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Äspö Hard Rock Laboratory

Overcoring rock stress measurements at the Äspö HRL

Prototype Repository: Borehole KA3579G (Revised data) and K – tunnel: Borehole KK0045G01

Hans Klasson
Mats Persson
Christer Ljunggren

SwedPower

February 2000

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

Äspö Hard Rock
Laboratory

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Author	Date
Hans Karlsson Mats Persson Christer Ljunggren	Feb. 2000
Checked by	Date
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Hans Klasson

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Abstract

The present report includes the results from three-dimensional overcoring rock stress measurements conducted in borehole KK0045G01, drilled from the drill-and-blast excavated K- or Demo-tunnel in the Äspö Hard Rock Laboratory. The borehole was drilled in a vertical direction from the tunnel floor for about 60 m. The report also comprise the revised results from the overcoring measurements in borehole KA3579G drilled vertically for about 25 m from the TBM-excavated Prototype Repository Tunnel (PRT). The overcoring data from the PRT had to be recalculated and results revised as it was recently found that incorrect input data had been used in the previous stress calculation process.

The tunnel excavations are located at the depths 420 m (K-tunnel) and 450 m (PRT) in the Äspö HRL.

In the PRT borehole ten successful tests were conducted. Six of these where located within the near-tunnel stress field, 2-8 m below the tunnel invert. The remaining four test points were between 22 m and 25 m away from the exavation. A total of 15 successful measurements were completed in the K-tunnel borehole. Ten tests were located within 10 meters distance from the tunnel invert and thus influenced by the tunnel excavation. In order to determine the stress field in the undisturbed rock mass two test levels were located further away from the excavation. One level including two successful measurements was completed at about 30 meters from the tunnel and the other, comprising the three remaining tests, at the bottom of the 60 m deep borehole.

The results indicate that the stress field around a horse-shoe shaped drill-and-blast tunnel is more disturbed than around a circular TBM excavation. For the latter, stress growth takes place almost immediately when moving away from the tunnel perimeter and stress directions are rather consistent. The results gathered in the rock adjacent to a drill-and-blast opening is more scattered and display lower magnitudes. A zone of high stress in one direction is indicated by the result from one test point located 1.2 m from the K-tunnel perimeter. Test points located 2-5 m away from the tunnel conclude considerably lower stresses. The zone of influence around the K-tunnel extends at least 5 meters out into the rock mass.

The compound results as interpreted for the primary stress field are:

σ_1 = 19-35 MPa, σ_2 = 15-18 MPa, and σ_3 = 10-13 MPa.

σ_1 trends NW-SE (magnetic system) and plunges 0º-20º to the SE.

σ_H = 18-34 MPa directed NW-SE

The magnitude intervals are supposed to define the magnitudes for the average stress tensor around 450-480 m depth in the Äspö HRL.

Sammanfattning

Denna rapport redovisar resultaten av bergspänningsmätningar med den tre-dimentionella överborrningsmetoden. Mätningarna utfördes i borrhål KK0045G01, borrat från K–eller Demo tunneln i Äspö Hard Rock Laboratory. Borrhålet utfördes vertikalt från tunnelgolvet cirka 60 m neråt. Rapporten redovisar också reviderade resultat från överborrningsmätningar i borrhål KA3379G borrat 25 m vertikalt neråt från TBM–tunneln Prototype Repository tunnel (PRT). Dessa resultat reviderades på grund av att felaktiga indata använts i tidigare spänningsberäkningar.

Tunnlarna ligger på 420 m (K-tunneln) respektive 450 m (PRT) djup i Äspö HRL.

I borrhålet från PRT utfördes tio lyckade mätningar. Sex av dessa utfördes i tunnelns influensområde på spänningsfältet, cirka 2-8 m under golvet. De andra fyra mätningarna utfördes mellan 22 och 25 m under tunneln. Totalt 15 lyckade mätningar utfördes från K-tunneln. Tio tester utfördes inom 10 m från tunneln, och resultaten är influerad av denna. Mätningar gjordes även på ytterligare två mätnivåer för att bestämma det ostörda spänningsfältet. Den första mätnivån med två lyckade mätningar, utfördes ungefär 30 m från, och den andra mätnivån, med tre tester, utfördes 60 m under tunneln.

Mätningarna indikerar att spänningsfältet under en hästskoformad sprängd tunnel är mer störd än kring en cirkulär borrad tunnel. I det senare fallet avtar influensen av tunneln relativt fort, och spänningarnas orientering är tämligen konstant. Mätresultaten i bergmassan nära en hästskoformad sprängd tunnel sprider mer, och uppvisar lägre magnituder. Höga spänningar är indikerade av en mätning 1.2 m under K-tunneln. Mätningen 2.5 m under tunneln visar betydligt lägre spänningar. Zonen där spänningsfältet påverkas runt K-tunneln är minst 5 m.

De samlade resultaten av det ostörda spänningsfältet är:

σ_1 = 19-35 MPa, σ_2 = 15-18 MPa, och σ_3 = 10-13 MPa.

σ_1 orientering är NV-SO och stupar 0º-20º mot SO.

σ_H = 18-34 MPa riktat NV-SO

Spänningsintervallen antas omfatta spänningsspridningarna och medelspänningen inom 450 – 480m djup i Äspö HRL.

Contents

1 Introduction

The report at hand comprises the presentation of the results from overcoring stress measurements in two boreholes in the Äspö Hard Rock Laboratory (HRL). One borehole is located in the Prototype Repository Test Area whereas the other is located in the K-, or Demo-tunnel.

Overcoring test results from the Prototype Repository have been reported before, SKB Progress Report HRL-98-09. Recently, however, it was discovered that the data file used to calculate the stress tensor from the registered strains in the Prototype borehole contained incorrect input data, thus rendering corrupt results in the report. The final results from the Prototype Repository measurements have been recalculated and revised. These are presented together with the results from the K-tunnel measurements in the present report.

1.1 Scope

This report constitutes the fulfillment of Purchase Order 54920 97 186 2220, Purchase Order 37300 98 002 3730 and Purchase Order 52048 98 220 2220 placed with Swedpower AB (formerly Vattenfall Hydropower AB) by the Swedish Nuclear Fuel and Waste Management Company (SKB). The orders state that SwedPower AB shall conduct rock stress measurements using three dimensional overcoring equipment in two boreholes in the Äspö Hard Rock Laboratory in south-eastern Sweden; the first drilled vertically from around the 450 m level (the Prototype Repository) and the other drilled vertically from the the 415 m level approximately (the K- tunnel).

Within the scope of SKB’s program for RD&D 1995, and as part of the ”Engineered Barrier Project”, SKB decided to carry out a ”Prototype Repository Test”. The aim of the Prototype Repository Test is to test important components in SKB´s prioritised deep repository system in full-scale and in a realistic environment. The Prototype Repository is located at about 450 m depth, in the inner part of the TBM Prototype tunnel, which has a total length of 90 m, Figure 1-1.

As part of the RD&D 1995, SKB also initiated a project with the designation ”Demonstration of Repository Technology”. The aim of that project is to develop and test methodology and equipment for deposition of canisters in full-scale and in a realistic environment. The drill and blast excavated K-tunnel that will be used for the demonstration is situated around the 415 meter level in the Äspö HRL, Figure 1-1.

The stress measurements being part of the Prototype Repository Test investigation programme commenced on September 27, 1997 and was completed on October 8, 1997. The overcoring tests were carried out in borehole KA3579G.

The field stress measurements in the K-tunnel commenced on March 17, 1998 and was completed on August 12, 1998. Tests were conducted in borehole KK0045G01.

1.2 Objectives

The objectives with the stress measurements were to:

- Provide data on the stress conditions to enable prediction and interpretation of the results from ongoing tests in the HRL.
- To study the influence on the stress field when disturbed by the presence of the a TBM-tunnel as well as of an drill-and-blast excavated tunnel, and the alteration in the stress state when moving away from the opening towards more undisturbed conditions. This was accomplished by locating a number of stress measurement points within 1 m-10 m distance from the tunnel floor.
- To determine the complete stress field in the undisturbed rock mass, away from the tunnels. This was achieved by conducting a few measurements beyond the distance of which the stresses are assumed to be influenced by the existence of the tunnel excavation.

The report provides a detailed presentation of the stress measurements conducted. Chapter 2 summarizes the instrumentation and experimental procedures employed. The field work is summarized in Chapter 3. Chapter 4 and Chapter 5 present in detail all results obtained in the Prototype Repository Tunnel (PRT) and in the K-tunnel, respectively. Some brief comments on the results are also included in these chapters. Sources of errors are discussed in Chapter 6 and the results as such are dicussed in Chapter 7. A brief comparison between the results from the present work and overcoring results from other tests at depth in the Äspö HRL is given Chapter 8. The foremost conclusions of the work are presented in Chapter 9.

Raw data from the tests are reported in Appendices A to D.

It should be noted that the presentation is restricted to the work done and the results obtained, as such. It is neither attempted to put the data into a geological/tectonic context, nor to discuss the implications of the results for future work.

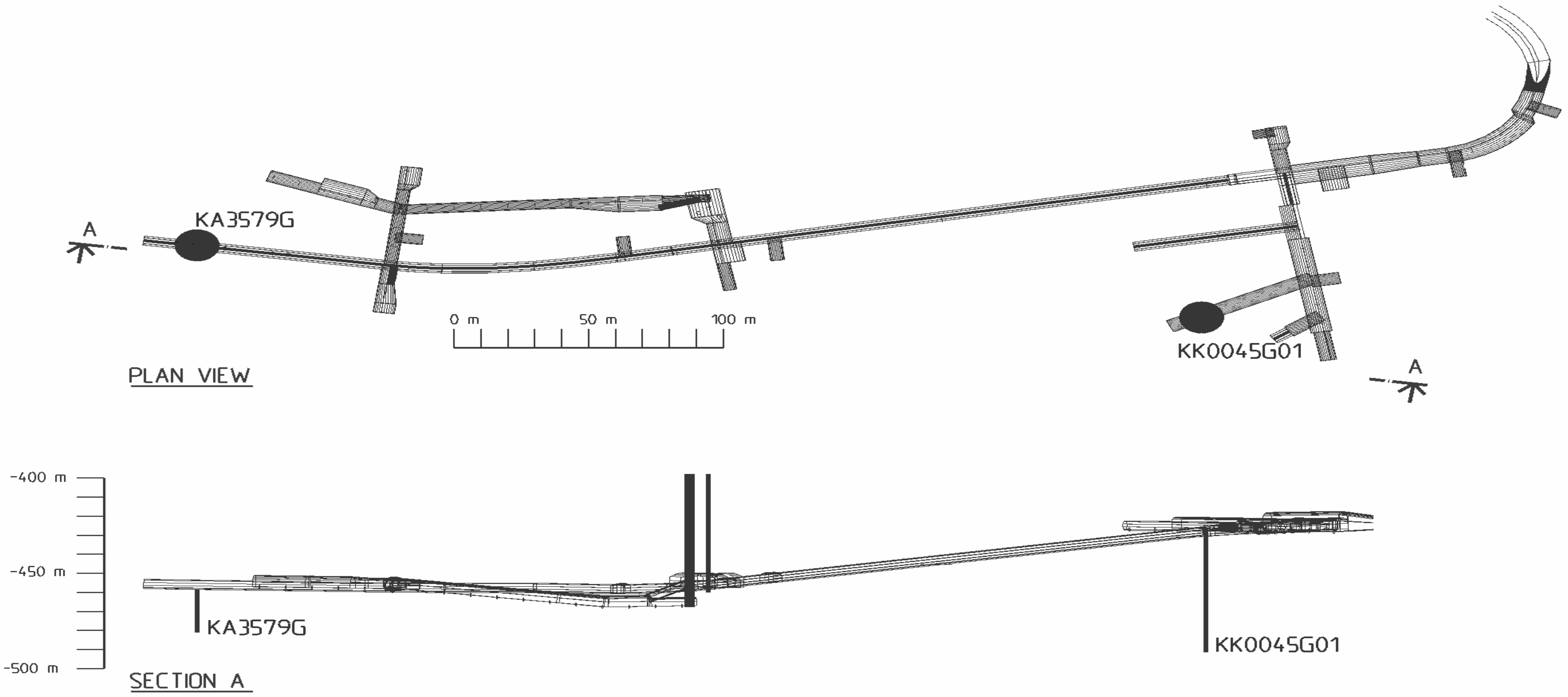


__Figure 1-1.__ Location of the test borehole KA3579G in the Prototype Repository Tunnel (PRT) and the KK0045G01 borehole in the K-tunnel within the Äspö Hard Rock Laboratory. Plan view and section.

