovery test data within the hydrogeological mapping in Sweden. The results from the tests were as follows:

Table 8.2 Recovery tests in wells at Staverhult

No	Depth	Capacity	Hydraulic conductivity
272	5.0	19.6 l/h·m	$1.2 \cdot 10^{-7}$ m/s
298	5.8	63.5 l/h·m	$4.7 \cdot 10^{-7}$ m/s

8.5.2 Discussions

There are discrepancies between the recovery tests in the tubes and in the wells. This may be due to a number of possible causes, for example:

* Different geological/hydrogeological conditions. The tubes are situated in the northern part of the area in relativily low topographical positions, where well-sorted sandy-silty sediments are to be found. Tube S1, S2 and S3 are also situated near a small rivulet, which perhaps will influence S3 and may explain its high value of transmissivity.

* Different recovery techniques and evaluation methods between wells and tubes.

The hydraulic conductivity evaluated for the dug wells, which are situated in till, is in good agreement with tubes, which are drilled and pressed down in superficial bedrock. The fact that well no 298 only showed a very slight reaction to the groundwater decrease in the underlying bedrock cannot be explained by any differences in the hydraulic conductivity for the well compared to that of the bedrock. Therefore, this well must be situated in a separate aquifer and it probably receives its groundwater from an adjacent till-covered hill. On the other hand, the superficial bedrock in topographical low positions (e.g. near the Staverhult line) is crushed and together with well-sorted Quaternary deposits in some depressions, drainage from the soil aquifer into the bedrock may occur.

8.6 Geophysical logging in boreholes

8.6.1 Methods

Geophysical logging has been carried out in 5, 50 m deep boreholes, BBH1, BBH2, BBH3, BBH7 and BBH8. Their geographical position can be seen in Figure 4.1. The objective was to collect data regarding fractures together with water inflow in the boreholes in order to, among other things, plan a tracer experiment (see Chapter 8.7). Hence, temperature, electric conductivity, SP (self potential) and borehole diameter were measured.

8.6.2 Results

It may be concluded from the logging data that borehole BBH2 and BBH7, which show slight or no influence from the tunnel, have very few fractures with water inflow (Olofsson 1988). All but one recognized fractures in BBH3 contain water, which may explain the exceptional lowering of the groundwater level in that borehole.

The logging data show that the borehole logging technique in some cases may be a useful tool for predicting the degree of influence from adjacent underground constructions on a borehole.

8.7 Tracer experiments

In order to clarify the direction of the drainage channels in the rock mass, two tracer experiments were conducted. The first experiment was to find out if there were any open fractures and hydraulic connection between the most influenced borehole BBH3, together with BBH1 and the tunnel. Two kinds of salts, NaBr and LiCl, were used and water samples were taken manually from leakage water in the tunnel for one week. Since there was no trace of the salts in the samples, a second experiment was conducted in BBH3 during August and September 1985, using a metal-complex, Cr-EDTA, together with a salt, NaBr. The tracers were injected by a handpump at different levels in the borehole, where geophysical logging had indicated open fractures with water inflow.

The direction of fractures with water seepage was determined along a sequence of the tunnel near the borehole. The distance between BBH3 and the tunnel is approximately 40 m. Water samples were taken daily from five leaking fractures which could be connected to the boreholes and serve as drainage channels. Sampling was carried out automatically from the fractures by a system of small plastic tubes and a sampler specially developed within the project.

Unfortunately, the tracer experiment had to be abandoned after 6 weeks because tunnel work had come to an end and the water pumps were removed earlier than expected. Analysis of the

leakage water showed no increased concentration of the tracers, which could be due to one or several of the following possibilities:

* The injection of the tracers from the borehole into the fractures was unsuccessful.

* No single fracture served as a drainage channel between the bore hole and the tunnel. The groundwater movement was of a more complex nature.

* The water flow was so slow that the tracers did not reach the tunnel during the time of the experiment.

* The tracers reached the tunnel through some unexpected fractures outside the sampled tunnel sequence. However, reference samples were taken manually a couple of times from some leakages outside the actual sequence.

* The tracers did not function well because they were delayed or adsorbed by reactions with the surrounding rock material and/or mineral fillings in the fractures. However, the metal-complex was prepared according to a method, described by Knutsson(1967) and this kind of tracer had been used earlier during several successful tracer experiments.

* The dilution of the tracers was too high, a thousandfold, so that detection was impossible.

