Äspö Hard Rock Laboratory

Prototype Repository

Installations for measurements of flow into tunnels, water pressure in rock and hydromechanical responses in boreholes during operation phase

Patrik Alm

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SWECO VIAK

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SKB

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Abstract

The Prototype Repository is an international, EC-supported activity with the objective to investigate, on a full-scale, the integrated performance of engineered barriers and near-field rock of a simulated deep repository. This is done in crystalline rock regarding heat evolution, rock mechanics, water flow, water chemistry, gas evolution and microbial processes under natural and realistic conditions at approximately 450 m depth below the ground surface. The test site is a 65 m long TBM-bored drift from which six 1.75 m diameter deposition holes extended downwards to about 8 m depth in accordance with the KBS-3 concept. The test site is divided in two parts; an inner 40 m long section (Section I) with 4 deposition holes and an outer section (Section II) with two deposition holes. Stiff and tight plugs will separate the sections and Section II from the rest of the Äspö Hard Rock Laboratory.

A large number of boreholes have been drilled to characterize the rock mass. These boreholes will be used for the long-time monitoring of the Prototype Repository. Packers, 1-5 in each borehole, are installed to facilitate monitoring of the water pressure and water chemistry in borehole sections. Temperature and displacement sensors are installed in some of the boreholes sections. Tubes and cables from the borehole sections are lead to a nearby G-tunnel, where the pressure, displacement and temperature are measured and the water is sampled. Hydraulic tests will also be performed from the G-tunnel by flowing of borehole sections (one by one) and measuring the pressure responses.

This report describes the installations for measurements of flow into tunnels, water pressure in the rock and hydro mechanical responses in boreholes during operation phase.

Sammanfattning

Prototype Repository Project är ett internationellt, EC-stött projekt med syfte att i full skala undersöka den integrerade funktionen hos ingenjörs-barriärer och närfältsberg i ett simulerat slutförvar i kristallint berg med hänsyn till värmeutveckling, bergmekanik, vattengenomströmning, vattenkemi, gasbildning och mikrobiologi under naturliga och realistiska förhållanden på ca 450 m djup. Försöksplatsen är en 65 m lång TBM-borrad ort från vilken sex vertikala deponeringshål med 1.75 m diameter och 8 m djup borrats i enlighet med KBS-3 konceptet. Testplatsen är delad i två delar; en inre 40 m lång sektion (sektion I) med 4 deponeringshål och en yttre del (sektion II) med två deponeringshål. Stela och täta pluggar separerar sektionerna och sektion II från resten av Äspölaboratoriet.

Ett stort antal borrhål har borrats för att karakterisera berget. Dessa borrhål kommer att användas för långtidsmoniteringen av Prototyp förvaret. Manschetter, 1-5 i varje borrhål, har installerats för att möjliggöra instrumentering av vattentryck och vattenkemi i borrhålssektioner. Temperatur- och förskjutningsgivare är installerade i vissa borrhåls-sektioner. Tuber och kablar från borrhålssektionerna leds till en parallellt liggande tunnel, G-tunneln, där tryck, förskjutningar och temperatur mäts och vattenprov tas. Hydrauliska tester görs också från G-tunneln genom att flöda borrhålsektioner (en i taget) och mäta tryckresponserna.

Denna rapport beskriver installationer för mätning av inflöde till tunnelsystemet, vattentrycket i berget and hydromekaniska deformationer i borrhål under driftfasen av Prototyp-förvaret.

Executive Summary

The Prototype Repository is an international, EC-supported activity with the objective to investigate, on a full-scale, the integrated performance of engineered barriers and near-field rock of a simulated deep repository. This is done in crystalline rock regarding heat evolution, rock mechanics, water flow, water chemistry, gas evolution and microbial processes under natural and realistic conditions at approximately 450 m depth below the ground surface. The test site is a 65 m long TBM-bored drift from which six 1.75m diameter deposition holes extended downwards to about 8 m depth in accordance with the KBS-3 concept. The test site is divided in two parts; an inner 40 m long section (Section I) with 4 deposition holes and an outer section (Section II) with two deposition holes. Stiff and tight plugs will separate the sections and Section II from the rest of the Äspö Hard Rock Laboratory.

A large number of boreholes have been drilled to characterize the rock mass. These boreholes will be used for the long-time monitoring of the Prototype Repository. Packers, 1-5 in each borehole, are installed to facilitate monitoring of the water pressure and water chemistry in borehole sections. Temperature and displacement sensors are installed in some of the boreholes sections. Tubes and cables from the borehole sections are lead to a nearby G-tunnel, where the pressure, displacement and temperature are measured and the water is sampled. Hydraulic tests will also be performed from the G-tunnel by flowing of borehole sections (one by one) and measuring the pressure responses.

During the characterisation of the rock around the Prototype Repository a large number of core boreholes have been drilled. Most of these boreholes has been equipped with packer systems to allow for:

- Pressure measurements

- Water sampling

- Dilution measurements

- Interference tests

- Hydro mechanical measurements (HM) and tests

This report describes the installations for measurements of flow into tunnels, water pressure in the rock and hydro mechanical responses in boreholes during operation phase.

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1 Background

1.1 Äspö Hard Rock Laboratory

To prepare for the location of a site and licensing of a spent fuel repository SKB has constructed an underground research laboratory.

In the autumn of 1990, SKB began the construction of Äspö Hard Rock Laboratory (Äspö HRL), see Figure 1-1, near Oskarshamn in the south-eastern part of Sweden. A 3.6 km long tunnel was excavated in crystalline rock down to a depth of approximately 460 m, see Figure 1-2.

The laboratory was completed in 1995 and research concerning the disposal of nuclear waste in crystalline rock has since then been carried on.

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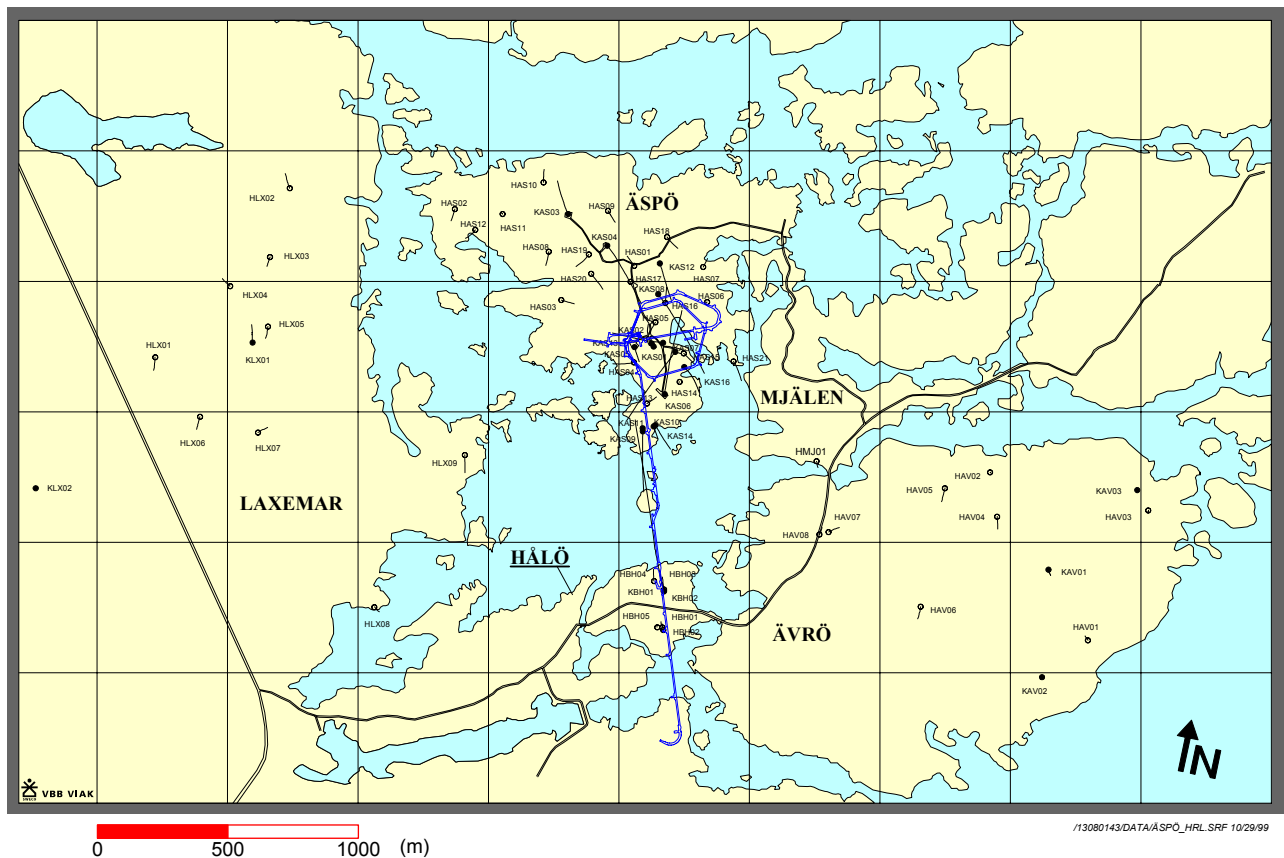
Figure 1-1 Plan view of Äspö Hard Rock Laboratory.