2 Experimental

2.1 The overcoring method

2.1.1 Background

The overcoring technique to determine in situ stresses utilizes the principle of stress relief. The method involves measurements of the displacements in a piece of rock when it is released from the rock mass. The in situ stresses are calculated using the measured strains and the elastic properties of the rock according to classical theory presented by Leeman and Hayes, 1966.

The past three decades have seen the development of a variety of overcoring instruments which permit the determination of the complete three-dimensional stress tensor from a single measurement. The technique used in the present case consists of coring a borehole at large (76 mm) diameter over a coaxial small-diameter (36 mm) pilot hole in which a strain-measuring instrument is located. Thus, the cylindrical core sample is isolated from the stress field in the rock mass and the initial state of stress can be calculated from the deformations or strains occurring in the sample during overcoring.

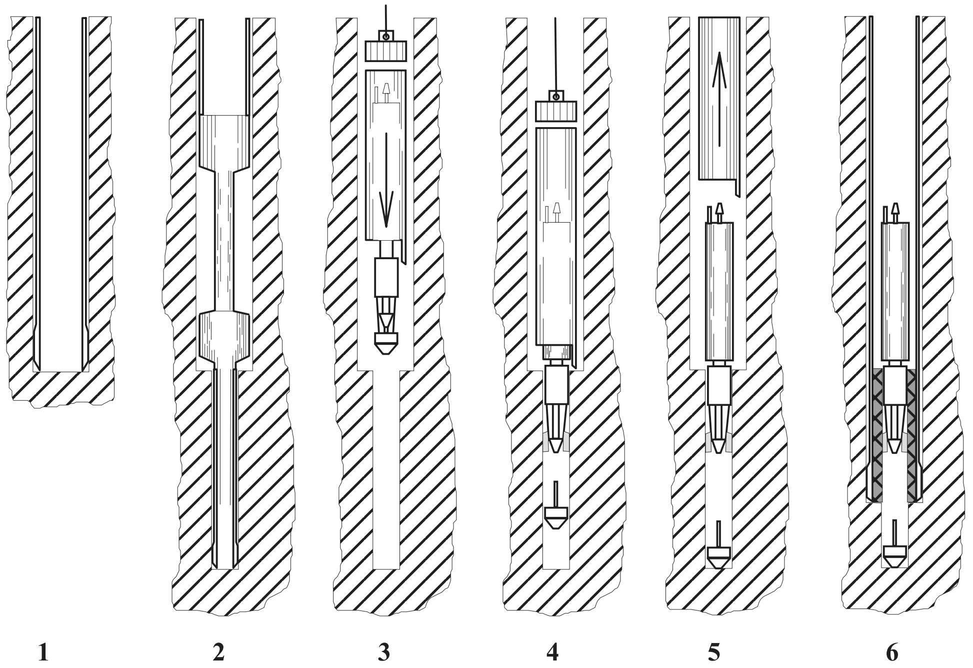
The calculation of stresses utilizes the elastic theory and it is assumed that the rock behaves in a linearly, isotropically elastic manner, implying that the deformation of the core sample during stress relief is identical in magnitude to that produced by the in situ stress field but opposite in sign. It is further assumed that the rock volume is both continuous and homogeneous. Application of the elastic theory also requires knowledge of the elastic parameters of the rock material, E (Young's modulus) and ν (Poisson's ratio).

2.1.2 The Borre Probe

The Borre Probe employed by SwedPower AB is a triaxial strain-measuring instrument, which allows for the derivation of the complete state of stress tensor in three dimensions from one successful measurement.

The Borre Probe has been developed in Sweden by Vattenfall over the last 25 years to perform stress measurements in deep, water-filled boreholes drilled from surface by conventional drilling techniques. More recent development and commercial operation of the equipment has been carried out by SwedPower AB. The Borre Probe, described fully in Hallbjörn et al., 1990, has been used in several countries on several occasions in the 1980s and 90s. The measurement procedure is illustrated in Figure 2-1.

The evaluation of the complete stress tensor from measurements with a triaxial device such as the Borre probe requires only the strains induced by overcoring, the orientation of the probe (generally to magnetic north) and the elastic properties of the rock material. Since the stiffness of the probe's gauges is negligible in comparison to the stiffness of the rock, the over-coring strains represent a complete relaxation of the core. Hence, the core dimensions do not enter into calculations, except in the evaluation of the elastic properties as determined on the core specimen.



1 Advance ϕ76 mm main borehole to measurement depth

2 Drill ϕ36 mm pilot hole and recover core for appraisal

3 Insert Borre probe in installation tool into hole

4 Probe releases from installation tool. Gauges bonded to pilot-hole wall under pressure from the nose cone

5 Pull-out installation tool. Probe bonded in place

6 Overcore the Borre probe and recover in core barrel.

Figure 2-1. *Measurement procedure using the Borre Probe.*

The probe is cylindrical with a maximum diameter of approximately 54 mm and a length of about 550 m. It is lowered into the borehole by rods in a combined installation tool and weight. A brief summary of the component parts of the instrument follows.

2.1.3 Strain gauges

The instrument carries nine electrical resistance strain gauges mounted in three rosettes. Each rosette comprise three strain gauges oriented parallel, at 45° angle and perpendicular to the borehole axis. Strain gauge configuration is summarized in Table 2-1.

Table 2-1. Orientation of the strain gauges in each rosette on the Borre Probe.

Rosette No.	Gauge No.	Orientation of gauge within rosette
1	1	Axial / Longitudinal
	2	Circumferential / Transverse
	3	45°
2	4	Axial / Longitudinal
	5	Circumferential / Transverse
	6	45°
3	7	Axial / Longitudinal
	8	Circumferential / Transverse
	9	45°

The strain-gauge rosettes are bonded to three plastic cantilever arms at the lower end of the probe which is the only part of the instrument that enters into the pilot hole. The arms are located 120° apart with a known orientation to the main body of the instrument. Thus, the nine strain gauges of the Borre Probe form an array representing seven spatially different directions. As strain measurements in six independent directions are required to determine the complete stress tensor, the Borre Probe provides redundant strain data. Hence, up to one non-parallel gauge and two parallel gauges may be rejected or malfunction during the overcoring procedure without impairing complete calculation of the stress tensor. The strain gauges are connected to a data logger up the inside of the probe.

2.1.4 Data logger

Besides the nine strain gauges, the Borre Probe also contains a thermistor and one dummy gauge to assess the temperature effects on the readings during the overcoring phase. The downhole data logger is located in the main body of the probe, Figure 2-1, and records eleven channels of data at preset intervals from a preset start time. The logger, powered by a battery also located in the probe's main body, is capable of storing 8 h of data recorded at 60 s intervals.

Prior to the installation of the probe, the data logger is connected to a portable computer and programmed with the measurement start time and recording interval. No further connection to the ground surface is required after this programming. After overcoring, the probe is recovered with the overcore sample inside the core barrel. Before removal of the sample and disconnection of the strain gauges, the probe is again connected to the portable computer and the data recorded is retrieved using communication software.

2.1.5 Installation tool

Connected to rods, the installation tool carries the probe in the hole and releases it into the pilot hole. The tool contains a mechanical latch that is triggered when the base of the tool lands on the base of the main borehole. Triggering the latch releases the probe from the tool and forces the cantilever arms and strain gauges against the pilot-hole wall.

The installation tool also contains a magnetic compass, connected to the latch and mechanically fixed in its orientation when the latch is triggered. This effectively records the orientation of the probe as it can only be set in and released from the tool in one orientation.

2.2 Test procedure

2.2.1 Drilling the pilot hole

Stress measurements using the Borre Probe requires a centrally located, straight, clean 36 mm pilot hole at the end of the main 76 mm borehole. Diametrical accuracy is necessary as the probe has a limited operating range during installation. The pilot hole needs to be centrally located in the bottom of the 76 mm hole to enable overcoring and biaxial testing of the recovered cylindrical rock sample. At the position of the strain gauges, the pilot should be clear of drill cuttings to ensure a good bond between the gauges and the pilot-hole wall. It is preferable also to recover an intact core from the pilot hole. This core should be of sufficient quality to enable the quality of the rock in the large-diameter overcore sample to be anticipated so that the gauges are not located in a position over or adjacent to pre-existing discontinuities - normally, such locations will yield poor measurements.

If the core break in the main borehole is not flat enough to ensure centric location of the pilot hole, a specially manufactured planing tool run on the 76 mm core barrel is used to prepare the base of the 76 mm borehole prior to drilling of the pilot hole.

If the core recovered from the pilot hole carries discontinuities adjacent to the gauge position, the pilot hole is abandoned and overcored and another pilot hole is attempted. If the pilot core indicates suitable measurement conditions the Borre Probe is prepared for installation.

In the present case, all pilot holes were drilled to a length of approximately 50 cm. Flushing continued until return water was clear before recovering the pilot core in order to improve the conditions for a successful measurement by supplying a pilot hole free of drill cuttings.

2.2.2 Installation of the Borre Probe

The connection of the strain gauges to the logger and other preparation and testing of the instrumentation is generally carried out whilst drilling the pilot hole. The data logger is programmed and the compass and the probe are attached to the installation tool. The latching mechanism in the tool is armed and the tool is attached to a weight carried on the wireline. Finally, the adhesive is mixed and applied to the strain-gauge rosettes and the gauges are then covered with a protective cone before the whole assembly is inserted into the borehole by rods.

When the installation tool reaches the end of the 76 mm borehole the release mechanism is activated as the latch touches the ledge formed between the main borehole and the pilot hole. As the probe is installed, the protective cone preventing the adhesive from being removed when entering the probe into the hole is pushed away further into the hole allowing the gauges to contact the pilot-hole wall. The tool is left in the hole until the adhesive has set completely, normally 8 hours in water-filled boreholes.

2.2.3 Overcoring

The requirements for the overcoring of the Borre Probe are that the overcore is concentric to the pilot hole, drilled at a constant and steady rate, and that a suitable length of solid core is recovered at the position of the strain gauges. Concentricity of the overcore, which is governed by the positioning of the pilot hole, is both an operational requirement to ensure the safety of the downhole equipment, and necessary for the calculations of the stress distribution and material properties from biaxial testing of the core sample. A constant drilling rate during overcoring ensures that stress relief on the core occurs in a controlled manner and that the strain-gauge response is not unduly affected by the drilling. Controlling the rate of penetration reduces the possibility of the overcore sample cracking in weaker strata. The recovery of solid core of suitable length at the gauge position is required for subsequent biaxial testing. Cracking of the core in the proximity of the gauges can also influence the strain-gauge response and possibly render the measurement incalculable.

After the epoxy setting period and as the in-hole data logger is due to commence strain readings, the installation tool is pulled out from the borehole. The compass is removed from the tool and the compass reading is noted. The drill string, now carrying the Craelius T2-76 mm drill bit is then pushed in. While holding the drill bit about 10 cm from the end of the main borehole, flush water is circulated for a 10 - 15 min period to stabilize temperatures before overcore drilling commences. Overcoring is then performed to a length beyond the end of the pilot hole in order to recover the protective cone. After breaking the core loose, the drill string is retrieved and the overcore sample and the probe are taken out from the hole. In the present measurements, overcoring was carried out to a length of 60-70 cm.