8.8 Water chemistry investigations

8.8.1 Methods

Water sampling and physical/chemical analysis of groundwater has been carried out on many of the tubes, wells and boreholes in the Staverhult area. Some water samples have also been taken from leakage water in the tunnel. All samples have been analysed at the Department of Land Improvement and Drainage, Royal Institute of Technology. The objective of the water chemistry studies was to distinguish between different aquifers and to clarify the changes in the chemistry due to tunnelling through the area and the lowering of the groundwater level.

8.8.2 Classification of the groundwater

The groundwater from different aquifers has been classified using trilinear diagrams according to Hill(1940) and Piper(1944). Water samples from the tunnel are found relatively close together in the diagram and may be classified as calcium-magnesium-bicarbonate types. A comparison between tunnel water and water from the boreholes demonstrates significant differences between the two waters, e.g. a higher percentage of chloride- and sulphate-ions in the boreholes, Figure 8.7. However, the water samples from the boreholes are taken some ten meters above the tunnel roof.

Water from the tubes, which are drilled and pressed down into superficial bedrock, fall more or less on a line, from a true calcium-bicarbonate type of water to a more sulphate- and chloride-rich type without any particular predominant cation. This may be an effect of mixing between two waters, e.g. leakage from the soil aquifer into the superficial bedrock.

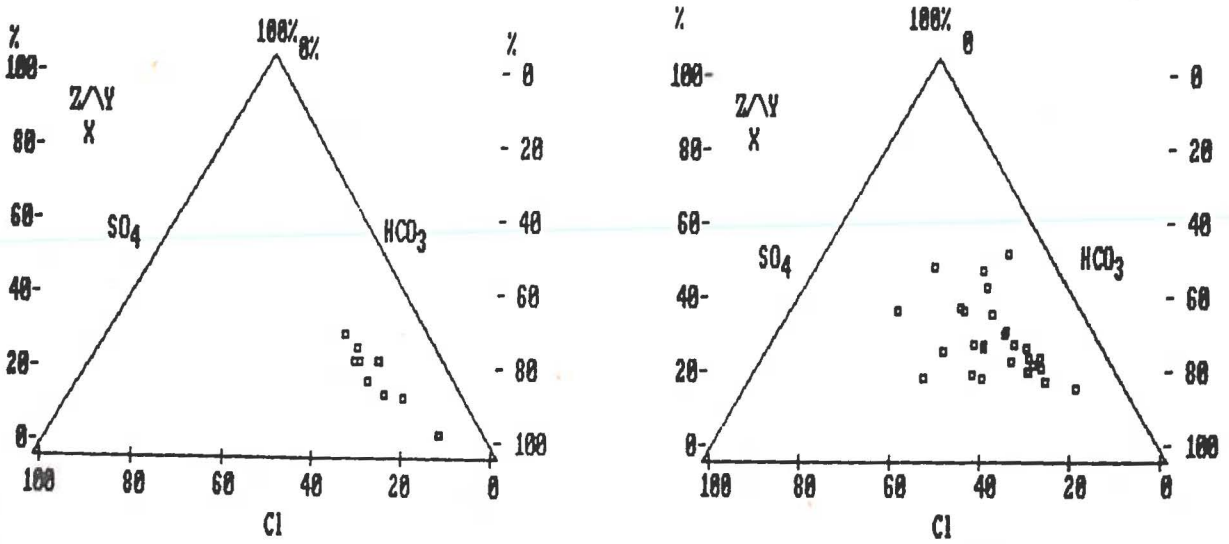


Figure 8.7 A comparison between water samples from boreholes and leakage water in the tunnel at the Staverhult area.

8.8.3 Chemical changes with time

The chemical analyses of water from different aquifers point out the fact that the chemistry fluctuates obviously more in the boreholes and drilled wells than in the tubes at the Staverhult area. BBH3, which suffers the greatest lowering of the groundwater level due to the tunnel excavation, also shows the most distinct water chemistry changes. The content of sulphate increases in BBH3, together with BBH1 but decreases at the same time in the boreholes BBH7 and 405. The alkalinity in BBH3 decreases together with the pH-value, which is lowered almost one unit. The nitrate content, at the same time, increases. Unfortunately, no water samples could be collected from BBH3 during 1986, due to a leakage of oil from hydraulic tests in the borehole.

Among the tubes in the soil aquifers, there are only small water chemistry fluctuations, e.g. in tube no S13, which is pressed down through peat into an underlying sandy-silty layer. A steadily increasing content of nitrate may indicate influence from an adjacent pasture land. The drawdown in S13 due to the tunnelling, is estimated to some decimeters.