Prototype Repository
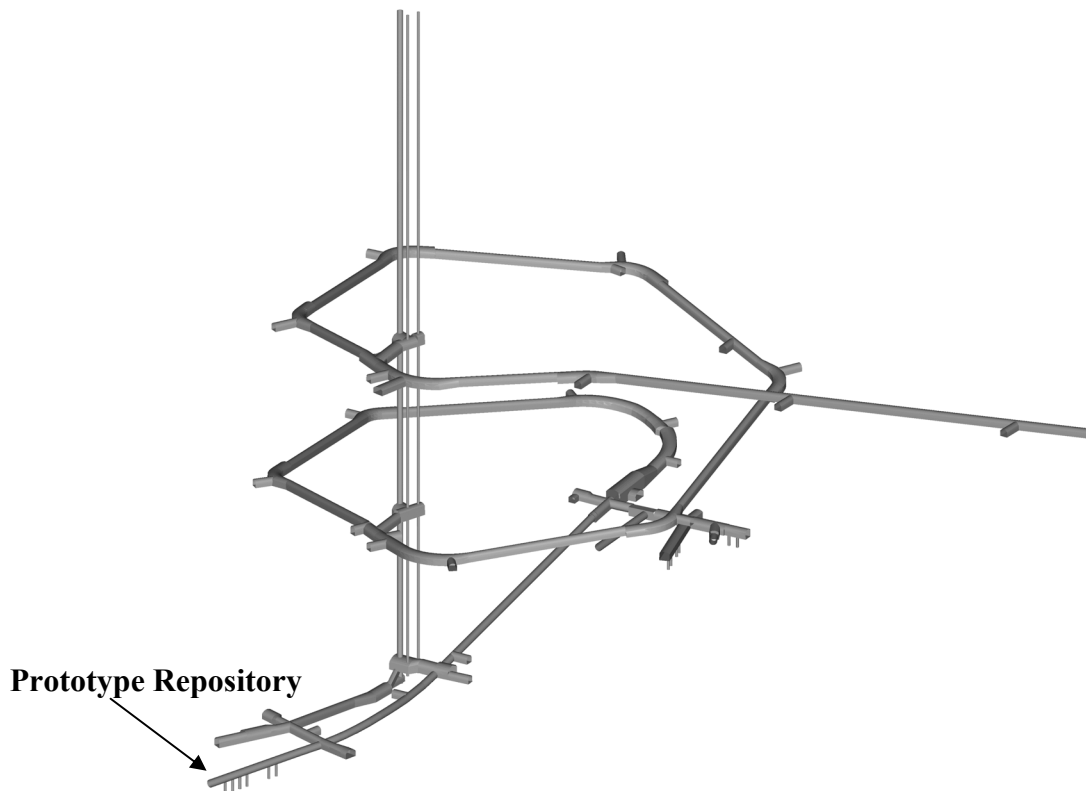
Figure 1-2 *Overview of the Äspö tunnel. The Prototype Repository is located at 450 m depth below the ground surface. The vertical lines show the elevator and ventilation shafts from the ground surface.*

1.2   Prototype Repository

The Äspö Hard Rock Laboratory is an essential part of the research, development, and demonstration work performed by SKB in preparation for construction and operation of the deep repository for spent fuel. Within the scope of the SKB program for RD&D 1995, SKB has decided to carry out a project with the designation "Prototype Repository Test". The aim of the project is to test important components in the SKB deep repository system on a full scale and in a realistic environment.

The Prototype Repository Test is focused on testing and demonstrating the function of the SKB deep repository system. Activities aimed at contributing to development and testing of the practical, engineering measures required to rationally perform the steps of a deposition sequence are also included. However, efforts in this direction are limited, since these matters are addressed in the Demonstration of Repository Technology project and to some extent in the Backfill and Plug Test.

Project plan and project description of the Prototype Repository are described in *Svemar and Pusch (2000)* and *Persson and Broman (2000)*.

1.2.1   General objectives

The Prototype Repository should simulate as many aspects as possible of a real repository, for example regarding geometry, materials, and rock environment. The Prototype Repository is a demonstration of the integrated function of the repository components. Results will be compared with models and assumptions to their validity.

The major objectives for the Prototype Repository are:

- To simulate part of future KBS-3 deep repository to the extent possible regarding geometry, design, materials, construction and rock environment except that radioactive waste is simulated by electric heaters.

- To test and demonstrate the integrated function of the repository components under realistic conditions on a full scale.

- To develop, test and demonstrate appropriate engineering standards and quality assurance methods.

- To accomplish confidence building as the capability of modelling EBS performance.

The objectives for the characterisation program are:

- To provide a basis for determination of location of the deposition holes.

- To provide data on boundary and rock conditions for enabling the interpretation of the experimental data.

1.2.2   Objectives with this report

The objectives with this report is to present a summary of the all hydro related instrumentation in the prototype repository area.
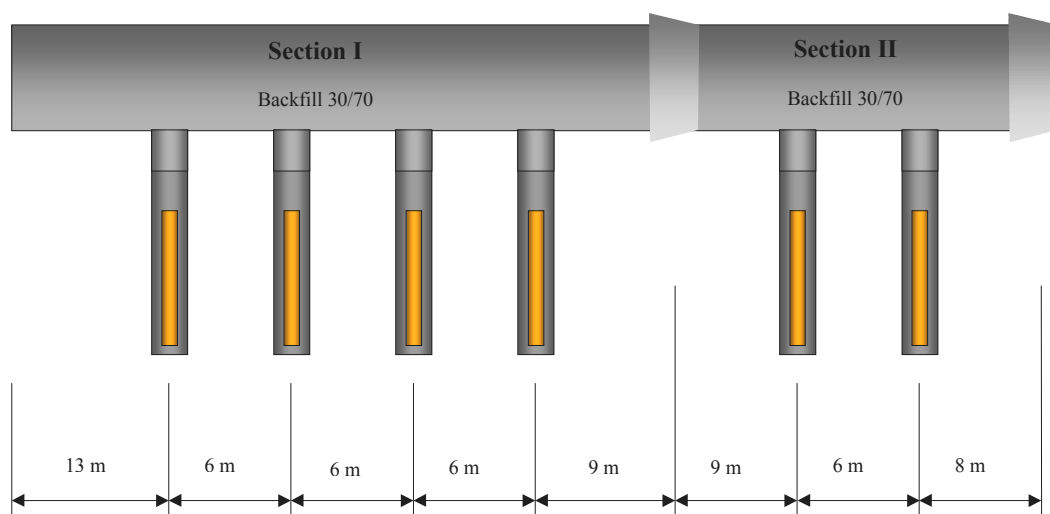
Figure 1-3 *Schematic view of the layout of the Prototype Repository and deposition holes (not to scale).*

2 Equipment and instrumentation of boreholes

During the characterisation of the rock around the Prototype Repository a large number of core boreholes have been drilled, see Figure 2-1*(Rhén et al, 1997), (Rhén, Forsmark, 1998a, 1998b), (Forsmark, Rhén, 1999), (Rhén, Alm, 2004)*. Most of these boreholes has been equipped with packer systems to allow for:

- Pressure measurements
- Water sampling
- Dilution measurements
- Interference tests
- Hydro mechanical measurements (HM) and tests

In some of the boreholes temperature measurements will be made. Below is an overview of the instrumentation given:

Section I (Rhen et al, 2001)   (No of)
- Bentonite packers (1-2 m long, 2-5 packers in each 8-50 m borehole):   49
- Mechanical packers (1 in each 2 m borehole, stainless):   16
- Pressure measurement sections: 65
- Circulation sections (two tubes):   5
- Flow sections (one-two tube-s):   7
- Hydro chemical sections: 6
- HM sections: 0

Section II*(Rhén et al, 2003)*   (No of)
- Inflatable packers (1m long, 1-5 in each 3-30 m borehole):   46
- Mechanical packers (one in each 2 m borehole, stainless):   6
- Pressure measurement sections :   52
- Circulation sections: 10
- Flow (one tube):   3
- Hydro chemical sections: 0
- HM sections (same as circulation sections):   10

G-tunnel+KA3510A01
- Inflatable packers (1m long, 5 in each 49-150 m borehole):   15
- Pressure measurements sections (5 in each borehole):   15
- Circulation sections (holes from G-tunnel):   2

- Flow (one tube, KA3510A01): 1

- Hydro chemical sections (holes from G-tunnel): 2

- HM sections (reference in G-tunnel, the north tunnel wall): 1

The tube types between and from packers will be according to below:

- Pressure: Polyamide

- Groundwater flow (Dilution measurements):
    - Circulation (two pipes):   Polyamide
    - Pressure: Polyamide

- Hydro chemical
    - Flow: PEEK
    - Pressure: Polyamide
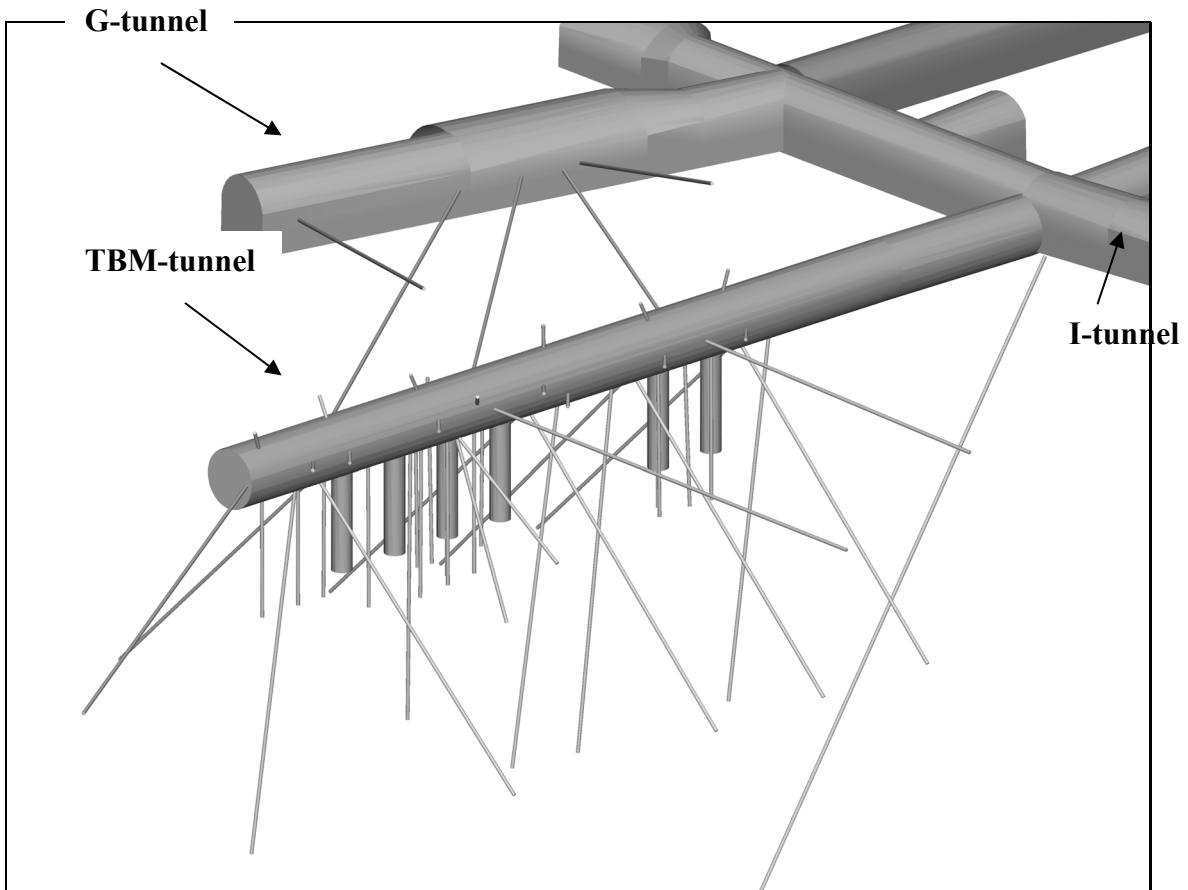
Figure 2-1 *View of the drilled core holes in the Prototype Repository. The length from the I-tunnel to the end of the TBM-tunnel is 90 m. The diameter of the TBM tunnel is 5m and the diameter of the deposition holes is 1.75 m. The depth of the deposition holes is 8.37 m in the centre and 8.15 m along the deposition hole wall. The diameter of the core holes is 76 mm except for the short core holes in the roof of the TBM tunnel that have a diameter of 56 mm.*

3 Geological description of HM and C sections

The detailed mapping of the Prototype tunnel was first presented in *Patel et al (1997)*. The fracture network for DFN modelling was analysed in *Hermansson et al (1999)* and later updated in *Stigsson et al (2001)*. Below is a brief description of the geology in the Prototype Repository area.

3.1 Geology and fractures

3.1.1 Geology

The mapping of the TBM tunnel between chainage 3500 and 3600 meter shows that the main rock type is Äspö diorite with veins and inclusions of fine-grained granite and greenstone.

3.1.2 Fractures in general

The mapped fractures from exploratory boreholes was analysed in *Stigsson et al (2001)*. The analyse showed that there are at least two major fracture sets, one that is sub-horizontal and one steep that strike north-west. A third steep north-east set has also been vaguely noticed. A lower hemisphere projection plot is presented in *Stigsson et al (2001)*, see Figure 3-1.
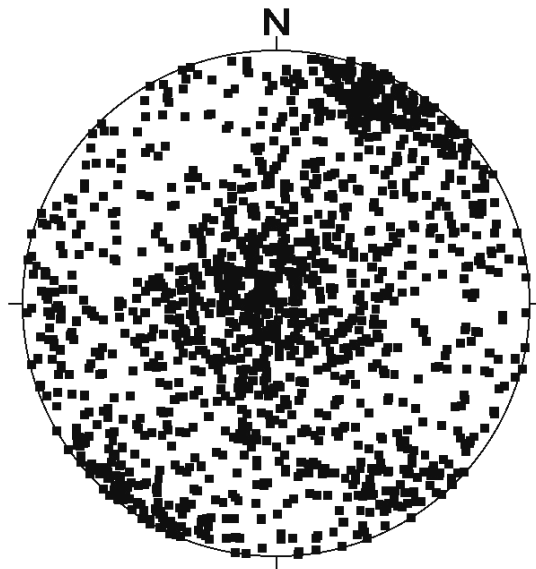
***Figure 3-1** Lower hemisphere projection of poles to fracture planes in the 36 bore- and exploratory holes.*

The north-west set is also the dominating direction of fracture at Äspö. Several tests have indicated that fracture sets and structures that strikes north-west are more hydraulically active.

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3.1.3 Selected fractures

The purpose of the hydro mechanical measurements is to see how the fractures and intact rock as well as the water flow behave during an increase in stress. For this purpose the following criteria has to be fulfilled

- The fractures should be water bearing

- There should be enough intact rock on both sides of the fracture

- The fracture should intersect the borehole as perpendicular as possible

- The measurement sections should be equally distributed in the rock volume

The fractures were selected by analysing the results from both flow tests (conducted in the boreholes) and core mapping.