When the overcore sample has been recovered, strain gauge data recordings are immediately transferred from the logger to a laptop computer. The Borre Probe, but not the strain gauges and their respective connecting cables, is dismounted from the overcore sample. Then, if recovery of unbroken core is of sufficient length, i.e. minimum 25 cm, the overcore sample is subjected to biaxial testing in order to determine the elastic properties of the rock.

2.2.4 Biaxial testing

The biaxial testing of the overcored specimens has two purposes; Firstly, it allows the elastic constants of the rock to be determined and secondly, it provides a check of the performance of the individual strain gauges 1-9, Table 2-1. The former is required for the subsequent stress computations, and the latter provides input to the examination of overcoring strains as well as to the overall judgement of the validity of the test.

All suitable overcore samples are tested in a biaxial test chamber to determine the elastic properties of the rock. During testing the strains induced in the core sample are monitored by the strain gauges installed by the Borre Probe connected to a digital strain readout.

The test sequence comprise both loading and unloading in order to study possible inelastic behavior of the rock. The maximum load applied during biaxial testing should preferably correspond to the measured stress magni-tudes. However, to reduce the risk of cracking the hollow cylinders, the maximum load applied to the core specimens is set to 10 MPa in load increments of 1 MPa. The core is then unloaded stepwise by 1 MPa increments. The results from the tests are visualized in the form of diagrams of recorded strains, plotted against applied pressure. A schematic plot is shown in Figure 2-2. Since geometry of the test is axisymmetric, the array of strain gauges of the Borre Probe represents three groups with respect to orientation, axial (parallel), circumferential (perpendicular) and at a 45° angle (to the hole axis). Theoretically, assuming isotropic and homogeneous rock properties, the gauges within each group should respond identically.

To derive the elastic properties the theory for an infinitely long, thick-walled circular cylinder subjected to uniform external pressure is considered. The assumption of plain stress applies as shown by Obert and Duvall, 1967. In the calculation of Young's modulus (E) and Poisson's ratio (ν), the parameters that has to be known are the core dimensions and the axial and circumferential strain readings at different pressure loads.

Since the Borre Probe incorporates three pairs of circumferential and axial strain gauges, three pairs of elastic property-values are obtained from each biaxial test. The aim is to obtain rock parameters that apply to the relaxation experienced by the rock during overcoring. Therefore, the values of E and ν are taken to be secant values, calculated from strain data obtained during unloading of the core specimen.

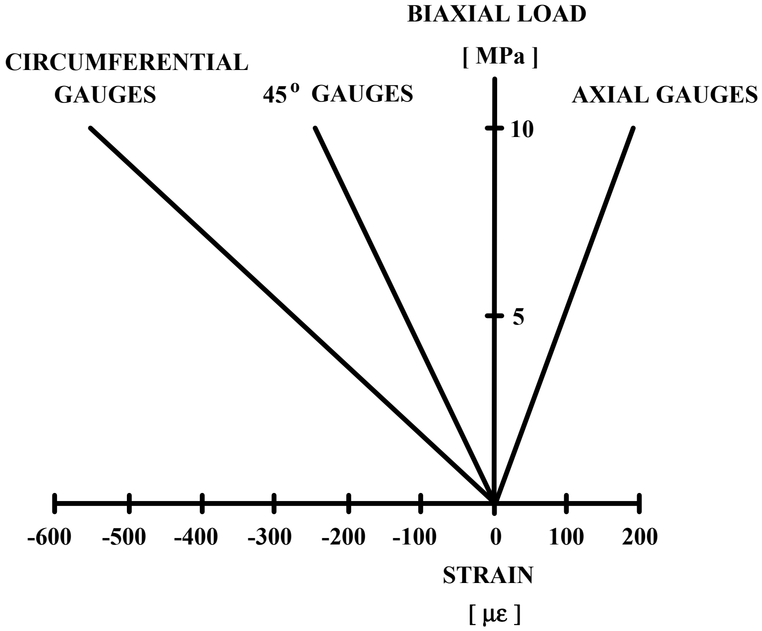


Figure 2-2. Hypothetical results from biaxial testing of an ideal linearly elastic material using the gauge configuration of the overcoring test .

2.3 Data reduction

The equations relating the strains occurring at the pilot hole wall as a consequence of overcoring, to the virgin stress field at the point of measurement are obtained from the classical Kirsch solution given in Jaeger and Cook, 1979. For isotropic material, the appropriate set of equations were presented by Leeman, 1968.

The program to calculate the stress tensor is based on the equations given by Leeman, 1968. To calculate the three-dimensional stress at a measuring point the program requires strain data from at least six independent directions (as described above), the orientation of the borehole, the orientation (magnetic bearing) of the Borre Probe and the elastic constants of the rock (Young's modulus and Poisson's ratio).

When all nine gauges function properly during a measurement, redundant strain data are obtained. The stress calculation program uses a least square regression procedure to find the solution best fitting all the strain data. From this solution, the program calculates the stress field in the horizontal plane and the magnitude and orientation of each of the three principal stresses. If more than one measurement has been carried out at the same level in a borehole, the program can be set to define all measurements in one and the same coordinate system and calculates mean values of the three dimensional stress field.

3 Field work

3.1 Prototype repository

The field work in the Prototype Repository started on September 27, 1997 and was completed on October 8, 1997. The measurement work went on smoothly.

Measurements were conducted in borehole KA3579G, drilled vertically from the floor in the TBM excavated tunnel at the 450 m level, Figure 1-1.

The coordinates at the top of borehole KA3579G, given in the Äspö local coordinate system, and the borehole orientation are the following:

x-coordinate:	7274.422
y-coordinate:	1886.684
z-coordinate:	-448.366
Bearing (gon):	296.6°
Dip (degrees):	-89.4°

It should be noted that dip is calculated positive from the horisontal and upwards, and bearing is calculated clockwise from the Äspö x-axis (local north). The bearing of the Äspö local x-axis is 12° west of the true magnetic North. The Prototype Repository Tunnel strikes 82° west of the local north.

Within the Prototype Repository, Äspö diorite is the dominating rock type. Fine grained granite, greenstone and pegmatite also occur (Patel, Dahlström and Stenberg, 1997). Detailed mapping by Patel op.cit. show that WNW trending, steep dipping joints are most frequent in the Prototype Repository area.

Overall a good rock quality was noticed. During the course of measurements in borehole KA3579A only a few the intended measurement positions were discarded due to healed or preexisting fractures at the intended gauge locations.

3.2 K- tunnel

The K-tunnel stress measurements were conducted during two separate phases; the first period occurred between March 17-24, 1998 whereas the second field period started on August 4, 1998 and was completed on August 12, 1998. The reason for the disrupted test sequence was that other tests had to be carried out during summer while conditions were more or less undisturbed around the K-tunnel.

The test equipment functioned well. Except for an electrical problem on the drill rig causing a stand-by at the very beginning of the first field period, the work went on uninterrupted.

Measurements were conducted in borehole KK0045G01. The hole is drilled from the floor of the K-tunnel at the 415 m level. For location of the borehole Figure 1-1 should be consulted.

The coordinates, given in the Äspö local coordinate system, and orientation data of borehole KK045G01 are the following:

x-coordinate: 7236.838
y-coordinate: 2259.527
z-coordinate: -416.356
Bearing (gon): 0°
Dip (degrees): -90°

It should be noted that dip is calculated positive from the horizontal and upwards, and bearing is calculated clockwise from the Äspö x-axis (local north). The K-tunnel strikes 64º east of the local north.

The K-tunnel is located in a rock dominated by Äspö diorite (65%). Green stone (20%), fine grained granite (10%) and pegmatite (5%) also occur (Hardenby, 1998). Detailed mapping show two major fracture systems in the K-tunnel area, one trending NW-WNW with steeply dipping joints towards NE, the other striking N-NNE with a steep dip towards east.

While drilling, borehole KK0045G01 penetrated into poor rock on occasion rendering twelve pilot boreholes to be discarded. A distinct and rather extensive fracture zone was encountered around hole depth 52 m when extending the borehole between test levels 2 and 3. The discontinuities influenced the qualities of pilot holes for the next 10 m and thus, the location of final test sequence had to be moved further away from the K-tunnel than originally planned.

4 Prototype repository results

4.1 General test data

The measurements in borehole KA3579G included a total of 11 tests of which 10 have yielded successful results. Table 4-1 summarizes the general information from all 11 measuring points.

Seven of the overcoring tests were located within 8 meters distance from the tunnel floor, Level 1 in Table 4-1. Six of these tests yielded results which have been included in the evaluation of stresses. Four other successful tests were located more than 20 meters away from the tunnel where rock conditions were unaffected by the presence of the excavation, Level 2. These four results are considered representative for the primary stress field at the corresponding depth, approximately 470 m below ground level. The strain gauge response curves registered during the overcoring process are presented in Appendix 1.

Table 4-1. General test data from measurements in PRT borehole KA3579G.

Level No.	Measuring point No.	Hole depth (m)	Comment	Incl. in Evaluation	Rock type
1	1	0.88	Test failed	No	-
1	2	2.04	Test OK	Yes	*Äspö diorite*
1	3	2.53	Test OK	Yes	Diorite
1	4	3.99	Test OK	Yes	Diorite
1	5	4.54	Unstable	Yes	Diorite
1	6	5.41	Unstable	Yes	Diorite
1	7	8.00	Test OK	Yes	Diorite
2	8	20.06	Test OK	Yes	Diorite
2	9	21.21	Test OK	Yes	Diorite
2	10	21.70	Test OK	Yes	Diorite
2	11	22.31	Test OK	Yes	Diorite

Note: Hole depth calculated from the tunnel floor.

4.2 Biaxial testing

All suitable overcore rock samples were tested in the biaxial cell to deter-mine the elastic properties. The gauge response-curves from these tests are given in Appendix 2. Table 4-2 shows the values of E and ν as interpreted from the biaxial tests. The elastic parameters were determined using the secant method from the unloading part of the biaxial testing curves.

Table 4-2. Results from biaxial tests on overcore rock samples from PRT borehole KA3579G. Only tests from successful stress measurement points are presented.

Level No.	Measuring point No./ Test No.	Hole depth (m)	Young's modulus, E [GPa]	Poisson's ratio, ν
1	1	0.88	-	-
1	2	2.04	(104)	(0.3)
1	3	2.53	(99)	(0.3)
1	4	3.99	63	0.24
1	5	4.54	(88)	(0.3)
1	6	5.41	55	0.23
1	7	8.00	66	0.27
2	8	20.06	73	0.30
2	9	21.21	73	0.30
2	10	21.70	73	0.26
2	11	22.31	65	0.30
	Average:		***67***	***0.27***

Note: Hole depth calculated from the tunnel floor.

From the biaxial testing it can be seen that the elastic parameters given by tests No. 2, 3 and 5 are unexpectedly high. Rock mechanical testing of Äspö diorite samples in the uniaxial compressive mode performed by Stille and Olsson (1996), gave a mean value on the Young's modulus equal to 73 GPa (interval 65-80) and a mean Poisson´s ratio equal to 0.24 (interval 0.22-0.29). Excluding tests No. 2, 3 and 5 in the KA3579G test series, mean values from the biaxial testing were $E = 67$ GPa and $\nu = 0.27$, Table 4-2. (Taking into account all biaxial tests performed on samples from KA3579G the mean values were $E = 76$ GPa and $\nu = 0.28$.)

As the rock type at the locations of test No. 2, 3 and 5 does not differ from that at the other test locations in KA3579G, the measured E and ν for these three measuring points were discarded in further processing of the data. Instead, the mean values of $E = 67$ GPa and $\nu = 0.27$ have been used in the stress calculation for tests No. 2, 3 and 5.