8.8.4 Summary of results

* Water taken from BBH3 is probably not in equilibrium with the surrounding rock material but may indicate an inflow of a more sulphate-nitrate-rich water, perhaps due to drainage of a swampy ground and/or an arable land.

* The fluctuations of the groundwater chemistry due to the lowering of the water levels are obviously different in each of the boreholes. Water can be obtained either from more distant parts of the rock aquifer or, in many cases, directly from the soil aquifer or any other adjacent water magazine, e.g. a lake or a swampy ground. It is very difficult to predict the water chemistry changes since the direction of each leaking fracture in the borehole cannot be determined. Hence, two adjacent boreholes, BBH3 and BBH8 can react very differently.

* The peat land in the north-western part of the Staverhult area consists of two separate aquifers. The small decrease of the groundwater pressure in the underlying sandy-silty layer is connected to some chemical changes, e.g. a higher nitrate content of the water.

* Water chemistry analysis is often a useful tool to clarify the influence from the overburden, for examples during pump tests in boreholes.

8.9 Final conclusions and remarks

The drawdown in the soil aquifers within the Staverhult area due to the tunnelling, was in the order of 0 - 3 m, rarely exceeding 1 m. The moderate lowering of the groundwater levels may be a combined result of local favourable geological conditions and sucessful actions during the excavation of the tunnel, i.e. moving of the tunnel route 75 m eastwards and pre-grouting in the Staverhult line. The overburden has played an important role as a groundwater reservoir on top of the bedrock. Depressions filled with well-sorted sediments in contact with a heavily crushed superficial bedrock have been drained, while till-covered areas in the central part of Staverhult consist of separate soil- and rock-aquifers. However, a slight lowering of the groundwater levels, in the magnitude of 0.1 - 1 m, can be observed in all tubes situated in the vicinity of the tunnel. A drawdown in the overburden has been observed as far as 800 m from the tunnel line, along one of the major tectonic zones running in the NE-SW direction.

The lowering of the groundwater level in the bedrock indicates two different hydrogeological situations; the northern and central part where the drawdown at some observation sites has been considerable and the southern part where only a small groundwater lowering has been observed. The strike of the predominant water leaking fractures in the tunnel indicates a hydraulic anisotrophy in WNW-ESE in the rock mass.

The main conclusion of the project is that the soil aquifers and the hydraulic contacts between the bedrock and the overburden must be taken into account during calculations of water leakage to an underground construction,

The project has also pointed out the possibilitiy of using the borehole logging technique for detection of fractures with water inflow and the use of water chemistry analysis as a method of tracing drainage of the soil aquifers, for example during test pumping of drilled wells.

9 RELATIONSHIP BETWEEN THE SITE INVESTIGATIONS (PREDICTIONS) AND THE CONDITIONS ENCOUNTERED IN THE TUNNEL

9.1 Introduction

As noted in Chapter 2, an extensive site investigation programme was executed in conjunction with the planning of the Bolmen tunnel. As the bedrock outcropped to only a very limited extent, the site investigations were mainly of a geophysical nature.

The tender documents contained a division of the rock into three classes and an assessment of the need for temporary shotcreting.

After completion of geological mapping of the tunnel it was possible to compare the predictions and reality as regards the distribution of rock types, rock quality and the need for temporary support works. A special evaluation was also carried out to assess the application and reliability of various geophysical methods of measurement used in rock construction work.

The results and experiences from the whole tunnel line have been reported to Sydkraft AB and presented at the Rock Mechanics Meeting in Stockholm 1986 (Stanfors 1986, Stanfors 1987). The following report is a comparison between the predictions in the detail studied area at Staverhult and the real hydrogeological conditions in the tunnel.

9.2 The Staverhult line

The main part of the research project has been concentrated to the area around Staverhult, station 10+000 - 12+000 in the tunnel. The topography in this area is relatively flat and the depth of overburden

ranges between five and ten metres. The predominant rock type, as described in Chapter 5, is a fine to relativily coarse-grained grey to reddish gneiss, sometimes with pegmatite veins. Based on documentation from well drilling and other sources, close interlayering of gneiss and amphibolite in form of lenses and dykes, probably extending to the WNW, was expected in the central section.

Seismic refraction measurements that originally were carried out during the site investigation period along the whole Bolmen tunnel, indicated distinct low-velocity zones in the Staverhult area. The tectonic zones run NE-SW, expressing the topography. The northern-most zone was identified seismically over a distance of about 1 km, where the seismic velocity in rock locally was below 3000 m/s.