Ten measurement sections (or fractures) that fulfilled the criteria were selected (see Table 3-1). In Figure 3-2 the location of the measurement sections compared to the tunnel and deposition holes is shown. In Figure 3-3 the lower hemisphere projection of the fractures is presented.

Table 3-1   Strike and dip of the investigated fractures. ID numbers of the fracture correspond to the number in Figure 3-2 and Figure 3-3.

Borehole	No. of fractures	ID (see figure)	Strike	Dip	Conductivity	Distance to frac. above	Distance to frac. beneath	Section
KA3539G	2	1	195	59	10^{-6}	~5	3	16.86
		2	53	27				16.87
KA3542G01	1	3	136	87	10^{-7}	0.77	1.85	19.27
KA3542G02	1	4	135	82	10^{-9}	3.53	0.7	26.6
KA3544G01	2	5	115	25	10^{-8}	5.73	0.76	9.92
KA3546G01	2	6	278	24	10^{-9}	1.52	0.61	7.77
		7	305	14		0.61	1.30	8.38
KA3548A01	2	8	303	76	10^{-7}	1.7	0.07	9.8
		9	108	82		0.07	0.16	9.87
KA3550G01	6	10			10^{-9}			6.19-6.62
KA3552G01	2	11	193	44	10^{-9}	0.89	1.13	5.04
KA3554G01	2	12	313	90	10^{-7}	~3.5	0.12	23.64
		13	308	86		0.12	0.47	23.76
KA3554G02	1	14	145	85	10^{-7}	2.17	1.45	11.2
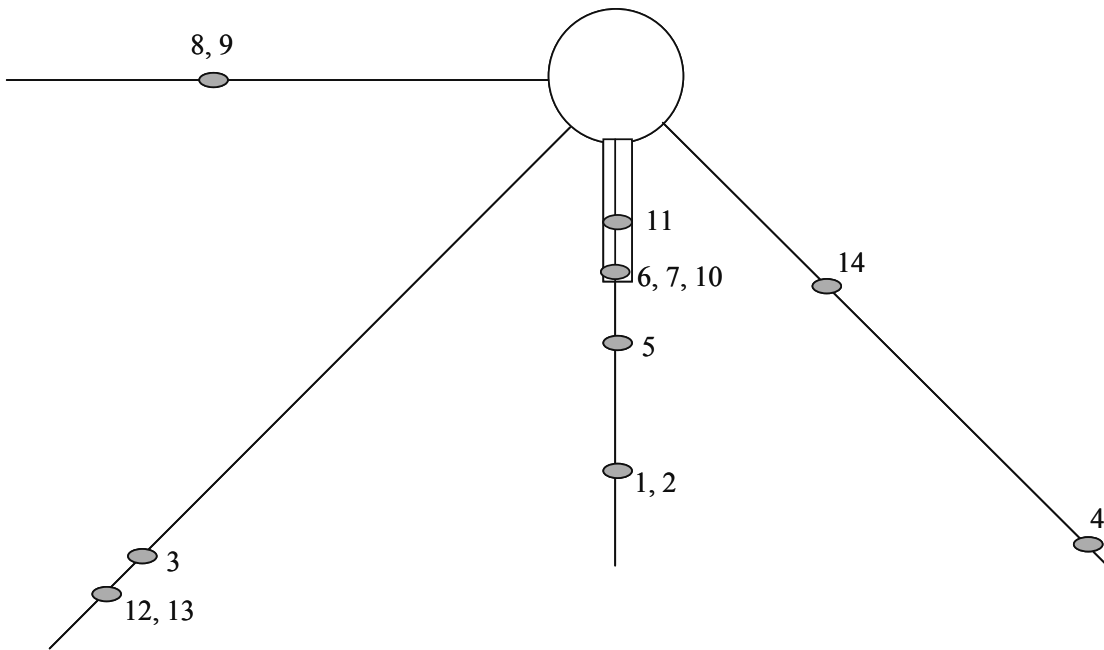
Figure 3-2 *The figure shows where the hydro-mechanical sections are situated in relation to the TBM tunnel. The viewpoint is placed in the I-tunnel and looking into the TBM-tunnel. The figures correspond to ID number in Table 3-1.*
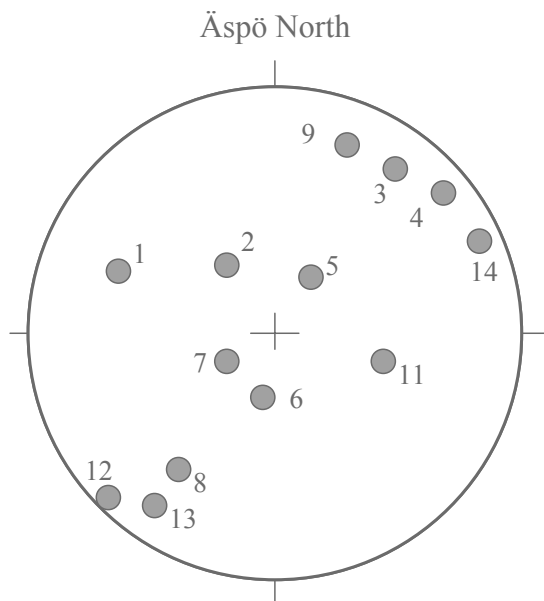
Figure 3-3 *Lower hemisphere projection of poles of the fracture planes reported in Table 3-1.*

4 Deformation measurements

4.1 Introduction

In order to investigate the hydro mechanical response of the fractures as a result of the increased thermal load, two different approaches are considered.

The first approach is to measure the change of the fracture width as function of temperature and time. As pointed out in Chapter 3.1.3 the displacement is both measured for the intact rock and for a section with one or more fractures, see Figure 4-4.

The second approach implies that the mechanical response is evaluated indirect by using the results from hydraulic tests. Hydro tests will be performed in the same sections as the mechanical measurements are made, see Chapter 2.

Displacement measurements will be made continuously. Hydraulic tests will be performed a number of times during the operation period for the ten measurement sections. Most tests will be made during the first years of operation when the largest displacements are expected.

In this section the first approach will be considered.

4.2 Measurement equipment

In order to measure the fracture deformation (and to separate the fracture deformation from the deformation of the intact rock) due to the increased temperature measurement equipment has been developed.