4.3 Primary stress field

The results from hole depths greater than 20 m in borehole KA3579G are supposed to represent the primary (undisturbed) stress situation at approximately 470 m depth. For the primary stress field the results are given in Table 4-3 through 4-5. A graphical presentation of the principal stress orientations found for the primary stress field is given in Figure 4-1.

Table 4-3. Primary stress field, PRT borehole KA3579G: Principal stress magnitudes as determined by overcoring.

Level No.	Measuring point No. / Test No.	Hole depth (m)	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)
2	8	20.06	34.5	17.6	11.4
2	9	21.21	29.0	15.1	11.0
2	10	21.70	43.7	20.5	15.8
2	11	22.31	30.4	18.2	12.7
	470 m lev. ave.		***34.2***	***17.7***	***13.1***

The average magnitudes for the primary stress field have been obtained by transformation of all applicable results to one common coordinate system, and then solving the average stress tensor for its eigen values.

Table 4-4. Primary stress field, PRT borehole KA3579G: Principal stress orientations as determined by overcoring. Orientations are given as trend/plunge of the stress vectors σ1, σ2 and σ3, respectively.

Level No.	Measuring point No.	Hole depth (m)	σ_1 Trend/pl.	σ_2 Trend/pl.	σ_3 Trend/pl.
2	8	20.06	138/01	034/86	229/04
2	9	21.21	150/00	240/60	060/30
2	10	21.70	135/02	238/80	044/09
2	11	22.31	145/10	276/76	053/11
	470 m lev. ave.		***141/03***	***245/80***	***050/10***

Note: Strike is calculated clockwise from the bearing of the local north of the Äspö local coordinate system (local north is 12º west of true magnetic north). Plunge is defined as being zero in the horizontal plane.

Table 4-5. Primary stress field, PRT borehole KA3579G: The horizontal - and vertical stress state as determined by overcoring.

Level No.	Measuring point No.	Hole depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)	Trend σ_H (º clockwise fr. local north)
2	8	20.06	34.5	11.4	17.5	138
2	9	21.21	29.0	12.0	14.1	150
2	10	21.70	43.6	15.9	20.5	135
2	11	22.31	30.1	12.9	18.3	144
	470 m lev. ave.		***34.1***	***13.3***	***17.6***	***141***

N/A Not applicable. Trend is calculated clockwise from the bearing of the local north.

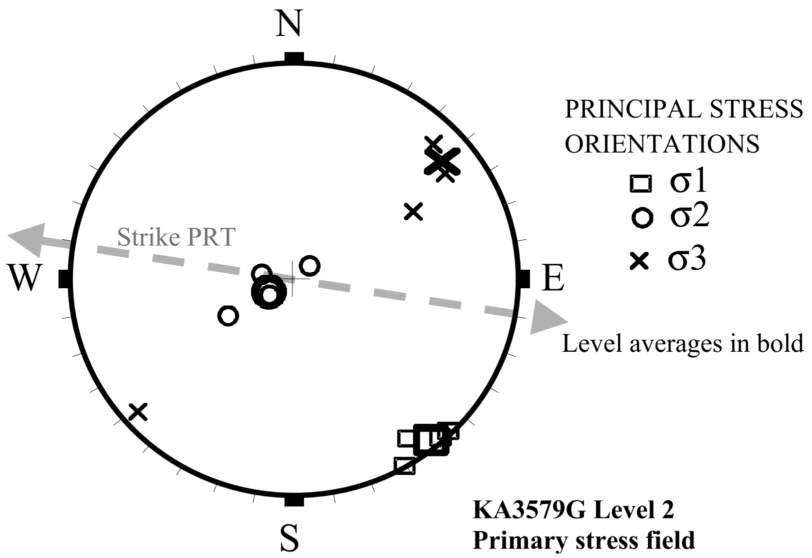


***Figure 4-1**. <u>Primary stress field, PRT borehole KA3579G</u>: Principal stress directions for test points located in undisturbed rock. Lower hemisphere, schematic plot. North refers to local north (Äspö x-axis). Data taken from Table 4-4. Tunnel strike 278°.*

4.3.1 Comments on the results – Primary stress field

- The magnitudes of all principal stresses show results that should be expected at these depths, Table 4-3. With a maximum value around 43 MPa at one measuring point, σ_1 averages around 34 MPa. The relationship σ_1/σ_2 is roughly 1.9 whereas $\sigma_1/\sigma_3 = 2.6$.
- Both the maximum and minimum principal stresses are close to horizontal; σ_1 trends 141° east of local north, Table 4-2 and Figure 4-1, and acts on the tunnel at a 45°-angle. The intermediate principal stress, σ_2, is nearly vertical.
- Average magnitudes in the vertical- and horizontal plane are: $\sigma_H = 34$ MPa, $\sigma_h = 13$ MPa, and $\sigma_v = 18$ MPa, Table 4-5. It is noted that the magnitude of σ_v is 40% higher than the stress corresponding to the overburden pressure.
- The direction of σ_H is uniform, Table 4-5. Transformed with respect to magnetic north the results yield a NW-SE direction for the maximum horizontal stress.

4.4 Near-tunnel stress field

For the near-tunnel stress field measured in borehole KA3579G the results are given in Table 4-6 through 4-8. A graphical presentation of the principal stress orientations measured in the test points located within 2-8 m from the tunnel floor is given in Figure 4-2.

Table 4-6. Near-tunnel stress field, PRT borehole KA3579G: Principal stress magnitudes as determined by overcoring.

Level No.	Measuring point No.	Hole depth (m)	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)
1	2	2.04	21.9	7.5	1.1
1	3	2.53	18.9	5.3	-4.2
1	4	3.99	26.1	5.3	2.5
1	5	4.54	26.7	6.8	2.4
1	6	5.41	26.1	10.6	8.1
1	7	8.00	26.7	14.8	13.1

Table 4-7. Near-tunnel stress field, PRT borehole KA3579G: Principal stress orientations as determined by overcoring. Orientations are given as trend/plunge of the stress vectors σ1, σ2 and σ3.

Level No.	Measuring point No.	Hole depth (m)	σ_1 Trend/pl.	σ_2 Trend/pl.	σ_3 Trend/pl.
1	2	2.04	321/01	229/53	052/37
1	3	2.53	325/03	227/71	056/19
1	4	3.99	335/19	210/59	073/24
1	5	4.54	320/24	201/48	066/32
1	6	5.41	323/23	198/54	065/26
1	7	8.00	327/18	074/42	220/43

Note: Trend is calculated clockwise from the bearing of the x-axis in the Äspö local coordinate system (local x-axis is 12º west of true magnetic north). Plunge is defined as being zero in the horizontal plane.

Table 4-8. Near-tunnel stress field, PRT borehole KA3579G: The horizontal- and vertical stress state as determined by overcoring.

Level No.	Measuring point No.	Hole depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)	Trend σ_H (º clockwise fr. local north)
1	2	2.04	21.9	3.4	5.1	141
1	3	2.53	18.8	-3.2	4.3	146
1	4	3.99	23.9	3.0	7.0	156
1	5	4.54	23.3	3.8	8.8	143
1	6	5.41	23.8	8.7	12.4	145
1	7	8.00	25.5	13.9	15.1	146

Note: Trend is calculated clockwise from the bearing of the local north of the Äspö local coordinate system (local north is 12º west of true magnetic north).

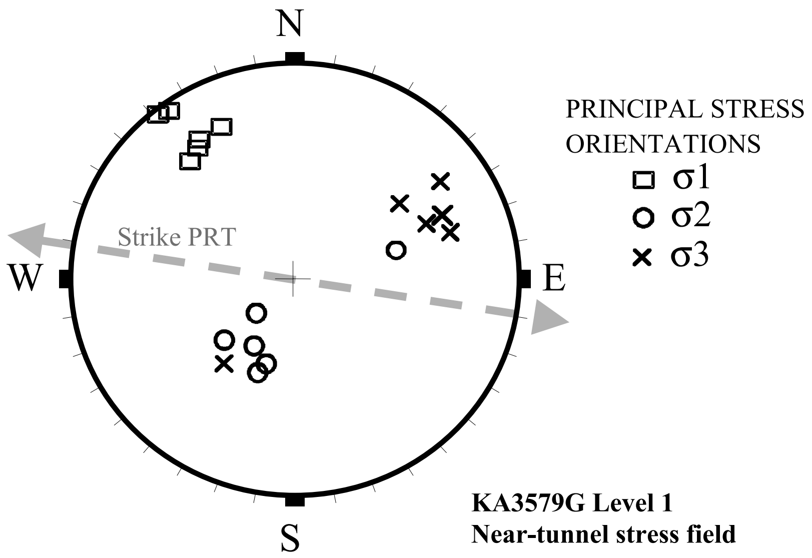


Figure 4-2. *Near-tunnel stress field, PRT borehole KA3579G: Principal stress directions for test points located in undisturbed rock. Lower hemisphere, schematic plot. North refers to local north. Data taken from Table 4-7. Tunnel strike 278°.*

Figure 4.3 illustrates the horizontal - and vertical stress state in the rock adjacent to the tunnel floor. For comparison, the lower half of the 5 m diameter TBM K-tunnel is shown in the figure.

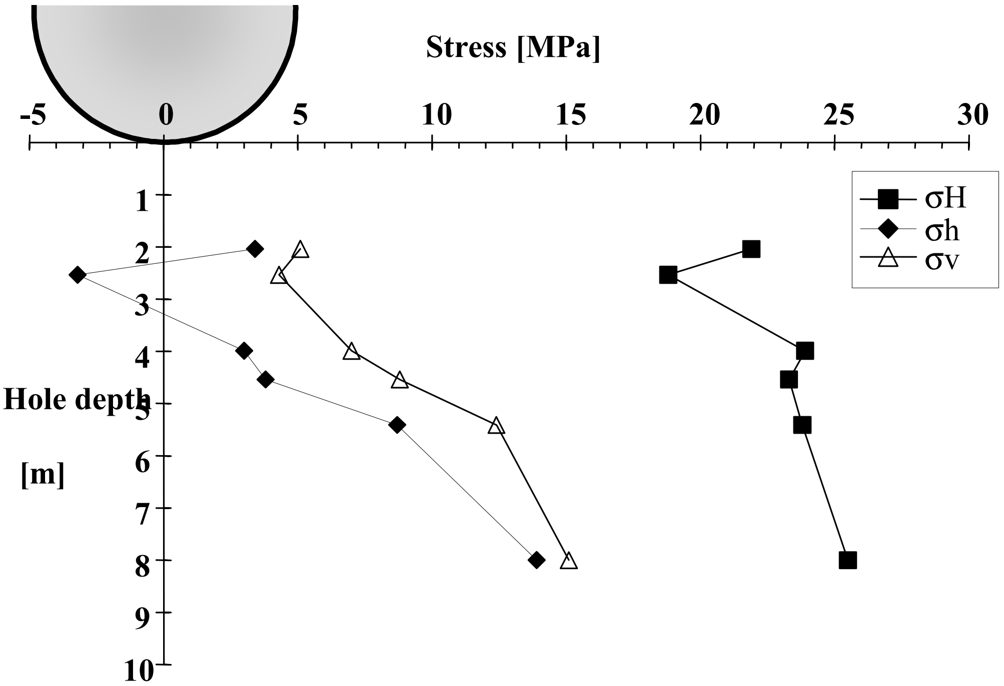


Figure 4-3. *Near-tunnel stress field, PRT borehole KA3579G: Vertical- and horizontal stresses as function of depth within the borehole section 0-10 m below the TBM tunnel.*

4.4.1 Comments on the results – Near-tunnel stress field

- The maximum principal stress, σ_1, has a considerably low magnitude throughout the depth interval, Table 4-6. The σ_1-magnitude seems more affected by the tunnel excavation in two tests within the first 2.5 m of the borehole, but stabilizes around 26 MPa at deeper measuring points.