Supplementary geophysical investigations were carried out along the intended tunnel route, using electric resistivity and seismic refraction methods. An extract of the results from the resistivity measurements from the northern part of the tunnel, which extends from station 7+000 to 13+000, is shown in Figure 9.1.

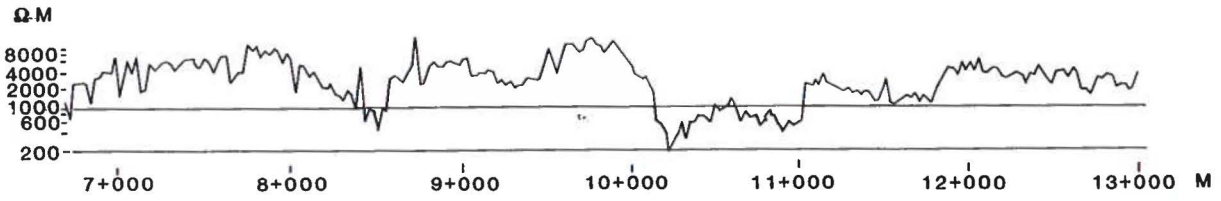


Figure 9.1 Results from resistivity measurements between stations 7+000 and 13+000. (Bäckblom & Stanfors, 1986).

The results show high values at station 7+800 and drop to 400 Ωm at station 8+500. High resistivity values, sometimes exceeding 10 000Ωm then follow together with a sudden drop over a distance of 2 km around the Staverhult line, between stations 10+000 and 12+000. This section exhibited exceptionally low resistivity values. The first profile was supplemented by additional parallel resistivity profiles 50 m to each side of the main tunnel route. The reason for these additional profiles was to study in greater detail the expected conditions in a possible locally changed tunnel route. In addition to the resistivity measurements, an electromagnetic survey using VLF (Very Low Frequency) was made. The results of these measurements are not presented here, but strong anomalies show up in the sections that exhibit low resistivity values (Arnbom & Jeppsson, 1985).

The seismic measurements were supplemented by investigations along a parallel line 75 m to the east of the original tunnel line and by lines at right angles to it. The location of the low-velocity zones encountered coincides relatively well with the low resistivity zones. The investigations showed that the strike of the zone is N60E and that the thickness appears to decrease towards the east. The results from the investigations between stations 10+050 and 12+060 favoured a route 75 m to the east of the original tunnel line.

A general picture of the tectonical conditions at the Staverhult area based on the geological and geophysical data is presented in Figure 9.2.

9.3 Correlation between the real conditions in the tunnel and the predicted model

Geological mapping in the tunnel showed that the section north of the Staverhult line is dominated by medium-grained, grey-red gneiss, with a variable dip of the foliation. Amphibolite occurs as cross-cutting dykes as well as in lenses and narrow bands, usually parallel to the foliation of the gneiss. The number of amphibolite veins and fracture frequences increase towards the Staverhult line.