The equipment consists of two hydraulic packers, which hydraulically isolate the test section. Between the packers three anchors are placed. These anchors are fixed to the borehole wall with fixed steel pins and are fully disconnected to the centre rod. Between the anchors sensors (strain gage) are mounted. The section between the fixed steel pins is called *mechanical measurement sections*. The sensors will register any relative movement between the anchors (see Figure 4-1 and Figure 4-2). The temperature is also measured in each sensor by a thermistor.
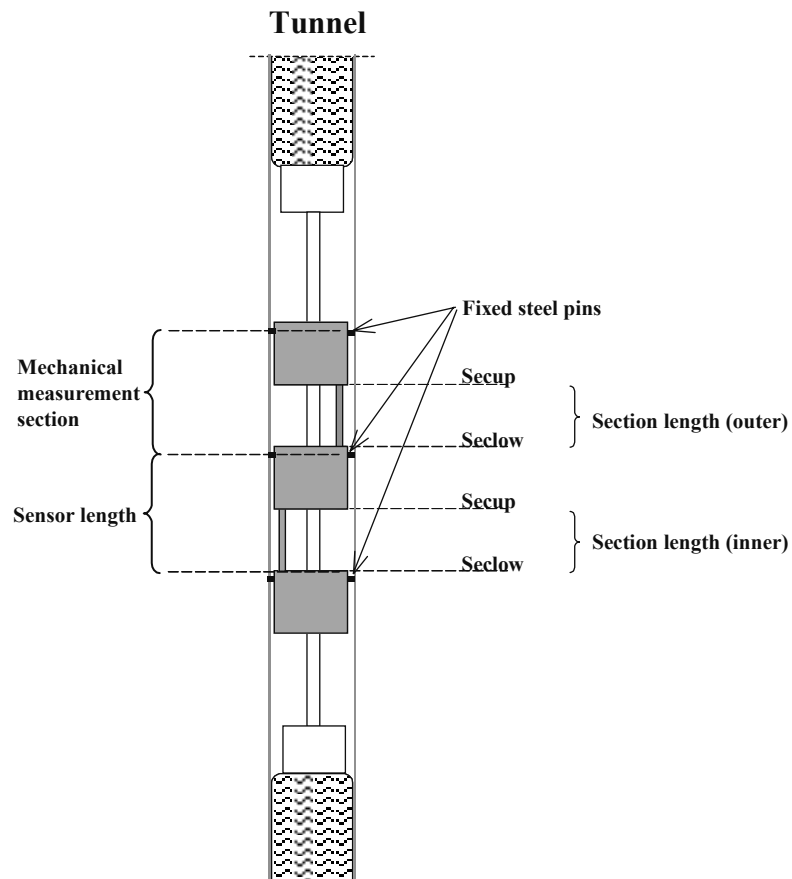
Figure 4-1   *A schematic figure, that shows the different parts of the test equipment and also the definitions of the terms outer and inner relative the tunnel.*
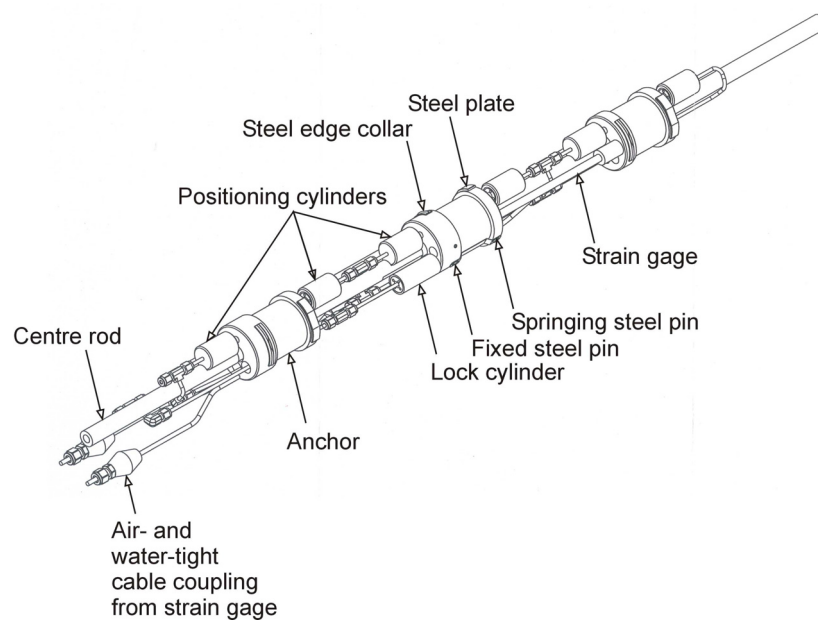
Figure 4-2   *A detailed figure of the three anchors, sensors (strain gage), positioning cylinder etc.*

The deformation is measured in two sections (inner and outer) in each borehole. One of the mechanical measurement sections is placed over a fracture (or fractures) and the other mechanical measurement section is placed over intact rock. That makes it possible to separate the fracture deformation from the deformation of the intact rock, see Figure 4-5.

Of all boreholes in the prototype tunnel, ten are equipped as described above. Five of the measurement sections are placed over a single fracture and the rest are placed over two to six fractures, see Table 4-1.

Since hydraulic packers isolate the test sections from rest of the borehole and the test sections have contact with the tunnel (atmospheric pressure) via tubes and valves it is possible to perform hydraulic tests in the sections.

Table 4-1   Data of the measurement sections (sensor ID, length, number of fractures etc).

Label	Cable mark	Sensor ID	Position	Secup	Seclow	Section length (m)	Number of fractures
KA3539G-2-1	HRA 1121	3511	Inner	16.77	16.97	0.20	2
KA3539G-2-2	HRA 1122	3510	Outer	16.47	16.67	0.20	0
KA3542G01-3-1	HRA 1231	3513	Inner	19.47	19.67	0.20	0
KA3542G01-3-2	HRA 1232	3512	Outer	19.17	19.37	0.20	1
KA3542G02-2-1	HRA 1321	3515	Inner	26.50	26.70	0.20	1
KA3542G02-2-2	HRA 1322	3514	Outer	26.20	26.40	0.20	0
KA3544G01-2-1	HRA 1621	3509	Inner	9.82	10.02	0.20	2
KA3544G01-2-2	HRA 1622	3508	Outer	9.52	9.72	0.20	0
KA3546G01-2-1	HRA 1721	3517	Inner	7.67	7.87	0.20	1
KA3546G01-2-2	HRA 1722	3516	Outer	7.37	7.57	0.20	0
KA3548A01-3-1	HRA 1831	3526	Inner	9.70	10.15	0.45	2
KA3548A01-3-2	HRA 1832	3518	Outer	9.40	9.60	0.20	0
KA3550G01-2-1	HRA 2121	3527	Inner	6.10	6.70	0.60	6
KA3550G01-2-2	HRA 2122	3519	Outer	5.80	6.00	0.20	0
KA3552G01-2-1	HRA 2521	3521	Inner	5.25	5.45	0.20	0
KA3552G01-2-2	HRA 2522	3520	Outer	4.95	5.15	0.20	2
KA3554G01-2-1	HRA 2821	3525	Inner	23.54	23.80	0.26	2
KA3554G01-2-2	HRA 2822	3522	Outer	23.24	23.44	0.20	0
KA3554G02-4-1	HRA 2941	3524	Inner	11.40	11.60	0.20	0
KA3554G02-4-2	HRA 2942	3523	Outer	11.10	11.30	0.20	1

4.2.1 Logger

In the hydro mechanical tests all data is registered and saved by an Model 8020 Micro-10 Datalogger. The Micro-10 Datalogger is based on an Campbell Scientific CR10X MCU. The number of channels is expanded by a multiplexer (Model 8032 Multiplexer (MUX)). The logger as well as the multiplexer is delivered by Geokon Inc. (Lebanon, USA).

The data loggers for all Hydro Mechanical tests connected to the Prototype Repository Test are placed in the G-tunnel, see Figure 4-3.

Figure 4-3 *Data loggers for the Hydro Mechanical equipment, located in Tunnel G.*

4.2.2 Sensors

The sensors are manufactured by Geokon Inc. The strains are measured using the vibrating wire technique: A length of steel wire is tensioned between two end blocks. Deformations (i. e. strain changes) will cause the two end blocks to move relative each other, thus altering the tension in the wire. The tension is measured by plucking the wire and measuring its resonant frequency of vibration using an electromagnetic coil.

The advantage of the vibrating wire technique lies mainly in the use of a frequency as the output signal from the strain gage. Frequencies may be transmitted over long cable lengths without appreciable degradation caused by variation in cable resistance, or leakage to ground.

The sensor model used in the hydro mechanical tests is type 4210, specifications are listed in Table 4-2 and Table 4-3.

Table 4-2 Measurement range and accuracy for each length of the sensors. (Geokon type 4210)

Length of sensor	Measurement range	Resolution (logger)	Accuracy (0.1% F.S.)
300 mm	0.90 mm	0.12 µm	0.90 µm
550 mm	1.65 mm	0.22 µm	1.65 µm
700 mm	2.10 mm	0.28 µm	2.10 µm
360 mm	1.08 mm	0.14 µm	1.08 µm
254 mm	0.76 mm	0.10 µm	0.76 µm

The normal accuracy for the hole measuring system including hysteresis, non-linearity, misalignment, batch factor variations etc is 1% F.S. according to Geokon.

Table 4-3 Data of the sensors (sensor ID, gage factor, thermal coefficient etc).