- The maximum principal stress, σ_1, show a distinct trend roughly 30º-40º west of the local north, Table 4-7 and Figure 4-2. It is noted that the stress vector is more or less horizontal in the two test points closest to the tunnel floor. A bit further out, in the four test points between hole depths 4 m and 8 m, the stress vector has an approximate 20º plunge, Table 4-7. Overall, σ_1 has a 50º-angle to the PRT in the horizontal, Figure 4-2.

- The minimum- and intermediate principal stresses are influenced and the magnitudes are reduced by the presence of the tunnel. In the zone 2-5 m out from the tunnel the magnitudes are conspicuously low, Table 4-6. The relationship σ_1/σ_3 rapidly decreases from 10 to 3 in the interval 4-6 m away from the tunnel.

- σ_2 and σ_3 both have an inclined orientation. σ_2 is most steep with a plunge of around 55º, Table 4-7 and Figure 4-2. The results in measuring point No. 7 (8.00 m) reveal a switch in the orientations of σ_2 and σ_3 as compared to other tests. This phenomenon is not uncommon when magnitudes for the intermediate and minimum stresses are alike, Table 4-6.

- The direction of σ_H is uniform. Data from all tests cluster around 35º west of the local north. Transformed with respect to magnetic north the results yield a distinct a NW-SE direction for the maximum horizontal stress.

- The magnitudes of the minimum horizontal stress, σ_h, and the vertical stress, σ_v, are strongly affected by the presence of the tunnel, Table 4-8 and Figure 4-3. For the test points closest to the TBM-excavation the reduction in magnitude is generally 50% for σ_v and as much as 75% for σ_h. Measuring point No. 7 yields a magnitude of σ_v, which is higher than the theoretical value, ρgz. The effect on the maximum horizontal stress, σ_H, is small.

- Stress magnitudes increase when moving away from the TBM tunnel, Figure 4-3.

4.5 Concluding remarks

As regards the primary stress field measured in the PRT borehole, the scatter in magnitude between individual measuring points is what should be expected from the measurement technique is used.

The stress orientations show a clear trend and repeatability between neighboring measuring points is good in the undisturbed rock mass as well as within the zone near the tunnel.

The results representing the primary stress field show higher magnitudes for all stresses compared to those near the tunnel, Table 4-3 and 4-6. Overcoring data indicate that the excavation yields a destressed area extending some 5 to 10 m around it.

The stresses measured in the near-tunnel stress field display an overall increase with distance from the TBM excavation, Figure 4-3.

The transition from the inside to the outside of the zone influenced by the excavation does not change the direction of the maximum horizontal stress. As is illustrated in Figure 4-4 below, the direction is distinct at NW-SE.

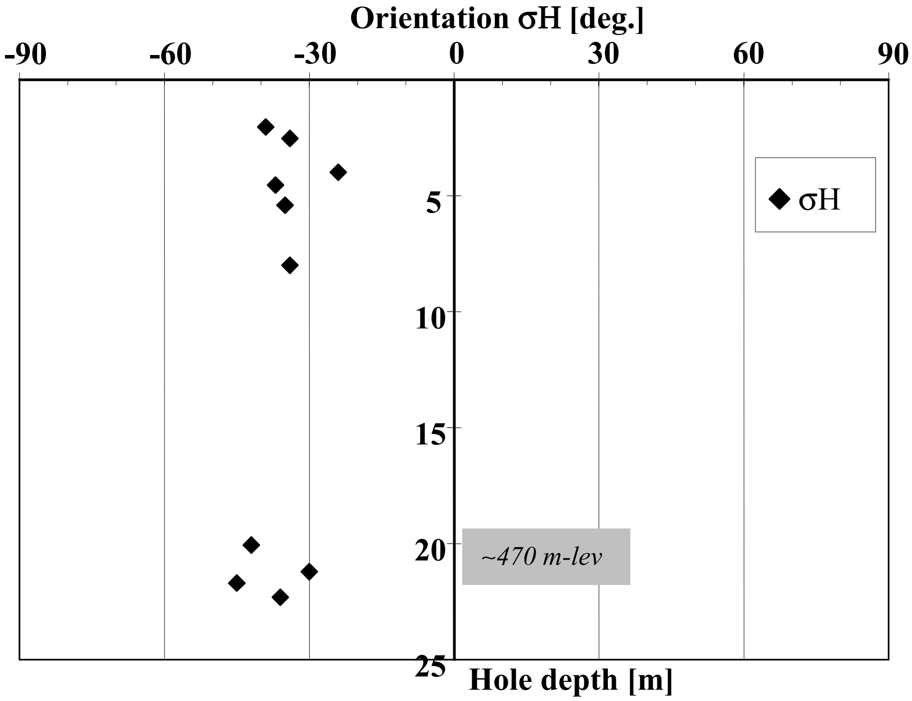


Figure 4-4. *Orientation of the maximum horizontal stress,* σ_H*, as referred to local north, PRT borehole KA3579G.*

5 K- tunnel results

5.1 General test data

The measurements in borehole KK0045G01 included a total of 19 tests of which 16 have yielded successful results. For practical reasons the tests attempted within the range 10 m from the tunnel opening have been taken as part of Level 1, whereas Level 2 and Level 3 are situated in the undisturbed rock mass around hole depths 30 and 60 m, respectively. Table 5-1 summarizes the general information from all 19 measuring attempts.

Seven overcoring tests were performed within 5 meters distance from the tunnel floor. Of these, six were successful. All four test attempts within the depth interval 5-10 m rendered reliable results.

Five tests at Level 2 gave reason to believe that three successful results had been collected. Later however, when studying the overcore samples more thoroughly, it was found that one strain rosette was misplaced with respect to the other two strain rosettes. This was strain rosette #1 in measuring point No. 1, 31.67 m, Table 5-1. It was concluded most probable that the holder of the rosette #1 had become bent during installation of the Borre probe. The offset of rosette #1 from its normal location was 10º-15º. A sensitivity analysis on the offest effect based on a 12.5º offset was conducted by Ask, 2000. The analysis concluded that the misplacement had the largest effect on σ_1 and σ_2, that the effect was greater on the magnitudes than on the orientation of principal stresses, the errors were within the uncertainty limit (<15%) stated by SwedPower AB for the Borre measuring technique from the true value.

Using a stereographic plot it could be shown that the stress vectors from measuring point No. 1 on test level 31.67 m were disoriented about 60° compared to the vector orientations from the other test levels within the primary stress field. SwedPower's conclusion was that the considerable dislocation of stress vector orientations in this particular measuring point originated from gauge offset, and that the discrete results could not be taken to represent the prevailing state of stress. It was thus decided to discard the data from measuring point No. 1 in the following stress calculations.

On Level 3, three consecutive tests gave reason to conclude the stress state at that depth. The strain gauge response curves registered during the overcoring tests in borehole KK0045G01 are presented in Appendix 3.

Table 5-1. General test data from measurements in borehole KK0045G01.

Level No.	Measuring point No.	Hole depth (m)	Comments	Incl. in Evaluation	Rock type
1	1	1.20	Test OK	Yes	*Äspö diorite*
1	2	2.24	Test OK	Yes	*Äspö diorite*
1	3	2.70	Test OK	Yes	*Äspö diorite*
1	4	3.33	Test OK	Yes	*Äspö diorite*
1	5	4.12	Test OK	Yes	*Äspö diorite*
1	6	4.53	Test OK	Yes	*Äspö diorite*
1	7	4.97	Unstable	No	*Äspö diorite*
1	8	5.51	Test OK	Yes	*Äspö diorite*
1	9	6.07	Test OK	Yes	*Äspö diorite*
1	10	6.50	Test OK	Yes	*Äspö diorite*
1	11	8.16	Test OK	Yes	*Äspö diorite*
2	1	31.67	Test OK	No	*Äspö diorite*
2	2	32.48	Unstable	No	*Äspö diorite*
2	3	33.35	Unstable	No	*Äspö diorite*
2	4	34.77	Test OK	Yes	*Äspö diorite*
2	5	35.48	Test OK	Yes	*Äspö diorite*
3	6	62.82	Test OK	Yes	*Äspö diorite*
3	7	63.59	Test OK	Yes	*Äspö diorite*
3	8	64.51	Test OK	Yes	*Äspö diorite*

Note: Hole depth calculated from the tunnel floor in the K-tunnel.

5.2 Biaxial testing

All suitable overcore rock samples were tested in the biaxial cell to determine the elastic properties. The gauge response-curves from these tests are given in Appendix 4.

Table 5-2 show the values of E and ν as interpreted from the biaxial tests. The elastic parameters were determined using the secant method from the unloading part of the biaxial testing curves.

Table 5-2. Results from biaxial tests on overcore rock samples from borehole KK0045G01. Only tests from successful stress measurement points are presented.

Level No.	Measuring point No. / Test No.	Hole depth (m)	Young's modulus, E [GPa]	Poisson's ratio, ν
1	1	1.20	64	0.24
1	2	2.24	59	0.24
1	3	2.70	54	0.24
1	4	3.33	54	0.30
1	6	4.53	64	0.26
1	8	5.51	63	0.27
1	9	6.07	45	0.22
1	10	6.50	45	0.19
1	11	8.16	53	0.29
2	1	31.67	52	0.22
2	2	32.48	59	0.29
2	4	34.77	66	0.26
2	5	35.48	56	0.17
3	1	62.82	65	0.26
3	2	63.59	55	0.20
3	3	64.51	55	0.19
	Average:		***57***	***0.24***

All tests show relatively low values for Young's modulus with an average E=57 GPa, Table 5-2. This value should be compared to E=73 GPa derived from rock mechanical testing in uniaxial compressive mode on Äspö diorite by Stille and Olsson (1996). The biaxial test average for Poisson's ration is ν=0.24 which is equal to that reported by Stille and Olsson.

For the evaluation of rock stresses at those test points where the quality of the overcored sample has rendered biaxial testing impossible (such as measuring point No. 5 at 4.12 m, Table 5-6), the mean values of E and ν from all successful biaxial tests, Table 5-2, have been utilized in the stress calculations.

5.3 Primary stress field

For the primary stress field measured in borehole KK0045G01 the results are presented in Table 5-3 through 5-5. A graphical presentation of the principal stress orientations is found in Figure 5-1. Results reflect the stress field at depths of around 450 m and 480 m below ground level, Figure 1-1.

Table 5-3. Primary stress field, borehole KK0045G01: Principal stress magnitudes as determined by overcoring.

Level No.	Measuring point No.	Hole Depth (m)	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)
2	4	34.77	26.1	17.3	8.9
2	5	35.48	18.1	12.3	5.0
	450 m lev. ave.		***22.0***	***14.8***	***7.1***
3	1	62.82	28.4	13.9	5.9
3	2	63.59	23.6	16.8	10.4
3	3	64.51	33.4	20.3	12.2
	480 m lev. ave.		***27.4***	***17.1***	***10.4***

N/A Not applicable

Table 5-4. Primary stress field, borehole KK0045G01: Principal stress orientations as determined by overcoring. Orientations are given as trend/plunge of the stress vectors σ1, σ2 and σ3.

Level No.	Measuring point No.	Hole depth (m)	σ_1 Trend/pl.	σ_2 Trend/pl.	σ_3 Trend/pl.
2	4	34.77	147/39	031/28	276/38
2	5	35.48	144/29	031/36	263/41
	450 m lev. ave.		***146/35***	***030/32***	***270/39***
3	1	62.82	119/02	027/51	211/39
3	2	63.59	130/23	014/45	238/36
3	3	64.51	119/34	012/24	254/46
	480 m lev. ave.		***122/20***	***012/43***	***230/40***

N/A Not applicable

Note: Trend is calculated clockwise from the bearing of the local north of the Äspö local coordinate system (local north is 12° west of true magnetic north). Plunge is defined as being zero in the horizontal plane.