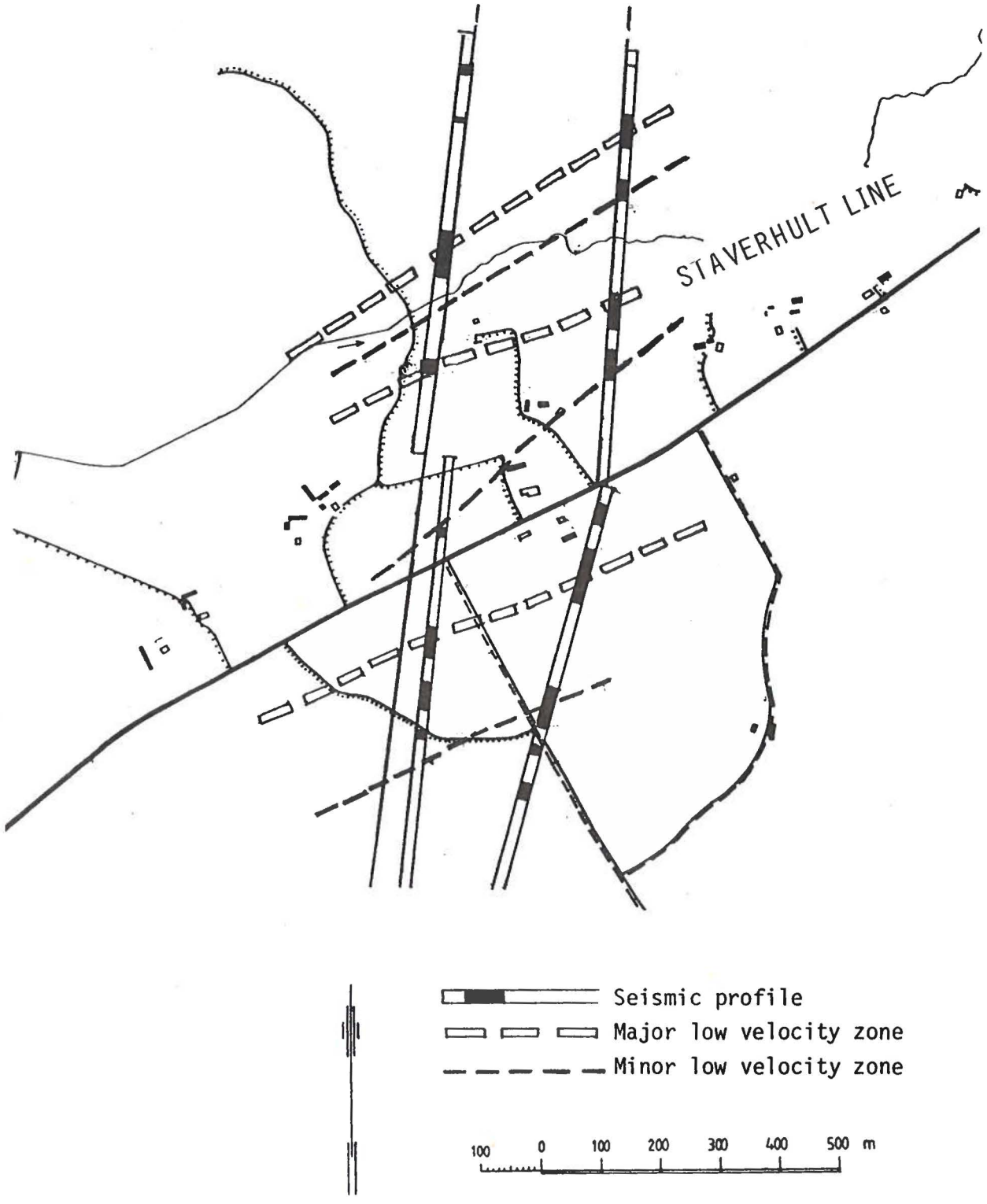


Figure 9.2 Geological and geophysical site investigations around the Staverhult area (after Bäckblom & Stanfors, 1986).

The central part of the Staverhult line, 10+000 - 10+300, is presented in figure 9.3 and characterized by:

* Intensive folding around an axis striking WNW. The central parts of the section show evidence of intensive thrust faulting, often along flat dipping amphibolite lenses and dykes.

* The number of amphibolite lenses and dykes increases markedly. Fractures are normally filled with chlorite and are smooth.

* The occurence of clay is noticeable, both in the amphibolite and in the gneiss. At stations 10+110, a 5 m wide zone of clay was encountered. Smectite was the main clay mineral in all clays.

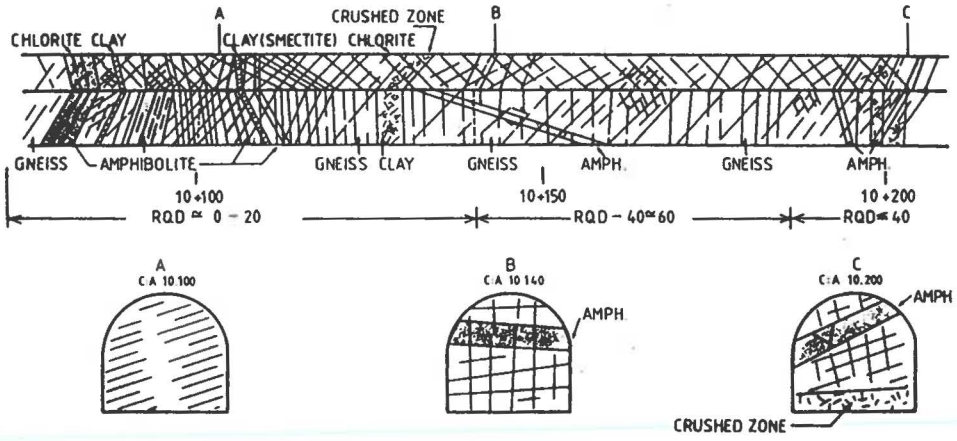


Figure 9.3 Geological mapping of the Staverhult line between 10+000 and 10+200 (Bäckblom & Stanfors, 1986).

The section between stations 10+300 and 10+700 was dominated by heavily fractured gneiss, in which limonite was the main filler of fractures. The rock was divided into small blocks by the fractures.