Label	Cable mark	Sensor ID	Sensor length (mm)	Mechanical measurement section (mm)	Gage factor (inch/digit)	Thermal coefficient (mm/deg C)
KA3539G-2-1	HRA 1121	3511	300	311	0.000004121	0.003582
KA3539G-2-2	HRA 1122	3510	300	323.5	0.000004098	0.003582
KA3542G01-3-1	HRA 1231	3513	300	311	0.000004101	0.003582
KA3542G01-3-2	HRA 1232	3512	300	323.5	0.000004133	0.003582
KA3542G02-2-1	HRA 1321	3515	300	311	0.000004107	0.003582
KA3542G02-2-2	HRA 1322	3514	300	323.5	0.000004132	0.003582
KA3544G01-2-1	HRA 1621	3509	300	311	0.000004087	0.003582
KA3544G01-2-2	HRA 1622	3508	300	323.5	0.000004081	0.003582
KA3546G01-2-1	HRA 1721	3517	300	311	0.000004109	0.003582
KA3546G01-2-2	HRA 1722	3516	300	323.5	0.000004090	0.003582
KA3548A01-3-1	HRA 1831	3526	550	561	0.000007793	0.006633
KA3548A01-3-2	HRA 1832	3518	300	323.5	0.000004122	0.003582
KA3550G01-2-1	HRA 2121	3527	700	711	0.000010005	0.008462
KA3550G01-2-2	HRA 2122	3519	300	323.5	0.000004110	0.003582
KA3552G01-2-1	HRA 2521	3521	300	311	0.000004121	0.003582
KA3552G01-2-2	HRA 2522	3520	300	323.5	0.000004125	0.003582
KA3554G01-2-1	HRA 2821	3525	360	371	0.000004982	0.004314
KA3554G01-2-2	HRA 2822	3522	300	323.5	0.000004117	0.003582
KA3554G02-4-1	HRA 2941	3524	300	311	0.000004119	0.003582
KA3554G02-4-2	HRA 2942	3523	300	323.5	0.000004128	0.003582

4.3   Calculation of displacement

The calculation has to be done in two steps, namely:

1. Calculate and evaluate the sensor deformation

The sensor deformation is a function of temperature (T), thermal coefficient of the sensor (α_{sensor}), thermal coefficient of the anchor body ($\alpha_{stainless\ steal}$), and the gage factor.

2. Calculate the rock and fracture deformation

In order to separate the fracture deformation from the deformation of the rock mass it is necessary to evaluate the strain of the intact rock.

4.3.1   Sensor deformation

The signal from the sensor is registered or presented as digits. Each sensor is calibrated and one digit represents a certain movement, *gage factor*. Since the sensor also is affected of the change in temperature the result must be compensated for the change in length due to the heat.

Furthermore, there is a distance, $L_{anchor\ body}$, between the fixed steel pin (i.e. the contact point between the anchor and the borehole wall) and the attach point of the sensor. The readout from the sensor must be corrected due to the thermal expansion of the anchor body.
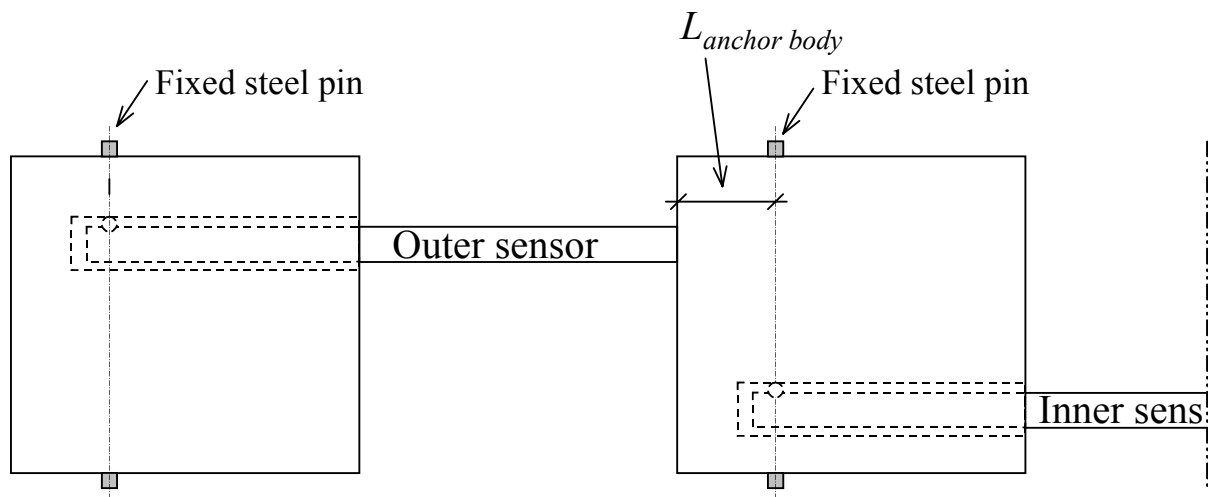
Figure 4-4   *The figure shows how the sensor is mounted to the anchor body as well as the fixed contact point (fixed steel pin) between the anchor and the borehole wall.*

The correction due to the thermal expansion of sensor and the anchor bodies is done as follows (consider the outer sensors in Figure 4-4):

$$\Delta x_{outer}^{corrected} = \Delta(number\ of\ digits) \times gage\ factor - (\alpha_{sensor} \times l_{sensor} \times \Delta T) -$$
$$(\alpha_{stainless\ steel} \times L_{anchor\ body} \times \Delta T)$$

where: α_{sensor} = thermal coefficient for the sensor

l_{sensor} = length of the sensor

ΔT = change in temperature

$\alpha_{stainless\ steel}$ = expansion coefficient for stainless steel

$L_{anchor\ body}$ = length of solid steel between the fixed steel pin and the attach point of the sensor.

4.3.2   Fracture deformation

Results from the measurement sections include deformation of intact rock as well as fractures and therefore need to be evaluated in order to separate the fracture deformation, $\Delta\delta_{fracture}$:

$$\Delta\delta_{fracture} = \Delta\delta_{fracture\ and\ solid\ rock} - \Delta\delta_{solid\ rock}$$

Since the length of the mechanical measurement sections varies the change in fracture deformation, is estimated by following calculation (see Figure 4-5):

$$\Delta\delta_{fracture} = \Delta x_{outer}^{corrected} - \left(\frac{\Delta x_{inner}^{corrected}}{L_{inner}} \times L_{outer} \right)$$

where: $\Delta x_{outer}^{corrected}$ = corrected change in length of outer sensor