Table 5-5. Primary stress field, borehole KK0045G01: The horizontal - and vertical stress state as determined by overcoring.

Level No.	Measuring point No.	Hole depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)	Trend σ_H (º clockwise fr. local north)
2	4	34.77	21.4	13.2	17.7	166
2	5	35.48	16.2	8.6	10.5	158
	450 m lev. ave.		***18.8***	***11.0***	***14.1***	***162***
3	1	62.82	28.4	9.0	10.8	120
3	2	63.59	22.3	12.8	15.7	138
3	3	64.51	27.8	18.0	20.1	131
	480 m lev. ave.		***25.9***	***13.5***	***15.5***	***127***

Note: The trend of σ_H is calculated in degrees clockwise from the local north.

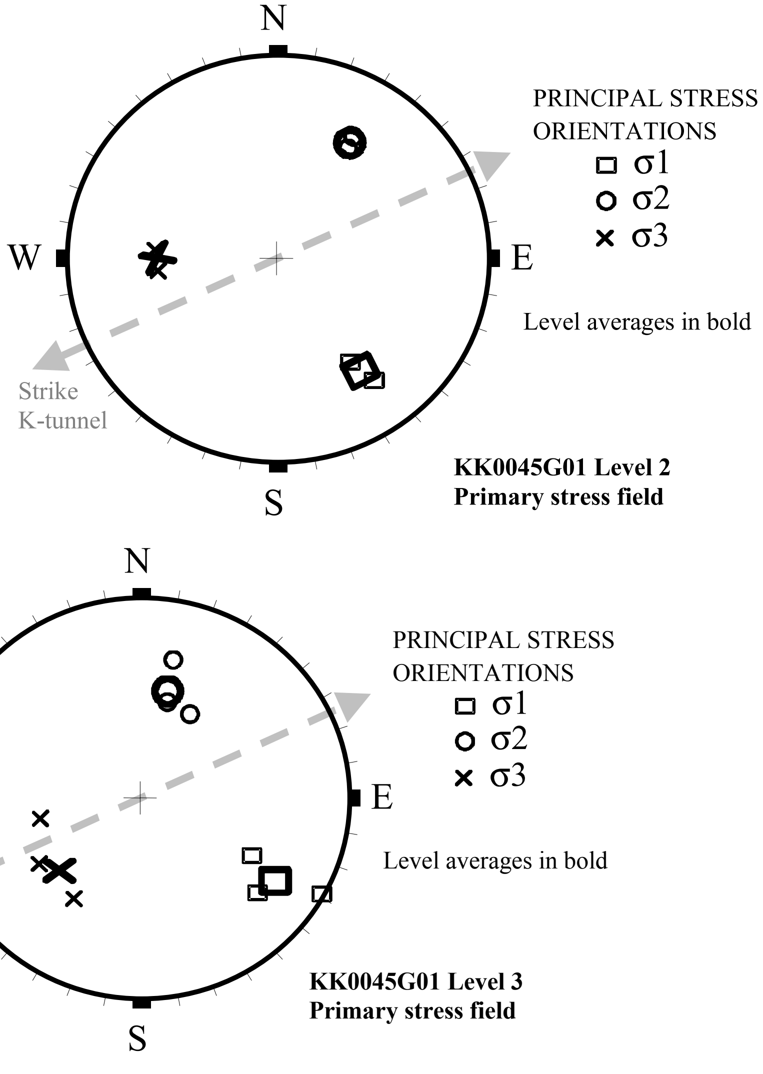


Figure 5-1. *Primary stress field, borehole KK0045G01: Principal stress directions for test points located in undisturbed rock. Lower hemisphere, schematic plot. North refers to local north (Äspö x-axis). Data taken from Table 5-4. Tunnel strike 244º.*

5.3.1 Comments on the results – Primary stress field

- The magnitude of the maximum principal stress, σ_1, is rather low at both depths; it averages 22 MPa at 450 m below ground level and around 27 MPa at 480 m, Table 5-3. For the primary stress field measured the relationship σ_1/σ_2=1.5-1.6 whereas σ_1/σ_3 is 2.6-3.0.
- None of the principal stresses is horizontal or vertical. The stress orientations also vary between measurement levels. σ_1 trends 146° east of local north at the 450 m level, but seems to rotate anti-clockwise with depth ending up at 122° at the deeper level, Figure 5-1.
- or both levels the average magnitude of the maximum horizontal stress, σ_H, is low compared to other measurements at similar depth. At the 450 m level it is around 19 MPa which is low, and 30 m further down σ_H increases to 26 MPa. The minimum horizontal stress measures 12-13 MPa in the undisturbed rock mass. σ_v averages around 14-16 MPa, which is 20-30% higher than expected from the weight of overburden at these depths.
- With respect to data from individual measuring points, Table 5-5, the direction of σ_H varies between measurement levels. However, a NW-SE direction for the maximum horizontal stress is outlined. This is roughly perpendicular to the strike of the K-tunnel, 244°.

5.4 Near-tunnel stress field

For the near-tunnel stress field measured in borehole KK0045G01 the results are given in Table 5-6 through 5-8. A graphical presentation of the principal stress orientations measured in the test points located within 1 m to 9 m from the tunnel floor is given in Figure 5-2.

Table 5-6. Near-tunnel stress field, borehole KK0045G01: Principal stress magnitudes as determined by overcoring.

Level No.	Measuring point No.	Hole depth (m)	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)
1	1	1.20	41.0	9.8	4.9
1	2	2.24	17.5	4.9	0.8
1	3	2.70	18.8	9.8	5.2
1	4	3.33	17.3	6.8	4.0
1	5	4.12	15.3	7.4	3.9
1	6	4.53	20.1	14.6	11.1
1	8	5.51	24.1	11.0	8.3
1	9	6.07	17.2	8.6	4.6
1	10	6.50	14.2	5.5	5.1
1	11	8.16	15.1	6.4	3.2

Table 5-7. Near-tunnel stress field, borehole KK0045G01: Principal stress orientations as determined by overcoring. Orientations are given as trend/plunge of the stress vectors $\sigma1$, $\sigma2$ and $\sigma3$.

Level No.	Measuring point No.	Hole depth (m)	σ_1 Trend/pl.	σ_2 Trend/pl.	σ_3 Trend/pl.
1	1	1.20	090/05	180/02	293/84
1	2	2.24	140/05	230/01	330/85
1	3	2.70	324/28	063/17	181/56
1	4	3.33	323/05	056/25	222/64
1	5	4.12	137/17	044/12	282/69
1	6	4.53	134/07	036/50	229/40
1	8	5.51	128/27	356/52	232/24
1	9	6.07	323/23	075/41	212/40
1	10	6.50	334/00	244/35	064/55
1	11	8.16	332/18	117/68	238/12

Note: Trend is calculated clockwise from the bearing of the local north of the Äspö local coordinate system (local north is 12° west of true magnetic north). Plunge is defined as being zero in the horizontal plane.

Table 5-8. Near-tunnel stress field, borehole KK0045G01: The horizontal - and vertical stress state as determined by overcoring.

Level No.	Measuring point No.	Hole depth (m)	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)	σ_H (° clockwise fr. local north)
1	1	1.20	40.7	9.7	4.9	090
1	2	2.24	17.4	4.9	0.9	140
1	3	2.70	15.9	9.2	8.7	138
1	4	3.33	17.2	6.3	4.6	143
1	5	4.12	14.3	7.2	5.1	139
1	6	4.53	20.0	12.5	13.3	135
1	8	5.51	21.3	8.9	13.3	130
1	9	6.07	15.6	6.5	8.3	138
1	10	6.50	14.2	5.4	5.2	154
1	11	8.16	14.2	3.3	7.1	151

Note: Trend of σ_H is calculated in degrees clockwise from the local north.

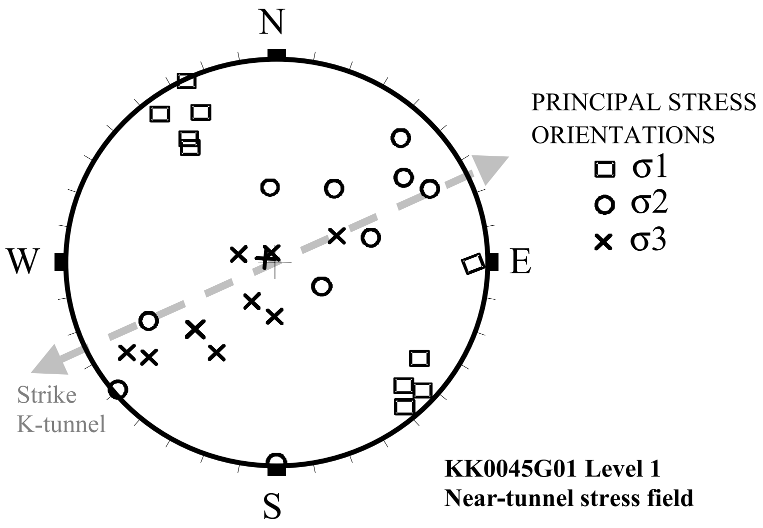


Figure 5-2. *Near-tunnel stress field, borehole KK0045G01: Principal stress directions for test points located in undisturbed rock. Lower hemisphere, schematic plot. North refers to local north. Data taken from Table 5-7. Tunnel strike 244º.*

Figure 5.3 illustrates the horizontal - and vertical stress state in the rock adjacent to the tunnel floor. For comparison, the lower part of the drill and blast, approximately 6.5 m wide K-tunnel is shown in the figure. Borehole KK0045G01 is located about 2.5 m from the left wall.

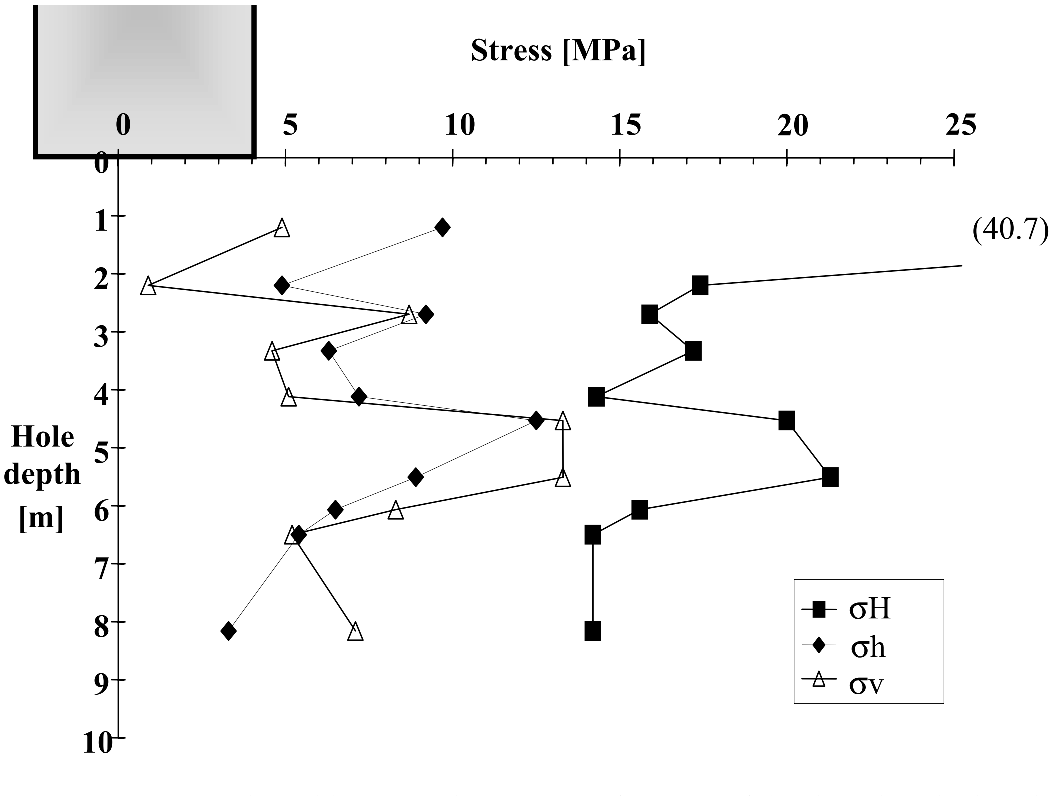


Figure 5-3. *Vertical- and horizontal stresses as function of depth within the borehole section 0-10 m below the tunnel floor, K-tunnel, borehole KK0045G01.*

5.4.1 Comments on the results – Near-tunnel stress field

- At measuring point no. 1, closest to the tunnel invert, the maximum principal stress, σ_1, is very high, 40.7 MPa. All other principal stresses show lower magnitudes within the depth interval 1-10 m, Table 5-6. At some test points magnitudes are considerably reduced compared to the primary stress field measured further away from the tunnel, Table 5-3. Close to the tunnel floor, σ_2 and σ_3 are more affected by the excavation than σ_1. Studying the near-tunnel stress field, data do not indicate that stress magnitudes recover when moving away from the tunnel, Figure 5-3.