The correlation between the geology and the results of resistivity measurements is shown in Figure 9.4, which also shows the support installed.

The figure shows that the occurence of resistivity anomalies correlates well with the shot-creting. Spiling was carried out in zones of pure clay and where the rock was too crushed to maintain the tunnel profile without pre-support work. Spot bolting was also necessary.

Grouting was carried out where limited flows of water were encountered during drilling of feeler holes. The aim was to ensure good conditions for subsequent shot-creting.

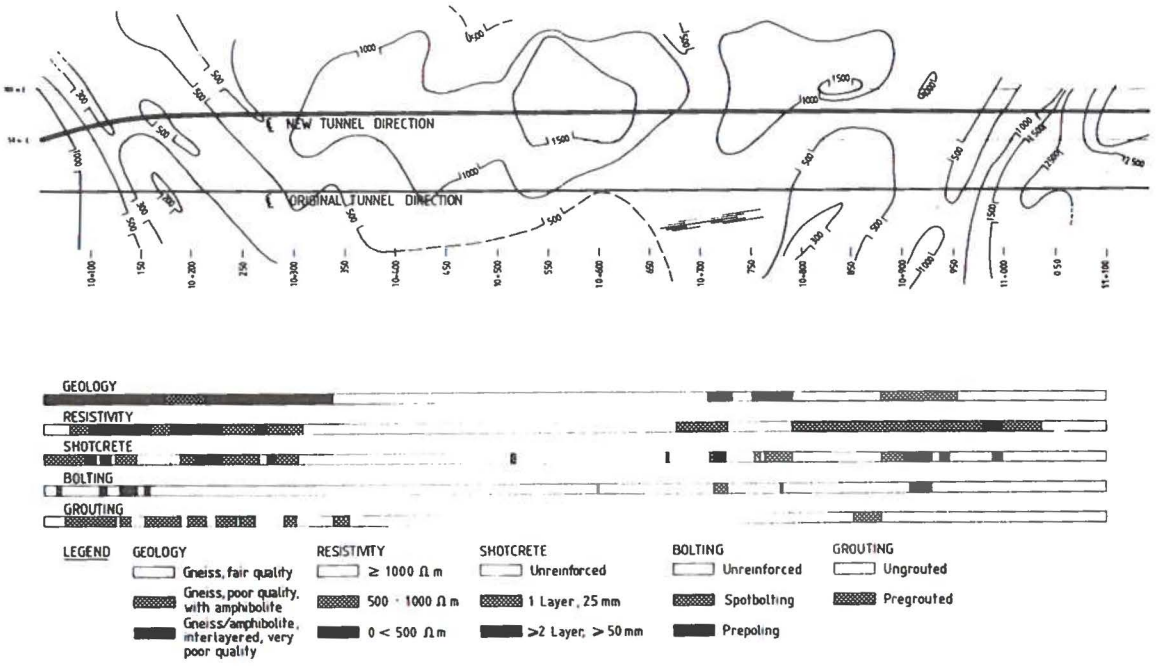


Figure 9.4 Correlation between geology, geophysical measurements and support installed (Bäckblom & Stanfors, 1986).

9.4 Conclusions

The project has shown that geophysical investigations using seismic refraction techniques and resistivity measurements are very useful for identifying and characterizing fracture zones. The supplementary investigations at the Staverhult area using VLF also showed that this is a good and inexpensive method of reconnaissance of fractured rock zones. The moving of the tunnel line 75 m to the east of the original tunnel line, based on the results from the resistivity measurements in the area, was a favourable decision, which reduced the cross-distance through the Staverhult line.

Compared to other sections of the Bolmen tunnel in which corresponding results from geophysical measurements have been available, the Staverhult area exhibited considerably better driving conditions partly due to much smaller amounts of water.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 The hydraulic properties of the bedrock and the overburden in the Staverhult area - general conclusions

Different investigations concerning the hydraulic properties of bedrock and overburden have been carried out in the Staverhult area. These investigations have given a general picture of the conditions that can be summarized as follows:

* The Quaternary deposits have a thickness of about 5 - 10 m and consist mainly of till. In some parts of the area well-sorted sediments of mainly sand, are deposited on the till. Low areas are frequently filled with peat.

* Stress measurements in the rock indicate low stresses at the tunnel depth and the existence of a zone of rapid stress relief extending from surface down to approximately 70-100 m depth. At greater depth the horizontal stress field is probably close to isotropic.

* Pumping tests in the boreholes have shown very uniform transmissivity values.

* The fracture system consists of several fracture sets that give the possibility for isotropic hydraulic conductivity to occur.