$\Delta x_{inner}^{corrected}$ = corrected change in length of inner sensor

L_{inner} = length of the inner measurement section

L_{outer} = length of the outer measurement section
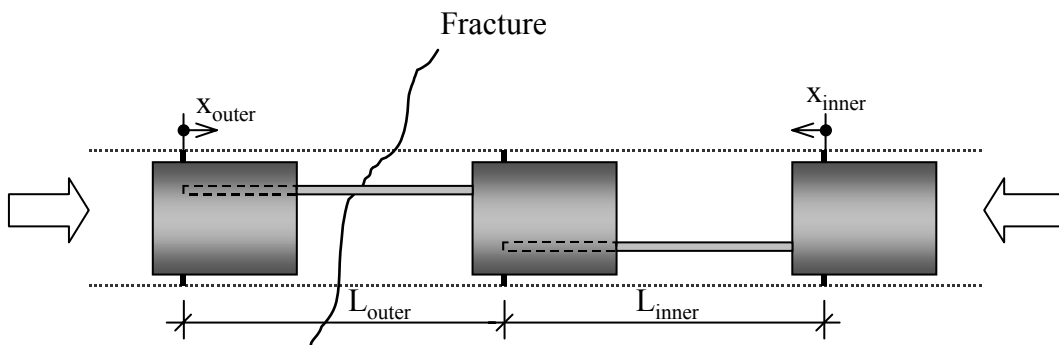
Figure 4-5   *Denominations used when calculating the fracture deformation.*
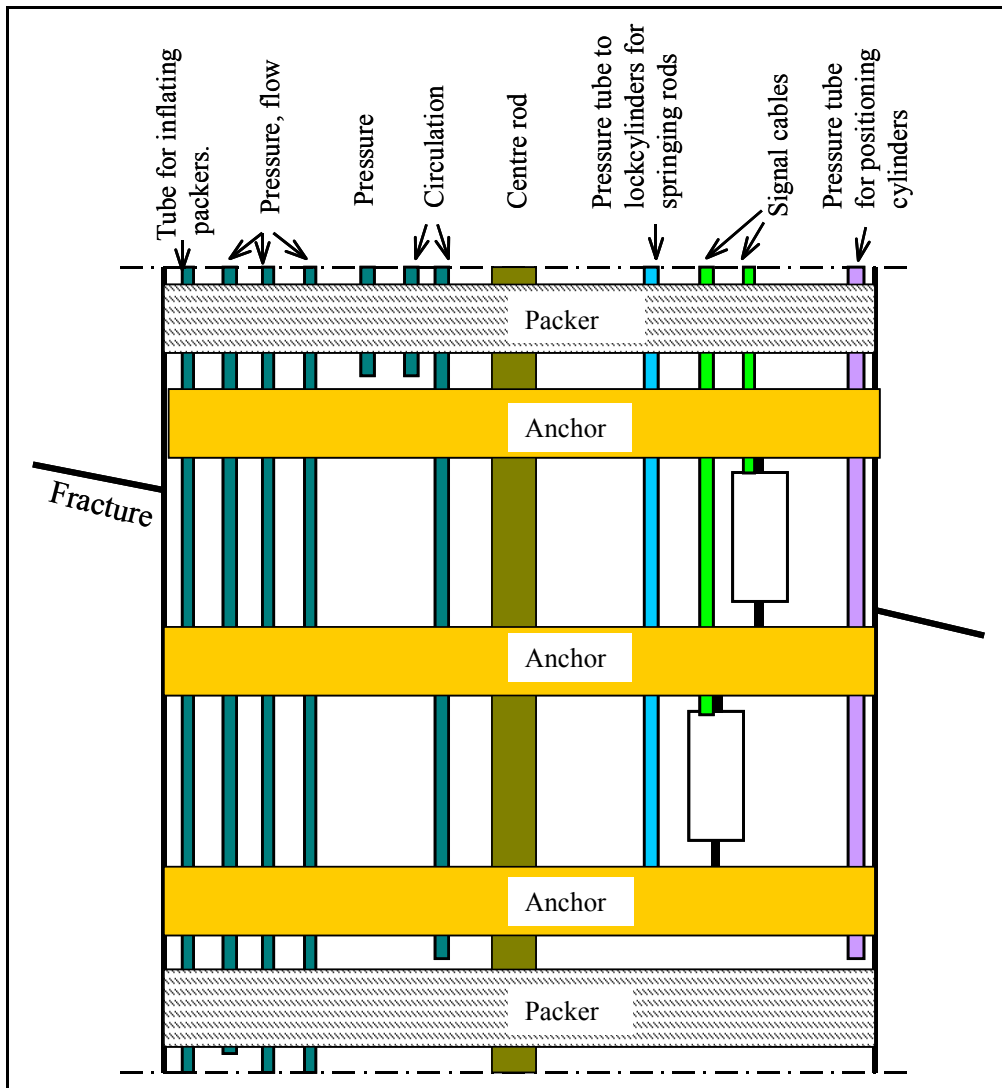
Figure 4-6 *Schematic figure of the measurement equipment and measurement sections.*

5   Flow rate measurements in the tunnels

The water flowing along the tunnel is collected at certain locations by concrete ditches across the tunnel, see Figure 5-1, and diverted to a gauging box equipped with a v-notch weir. The water level in the box is measured with ultrasonic transmitter, connected to the HMS, that is calibrated against a ruler mounted on the box. After passage through the gauging box, the flow is diverted to a discharge pipe common for a number of gauging boxes, which finally leads into the sumps in the tunnel.
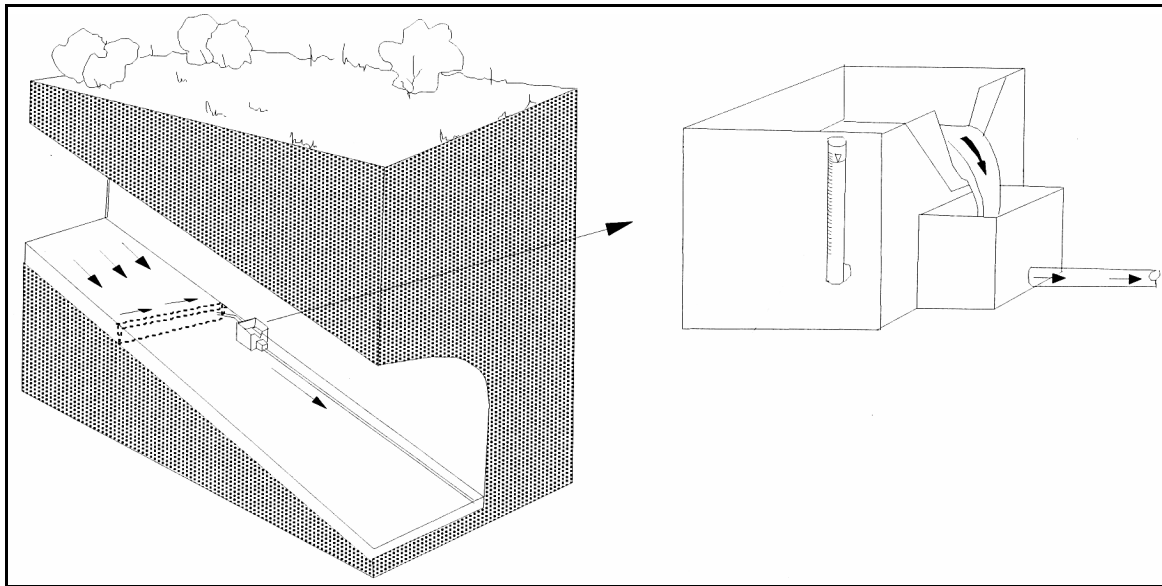
Figure 5-1 *Flow measurement principle at Äspö HRL*

The three weirs constructed closest to the prototype repository is shown in Figures 5-2 to 5-4. They are made of steel plates which form the collecting unit. The mesurement of the flow is done at the location of the weir itself.

The ultrasonic transmitters are of the type EXAC-/STA-270 and is placed above the water surface in the box and measures the level by means of an ultrasonic signal. The measuring range is 0.2 – 0.7 m.
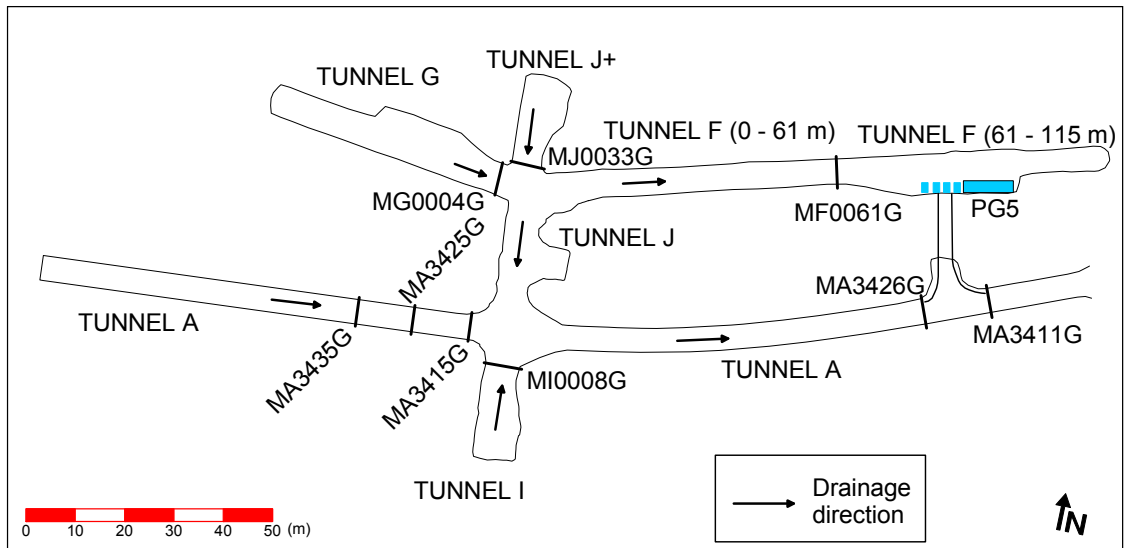
Figure 5-2 *Overview of the prototype area with weirs*
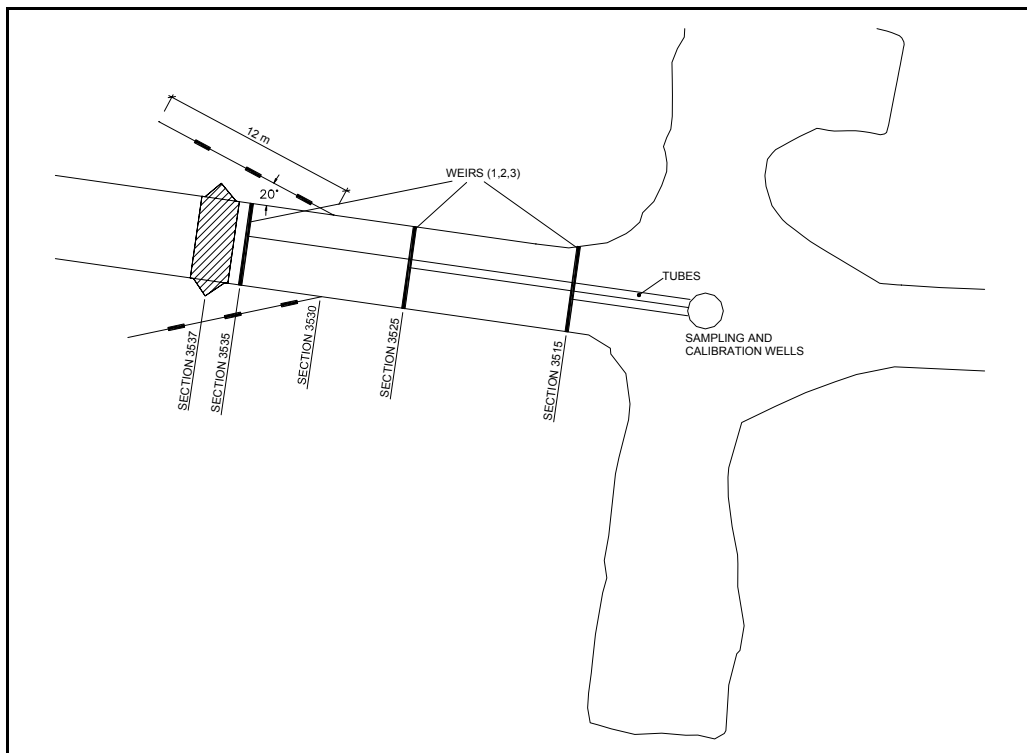
Figure 5-3 *The position of the three weirs downstream of plug 2*