- Excluding measuring point no. 1, σ_1 shows a distinct trend roughly 30°-40° west of the local north, Table 5-7 and Figure 5-2, and is near-horizontal. The orientations of the intermediate and minimum principal stresses display a wide scatter on the stereonet, Figure 5-2, trending from SW to NE (in relation to the local north). Data from test no. 1 display principal stress orientations which are governed by the excavation - σ_1 and σ_2 are horizontal whilst σ_3 is vertical, Table 5-7 and Figure 5-2. Similar data are found for test no. 2, but the directions differ some 40°.

- The direction of σ_H is concise around 40° west of the local north excluding data from test no. 1 at hole depth 1.2 m. Transformed with respect to magnetic north the results yield a NW-SE direction for the maximum horizontal stress.

- The magnitudes of the minimum horizontal stress, σ_h, and the vertical stress, σ_v, are low and scattered thus indicating influence from the drill-and-blast tunnel excavation on the stress field, Table 5-8 and Figure 5-3. At measuring point no. 1, 1.2 m from the invert, the maximum horizontal stress, σ_H, is increased.

5.5 Concluding remarks

For the primary stress field , the redundancy in stress orientation data is fair when Level 2 and Level 3 are compared, Figure 5-1. Neither of the principal stresses is horizontal or vertical. The redundancy between individual test points within each level is good. Regarding magnitude data, the principal stresses seem 20-40% higher on Level 3 than on Level 2, Table 5-3.

Moving from the near-tunnel stress field and away from the K-tunnel, there is a clear increase in magnitude for all principal stresses, Table 5-4 and Table 5-6. For σ_1 a distinct increase in magnitude can also be seen when comparing the data from Level 2 to those from Level 3. For the other two principal stresses, however, this growth is hardly detectable.

Within the near-tunnel stress field $\sigma_1$has a peak value at 40.7 MPa close to the tunnel floor and then drops to considerably lower magnitudes. No distinct stress increase is evident when judging from the data further away from the invert, Table 5-8 and Figure 5-3. The measurement results indicate that stresses are biased by the presence of the drill-and-blast tunnel at least within 10 m distance.

In Figure 5-2 the data for the maximum principal stress, σ_1, point out a distinct NW-SE orientation. Orientation data for the other two stresses are scattered, possibly indicating an influence from the K-tunnel above.

Except for the the shallowest test point, data from the near tunnel stress field data display a consistent trend around 40° west of the local north for the maximum horizontal stress, σ_H, Figure 5-4. On the 450 m-level, which should be governed by the primary stress field, the orientation data are more towards local north while at depth, on the and 480 m-level, results clearly indicate a NW-SE direction for σ_H.

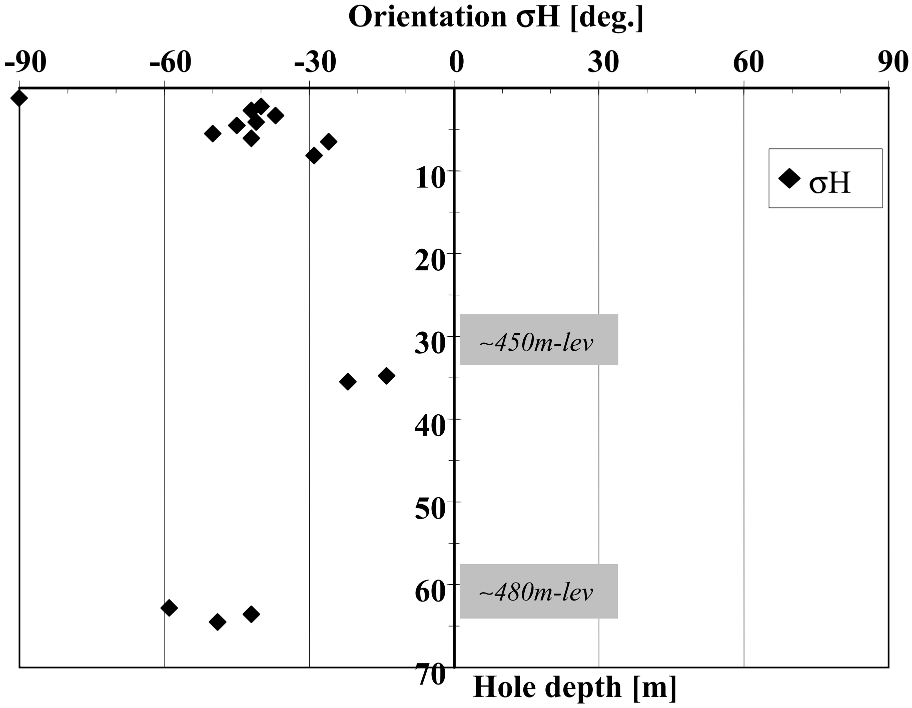


Figure 5-4. *Orientation of the maximum horizontal stress, σ_H, as referred to the orientation local north at Äspö, K-tunnel, borehole KK0045G01.*

6 Soures of errors and data confidence

When discussing the accuracy of a measurement result it must be distinguished between the degree of agreement between a measurement result and the real stress state in the point/location on one hand, and on the other hand, the representativity of the discrete measurement for the stress distribution in the rock mass. Here we only discuss the former issue.

The scatter in a result could arise from (i) measuring errors (systematic and non-systematic) attached to each test, (ii) true variations in the stress state along the borehole, or (iii) a combination of (i) and (ii).

By experience and testing it is known that instrument errors (that is; the difference between the actual strain subjected to a discrete gauge and the corresponding readout value) can be neglected for given circumstances. Temperature induced measuring errors have been found, given typical field conditions, to be less than ± 1 MPa (Leijon, 1988).

From measurements in rock that may be classified as almost ideal in the respect of homogeneity and linear elastic behavior etc. (i.e. uncertainties concerning Young's modulus can be neglected), it is known that the scatter in magnitude for a group of measurements at the same location is in the interval ± 1 MPa to ± 3 MPa for magnitudes in the order of 15 - 25 MPa. This spread can be regarded as a conservative estimate of the non-systematic measurements. As SwedPower have developed routines for a step-by-step process during measurements, there are no reasons to believe that systematic errors will add to these values. In this particular case the detection of the error introduced in the former stress calculation performed on PRT data, from which the present revision of results from the PRT measurements originated, called for a thorough scrutiny of all documentation from the PRT and the K-tunnel measurements. This examination has diminished any further systematic errors which may have been introduced in the measurement process. Hence, the interval ± 1 - 3 MPa is a conservative estimate of the total measurement error, keeping in mind the assumption that the rock allows for optimum measurement conditions.

The problem is then to estimate the errors introduced by the fact that the rock does not fulfill the assumptions of homogeneity and linear elastic behavior. By studying the results from the biaxial testing, Appendix B for borehole KA3579G and Appendix D for borehole KK045G01, it can be seen (in the strain gauge scale) that the material behaves in a varying manner, but on average is acceptable. The material defects consist of heterogeneity, unelasticity and in some cases non-linearity. All these factors do, of course, introduce errors. On the other hand, we know that the redundancy existing in each measurement and the calculation of mean values for locations subjected to the same loadings, effectively evens out the errors that can be related to heterogeneity.

Totally, it is judged that the errors in the results for a rock material which behaves almost ideally do not exceed 15%. This value shall be seen as a general judgement and no distinction is made between the different boreholes.

Regarding the introduction of incorrect input data into the stress calculation process, which occurred in a previous evaluation process of PRT data, it must be blamed on the human factor and the lack of a detailed checklist for the calculation procedure.

7 Diuscssion of the results

7.1 Near-tunnel stress field

One of the main purposes of the overcoring tests reported here was to study the influence from a TBM- vs. a drill-and-blast tunnel on stresses close to the tunnel perimeter/floor and the alteration in the stress state when moving away from the opening towards more undisturbed conditions. From the results reported here it is concluded that the influence from a TBM-excavation is much less than from a tunnel opening excavated using drill-and-blast technique. Figure 4-2 shows condense principal stress orientations for all test points close to the Prototype Repository TBM excavation. In Figure 4-3 a clear stress growth can be seen within 2-8 m from the TBM opening when moving away towards undisturbed conditions.

The results from measurements within the near-tunnel stress field around the drill-and-blast excavation (K-tunnel) point out disturbed conditions. The only parameter displaying some consistency is the orientation of the major principal stress, Figure 5-2, whereas the other two stresses are much scattered. The widely spread orientations for σ_2 and σ_3 measured 2-8 m below the invert of the drill-and-blast tunnel indicate influence from that tunnelling technique on the near-tunnel stress field. Moreover, magnitudes are generally low and data plotted in Figure 5-2 do not give reason to believe that magnitudes recover within the first 10 m when moving away from the excavation.

The test point located 1.2 m below the K-tunnel invert, indicates a peak magnitude at 41 MPa for σ_1 but not for the other two principal stresses. Here, σ_1 is more than twice the magnitude further away from the tunnel, Table 5-6. Data from this test point show that stress orientations and magnitudes are strongly governed by the excavation. The next data in the test series is from 2.24 m below the tunnel floor, where stress magnitudes were found to be considerably lower, $\sigma_1 = 17.5$ MPa. Thus, the test series lacks enough redundant data from adjacent test points to conclude a high stress magnitude around the K-tunnel perimeter.

Recently, Applied Seismology Consultants Ltd., 2000, have reported an analysis of the *in–situ* principal stress field using acoustic emission data around the Prototype Repository Tunnel. By applying an Examine^{3D} model to background data presented by Leijon, 1995, and referred to as “stress Field A”, the maximum principal stress, σ_1, has a maximum of 53 MPa in the roof and floor of the TBM excavation. The magnitude for σ_1 given by the overcoring measurements closest to the tunnel floor is less than 50% of that figure, Table 4-6. The discrepancy is large and is not explained by the fact that the first overcoring tests in the series were located some 2 m out from the tunnel perimeter. However, judging from data at 1.2 m distance from the K-tunnel invert, higher magnitudes should be expected close to the perimeter of the TBM-tunnel as well.

However, regarding the anticipated zone of high stresses in one direction around the tunnel excavation, the data conclude that the width of this zone is less than 2 m out from the tunnel perimeter. It is further indicated that the stress magnitude decrease rapidly within a distance 1.0-1.5 m out from the excavation.

7.2 Stress orientations

Overall, the principal stress orientations derived from the results, point out a clear trend and repeatability between neighboring measuring points on all measurement levels, with the exception of Level 1 in the K-tunnel borehole.