The simplest conclusion to be drawn from these results is that the hydraulic conductivity of the bedrock is isotropic and homogeneous. Against this conclusion speak the results from the injection tests that show a very inhomogeneous conductivity distribution, the varying water chemistry in the tunnel and the experience from other areas in crystalline bedrock. The impression of hydraulic isotropy may be a result of the borehole configuration but in the data no clear anisotropy can be found.

Analyses of the hydraulic conductivity in the overburden and in the bedrock show a conductivity in the range of $K=10^{-6}$ m/s in the overburden and about $K=10^{-7}$ m/s in the bedrock.

Furthermore, the groundwater level observations show a very good contact between bedrock and overburden, especially in topographically low parts of the investigation area. The overburden thus acts as a water reservoir situated on top of the bedrock. This reservoir evens out the reactions in pumping tests and other disturbances of the groundwater balance, thus giving the impression of homogeneity obtained by pumping tests.

The final picture of the hydraulic properties of the area thus shows a fairly homogeneous overburden with an inhomogeneous bedrock below. The hydraulic conductors in the bedrock are fractures and fracture zones. Where they are in contact with the overburden they give local drawdowns caused by the tunnel. The drawdowns are however evened out by the higher conductivity in the overburden.

In order to make a prognosis of the leakage to the tunnel, it is practical to consider the groundwater level in the overburden as a constant head boundary, and the bedrock, in the large scale, treated as a continuum with a hydraulic conductivity that decreases with depth.

The project has also shown the necessity to take into account the hydraulic properties of the overburden and the contact between rock and soil when making prognoses of leakages into underground constructions.

10.2 Recommendations for planning and construction of underground works

One of the fundamental objectives of the research project as a whole was to develop methods for the prognosis of leakage into tunnels. Hence, several different methods have been tested in the Staverhult

area including rock stress measurements, geophysical investigations, tracer experiments and investigations of the hydraulic properties of the overburden and the bedrock. Taking all results from these investigations into account, it is possible to give some recommendations regarding site investigations for future rock construction works, where a prognosis of water leakage is required.

The recommended methods are in no order of preference and the applicability depends on the type and design of construction, the geological and tectonical conditions and also the need for precision in the prognosis of water seepage.

Geophysical site investigations

Geophysical methods of measurements are often necessary and are excellent aids for planning underground construction work. However, the method selected should be carefully matched to the problem. A thorough knowledge of the composition of the bedrock and its tectonic features is a necessary base for the interpretation of different geophysical measurements.

The Bolmen tunnel project has shown that:

VLF is a good and inexpensive method of reconnaissance for fractured/crushed rock zones. Unfortunately it is also very sensitive to external disturbances (cables etc.).

The resistivity method is considerably more expensive, but it is very good for detailed investigation of features, including clay altered zones of disturbance. This has previously been pointed out by Stanfors et al (1985) and Stanfors (1987)

The best results are obtained if the results from two or more correctly selected geophysical methods are interpreted together. However, awareness of the limitations of the methods is very important. Very narrow weakness zones (less than 5 m) and flat lying zones are usually very difficult to observe.

The research project has also pointed out the possibility of using geophysical borehole logging technique for the detection of leaking fractures in the bedrock.

The hydraulic properties of the bedrock and the overburden

Site investigations for an underground construction should include modern testpumping technique for the estimation of water leakage to a rock foundation. This is one of the principal assumptions for a successful construction process. Groundwater studies and pumping tests with regard to analytical mathematical methods are an important tool for the calculation of flow in fractured aquifers.

The Bolmen tunnel research project has shown that the overburden plays an important role as a water reservoir on top of the bedrock. This must be taken into consideration during planning and construction of rock caverns and tunnels. A reservoir consisting of well-sorted sediments with hydraulic contact through open fractures in the bedrock may enable considerable water leakage to the rock cavern and also cause environmental problems such as land subsidence and drained wells. Hence, careful examination of the Quaternary deposits and their hydraulic properties are recommended.

Pumping tests in boreholes and wells as a site investigation method often give a rough prognosis of the leakage to the underground construction. On a detailed scale, the amount of seepage water to a particular rock cavern may differ from the predicted value if the cavern is in contact with specific leaking fracture zones. In order to provide these more specific prognoses, it is nessesary to carry out hydraulic tests in situ continuously during the construction period. This can be done using a pilot hole for the hydraulic tests at the construction site and continuous studies of the tectonic-geological and water conditions. This is one of the areas in which future development is urgent. The method developed must be elementary and take into consideration working routines, economy and excavation rate etc.