The average orientation of the maximum horizontal stress given by the least square regression analysis on the test conducted in the rock mass governed by the primary stress field indicate an overall (magnetic) NW-SE direction, Figure 4-4 and Figure 5-4. This is equivalent to a σ_H–direction trending 130º-140º east of local north in the undisturbed rock mass. The main part of stress measurements conducted at the Äspö site since 1988 recognize a NW-SE trend for σ_H.

For the primary stress field, the orientation of the maximum principal stress, σ_1, is directed towards the "local" NW. Based on PRT data σ_1 is more or less horizontal. In the K-tunnel, the average dip angle ranges from 20° (Level 3) to 35° (Level 2), Figure 5-1. The majority of other overcoring measurements conducted in undisturbed rock at Äspö have arrived at a dip angle of less than 30° from the horizontal for the maximum principal stress (Leijon, 1995).

7.3 The vertical stress

Overall, the overcoring results reported here show higher values for the primary vertical stress than what should be expected, Table 4-5 and Table 5-5. The excess is 25-40% compared to lithostatic values. In this case, when biaxial testing yield low to moderate values for Young's modulus, it is hard to find a sound explanation for an excessive magnitude in the vertical direction.

7.4 Biaxial tests

7.4.1 General

It is noted that for the overcore samples of diorite in the PRT (borehole KA3579G), the average Youngs's modulus is around 10 GPa higher than that concluded by biaxial tests on the diorite in the K-tunnel.

Stress calculations in this study utilized elastic constants determined by the secant method, c.f. Section 2.2.4, applied on the data during unloading of the overcored core in the biaxial test chamber. Normally, the secant method yields lower values for Young's modulus compared to the tangent method. A higher value on Young's modulus increases the stress magnitudes derived. The influence from Poisson's ratio on the stress magnitudes is such that the magnitudes increase progressively with increasing Poisson's ratio.

However, the value determined for Young's modulus has a greater impact on the stress magnitude than does the Poisson's ratio. From the 10-20 GPa difference found on tabulated values for Young's modulus for the Äspö diorite, it can be concluded that magnitudes increase about 20-30 % when the higher E-value is used.

The biaxial testing of the overcore samples were conducted applying a maximum confining pressure of 10 MPa. Ideally, the maximum pressure should correspond to the magnitude of the major principal stress, as it is of interest to cover the in-situ elastic behavior of the rock material as closely as possible. It was however judged that a 10 MPa limit should be set in order not to break the cores during pressurization, and thereby risking to not obtain any data at all for E and ν. It is believed that an increase in confining pressure to 20 MPa would only marginally affect the resulting elastic parameters.

7.4.2 Prototype Repository results

The biaxial tests gave mean values of E=67 GPa and ν=0.27 for the Äspö diorite in borehole KA3579. These figures coincide with results from Patel, Dahlström and Stenberg, 1997, which determined Young's Modulus, E=69 GPa and Poisson's Ratio, ν=0.25. However, for Young's modulus the value is lower than the average presented by Stille and Olsson, 1996, 73 GPa for Äspö diorite.

Using E^{50}=73 GPa and ν^{50}=0.28, determined for PRT core samples by uniaxial compression tests on core samples at the Luleå University of Technology and presented by Nordlund, Li and Carlsson, 1999, yield magnitudes 2-4 MPa higher than those reported here.

7.4.3 K-tunnel results

Biaxial tests gave mean values of E=57 GPa and ν=0.24 for the Äspö diorite in borehole KK045G01. The average for Poisson's ratio is equivalent to that presented for similar rock samples by Stille and Olsson, 1996. However, the value measured for Young's modulus in the biaxial tests is almost 20 GPa lower than that determined by Stille and Olsson, and more than 10 GPa lower than results from Patel et al., 1997. The reason for this is unclear. It is concluded however, that the main reason for the low magnitudes measured for the primary stress field below the K-tunnel, Table 5-3, is the fact that the biaxial tests displayed a low value for Young's modulus for the diorite in that borehole.

Assuming Young's modulus to be 10-20 GPa higher than given by the biaxial tests on the K-tunnel core samples, recalculation of the stresses yield the following magnitude increase on the 450 m- and 480 m-levels: σ_1 5-9 MPa, σ_2 3-6 MPa and σ_3 2-4 MPa.

7.5 Other

Detection of the mistake in handling of input data called for a detailed study of the all quality documents involved in the overcoring measurement program. This study has been executed at SwedPower AB and is now evaluated. It involved a step-by-step process comprising gauge handling, connecting of gauges to the Borre probe, connecting of gauges to the biaxial test data acquisition system, probe function tests, biaxial tests, data recovery, handling and processing of data, stress calculation etc. The outcome will be revised and more detailed checklists to aid the measurements as well as the data evaluation process. It stands clear however that if gauges, for some reason, are connected in an improper way; during preparation, to the probe or to the biaxial cell; such defective handling is discovered by the existing quality assurance program executed in the field, long before raw strain data are entered into calculations for the elastic parameters and/or the computerized stress calculation program.

8 Brief comparsion of overcoring results from the Äspö HRL

The stress magnitudes and orientations measured in boreholes at various locations down the Hard Rock Laboratory ramp have been summarized by Leijon, 1995. The compiled data could be taken to represent the stress tensor at approximately 420 m depth in the HRL.

Adding the PRT and K-tunnel results as well as the results from overcoring tests in the Zedex area (Ljunggren and Klasson, 1996) makes possible a brief comparison of all overcoring data for the primary stress field at depth in the Äspö HRL, Table 7-1 and Figure 7-1. It should be mentioned that the Zedex overcoring measurements were conducted in a horizontal borehole drilled from the Zedex tunnel located on the 420 m levele in-between the TBM-tunnel and the K-tunnel, Figure 1-1. The borehole KXZSD8HL was drilled towards the position of the K-tunnel before excavation started.

Table 7-1. Primary stress field: Summarized data from several overcoring measurements in the HRL ramp (Leijon, 1995), compared to data for the primary stress field, K-tunnel borehole KKG0045G01, PRT borehole KA3579G and Zedex borehole KXZSD8HL (Ljunggren and Klasson, 1996). Orientations given with respect to local north.

Stress component	Magnitude (MPa)	Trend (°)	Plunge (°)
σ_1 HRL, 420 m	32	131	0
σ_1 Zedex, 420 m	20	351	24
σ_1 K-tunnel, 450 m	22	146	35
σ_1 PRT, 470 m	34	141	3
σ_1 K-tunnel, 480 m	27	122	20
σ_2 HRL, 420 m	17	041	25
σ_2 Zedex, 420 m	9	230	49
σ_2 K-tunnel, 450 m	15	030	32
σ_2 PRT, 470 m	18	245	80
σ_2 K-tunnel, 480 m	17	012	43
σ_3 HRL, 420 m	10	229	65
σ_3 Zedex, 420 m	8	096	31
σ_3 K-tunnel, 450 m	7	270	39
σ_3 PRT, 470 m	13	050	10
σ_3 K-tunnel, 480 m	10	230	40

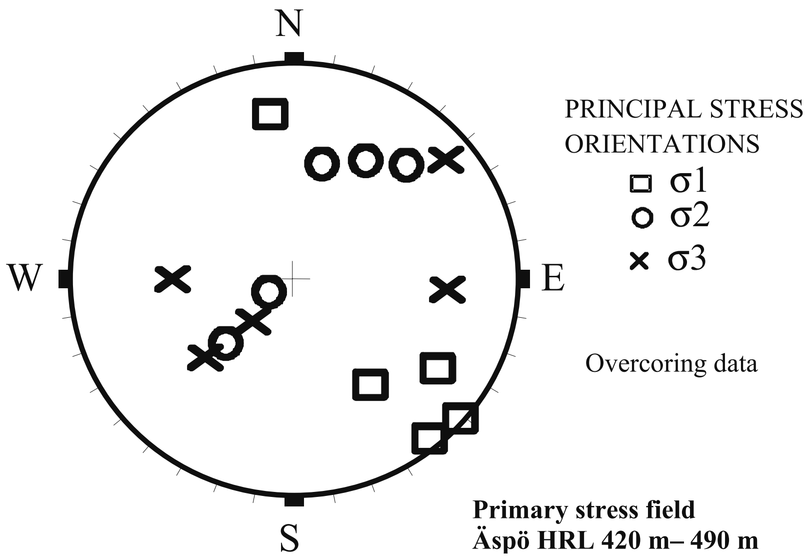


Figure 7-1. *Primary stress field, Äspö HRL 420 m-480 m level: Principal stress directions, level averages from test points located in the undisturbed rock mass. Lower hemisphere, schematic plot. North refers to local north. Data from Table 7-1.*

In Table 7-1 it can be seen that magnitudes for the major principal stress, σ_1, are scattered between 20 MPa and 35 MPa. On the other hand, magnitudes for the intermediate and minor principal stresses are similar when results from different sites are compared. A striking feature is the low magnitude measured for σ_2 (9 MPa) in the horizontal Zedex borehole at 420 m depth.

Figure 7-1 displays a some scatter in principal stress orientations with the majority of outliers represented by Zedex data. From the compound results, σ_1 is concluded to have a NW-SE trend in the undisturbed rock mass.

The outlier depicted for σ_1 in the Zedex horizontal borehole gives reason to believe that the borehole direction (horizontal vs. vertical) has an impact on the results. When comparing the results from the two vertical boreholes in the PRT and the K-tunnel to those from the Zedex borehole it seems as if the borehole orientation has an impact on the results, which cannot be neglected. This hypothesis is further supported by the comparatively low magnitude measured for σ_2 in the Zedex borehole.

Moreover, Ljunggren and Klasson, 1996, reported the vertical stress derived from the Zedex data being approximately 11 MPa and in accordance with the theoretical vertical stress at 420 m depth. Results for σ_v in the vertical boreholes drilled from the PRT- and K-tunnels arrive at magnitudes 25-40% higher than expected although E-values are low. These findings indicate that, depending on the purpose of three-dimensional overcoring measurements, great care should be taken when planning test programs, test locations and especially the orientation of the test boreholes.

9 General conclusions

The following general conclusions are drawn from the present work and comparison with results from earlier overcoring measurements within the Äspö HRL:

1. The primary stress field at depths between 420 m and 480 m can be described as:

   σ_1: 27 MPa ± 8 MPa

   σ_2: 17 MPa ± 2 MPa

   σ_3: 12 MPa ± 2 MPa

   σ_1 trends NW-SE and dips 0°-20° towards SE. The orientation of the other two principal stresses is unclear, but none of them seem to be strictly vertical or horizontal.

   The major horizontal stress, σ_H, has a NW-SE orientation. The magnitude of σ_H ranges between 18 MPa and 34 MPa.

2. The overcoring results obtained within 2-10 m distance from the Prototype Repository tunnel and the K-tunnel show that the influence on the stress field around a TBM excavation is much less than from a drill-and-blast tunnel. The stress growth around a TBM tunnel is immediate when moving away from the opening and stress orientations are consistent.

3. Though test data are insufficient to outline a zone of high stress around the tunnel excavation, the results show that the width of such a zone must be less than 2 m out from the tunnel perimeter. Data also indicate that stress magnitudes decrease rapidly within a distance 1.0-1.5 m out from the excavation.

4. Biaxial tests on overcore samples of Äspö diorite from the PRT and the K-tunnel boreholes show varying and generally low values on Young's modulus; 67 GPa in the PRT and 57 GPa in the K-tunnel. These values are 10-20 GPa lower than what was expected from previous tests on the same rock types. As the elastic parameters derived from the biaxial test were used in the calculation of stresses, the resulting magnitudes were generally lowered. This should be noted especially for the K-tunnel data.

5. Comparison to test results from a horizontal borehole drilled from the Zedex area into rock of virgin stresses, indicates that the borehole direction influence both the stress magnitudes and the stress orientations measured. Overall, the magnitude of vertical stress derived from tests conducted in vertical boreholes is often in excess when compared to theoretical lithostatic values. In the present work the excess is 25-40%.

10 References

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