Water chemistry analysis

The research project has shown that chemical analysis of water is a useful tool in clarifying the water flow in the rock mass. Analysis of water chemistry before and during pump tests can sometimes clarify the water paths in the ground and give a rough estimation of the hydraulic contact between the bedrock and the overburden.

Rock stress measurements

Development of the hydrofracturing method for rock stress measurements has enabled rock stress measurements to be carried out in existing boreholes prior to tunnelling and underground excavation. The magnitude and orientation of the maximum and minimum stresses in the horizontal plane can be determined at single test points. By measuring at different depths in the same borehole, the gradients of the in-situ stresses are determined. For construction of large underground excavations and tunnels, rock stress measurements, at the stage of feasibility study, are to be recommended.

Taking the Bolmen tunnel as an example, stress measurements in a single borehole in the Staverhult area would have shown the existence of low stress magnitudes for the uppermost 70 m of the bedrock and high stress gradients at shallow depth. This might have been important information for the design of the tunnel, and in particular its depth location.

The bulk of rock stress data in the world shows a strong tendency for a large scatter in magnitude and orientation of rock stresses at shallow depth in the crust. Most underground excavations are located at very shallow depth where local variations in the stress field may severely affect the performance and the stability of the excavation. Therefore greater emphasis should be put on assessing the effect of virgin stresses in combination with other factors like rock strength, geometry etc. which influences the design.

10.3 Recommendations for further research

Based on experience from the Bolmen Project, the following research proposals are suggested by the individual research groups. The proposals do not appear in order of preference.

* The Bolmen tunnel project has shown that geophysical methods are available today to detect and map geological discontinuities such as fracture zones and dykes. However, the water inflow associated with these anomalies cannot be predicted quantitatively with adequate accuracy. Therefore, a further development of rock mass characterization methods is needed to identify and map major leakage zones in crystalline bedrock.

* In 1986, when the Bolmen tunnel construction period had come to an end, a tunnel collapse was observed in the southern part of the tunnel. Hence additional rock stress measurements at the southern end of the Bolmen tunnel are suggested. The measurements should be located close to one of the highly water-bearing zones intersected by the tunnel or in the vicinity of the tunnel collapse area.

* Investigation of the role of loose overburden for the water inflow to the tunnel. Determination of water flow from overburden to the underlying rock in different geological and hydrological conditions. A pilot study financed by The Swedish Natural Science Research Council is in progress.

* A study of the effects of dominant fractures and sets of fractures on the shape of the drawdown during pump testing.

* Continued study of overburden as a water reservoir for groundwater flow in the underlying rock.

* Mathematical modelling of groundwater flow from loose overburden to the bedrock with special emphasis on boundary conditions and sensitivity analysis for input parameters.

* Statistical determination of the hydraulic conductivity of the rock mass as a function of fracture plane geometry and conductivity of single fractures and virgin rock stresses.

* Development of methods and instrumentation for "quick and simple" rock stress measurements by hydraulic methods (hydraulic fracturing and hydraulic testing on pre-existing fractures) at the pre-investigation stage of underground construction.

* Development of geological mapping techniques for tunnels and rock caverns that suits the combined purpose of analysing fragmentation, stability, grouting and water inflow. Mapping of dominant geological structures and rock types in combination with cell mapping of fractures might be a possible approach.

* Development of routine testing in pilot holes to predict hydrogeological and rock mechanical conditions ahead of the driving face in underground work.

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List of symbols and abbreviations

d_o	(m)	Static groundvater level
d_w	(m)	Borehole depth
K	(m/s)	Hydraulic conductivity
K_g	(m/s)	Gross hydraulic conductivity
K_{gM}	(m/s)	Gross hydraulic conductivity, mean value
ξ	(-)	Skin factor
Q	(m^3/s)	Discharge capacity
Q/s_w	(m^2/s)	Specific capacity
r_{wf}	(m)	Effective radius of the well
S	(-)	Storage coefficient
s_w	(m)	Drawdown in the well
σ_1	(MPa)	Maximum principal stress
σ_2	(MPa)	Intermediate principal stress
σ_3	(MPa)	Minimum principal stress
σ_{pa}	(MPa)	Horizontal normal stress parallel to tunnel axis
σ_{pe}	(MPa)	Horizontal normal stress perpendicular to tunnel axis
σ_v	(MPa)	Vertical stress
σ_H	(MPa)	Maximum horizontal stress
σ_h	(MPa)	Minimum horizontal stress
T	(m^2/s)	Transmissivity