Figure 5-4 *One of the three weirs downstream of plug 2 with the ultrasonic transmitter visible*

The weirs MG0004G, MF0061G, MA3411G and MA3426G works by following another principle. They consists of two units, a collecting unit and a measurement unit. The collecting unit is a below the rock floor concrete construction, see Figure 5-5. The collected water is then transported through tubes to the measurement unit at the location PG5, see Figure 5-2. A mesurement unit can be seen in Figure 5-6.

Two new concrete weirs are being constructed (October-November 2004) at the entrance to tunnels I and J respectively in order to more accurately measure the inflow from the rock into these parts of the tunnel system. They are of the same construction type as MG0004G, see Figure 5-5.

Figure 5-5 *The concrete weir MG0004G during construction*

Figure 5-6 *Measurement units for MF0061G and MG0004G at PG5*

6 Pressure measurements

6.1 Principle of measurements

In Figure 6-1 the pressure measurements principle is shown. Due to the difference in datum level between the mid-point in each borehole section (Z_S) and the level of the actual pressure transducer (Z_T), some correcting calculations must be done in order to obtain the correct pressure head and hydraulic (point water) head of each section.

The pressure head in each section is

$$P_{sect} = P_T + \rho_p \cdot g \cdot (Z_T - Z_S) \qquad (kPa)$$

where

- P_T is the measured pressure by the transducer
- Z is positive upwards

The hydraulic head is thus

$$H_{sect} = Z_S + P_{sect} / (\rho_p \cdot g) \qquad (masl)$$

$$g = 9.8185 \qquad (m/s^2)$$

In Table 6-1 different values of ρ_p at different depths are detailed

Table 6-1 Water density in tubes

Depth at Äspö HRL (m)	Density in plastic tubes (kg / m^3), ρ_p
0 - 80	999.8
80 - 245	999.8
245 - 415	999.6
415 - 500	999.4
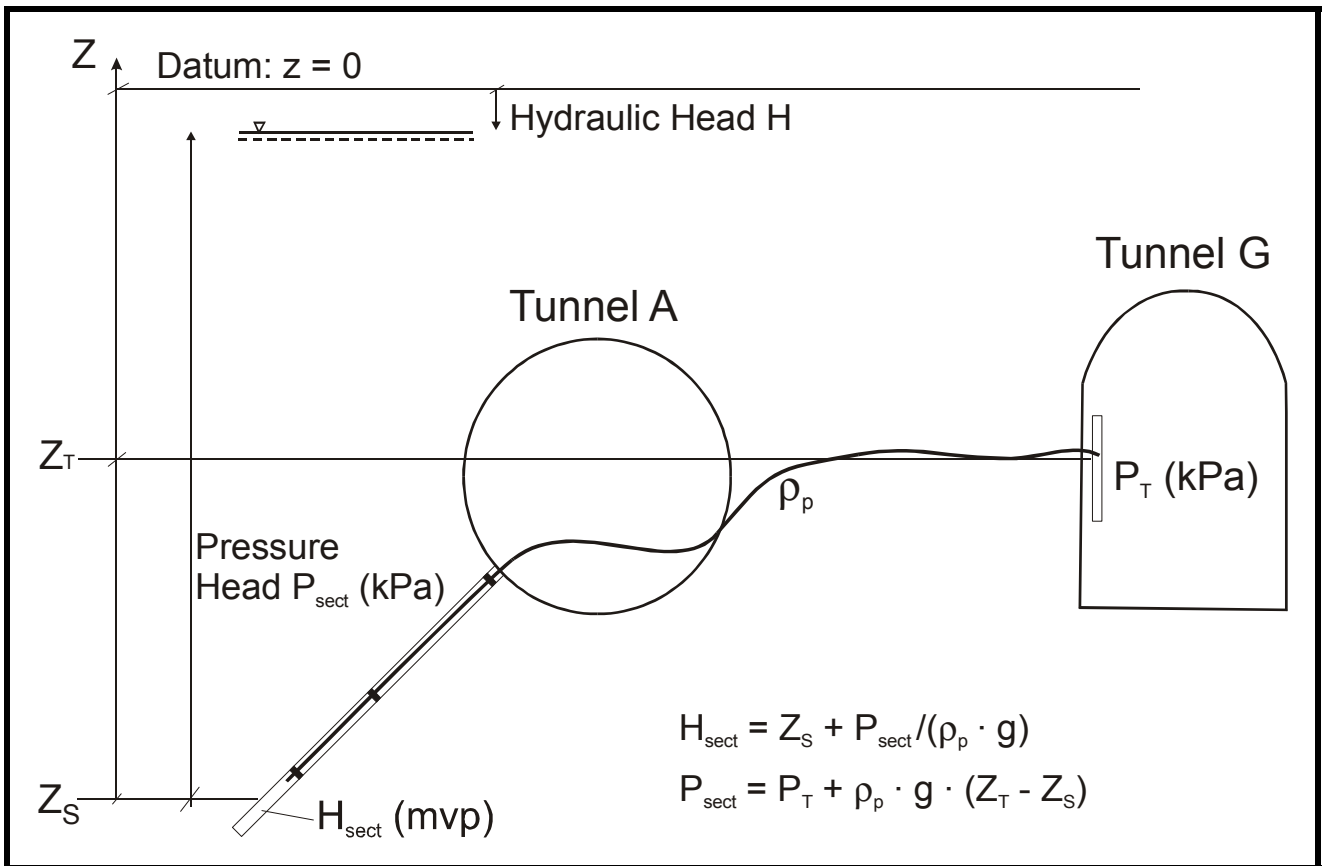
Figure 6-1 *Pressure measurements principle*

A pressure in a borehole section is transmitted via a plastic tube directly to a pressure transducer. A number of pressure transducers are mounted on a panel, *see Figure 6-4*, in tunnel G where also tubes from the pressure reference system are available to enable in-situ calibrations of the pressure transducers.

In Appendix 1 all mid-section levels and transducer levels are detailed in a table.

6.2   Description of equipment

A large number of boreholes were instrumented with one or several packers. In all packed-off sections, the water pressure will be measured. Each borehole section is connected to a tube of polyamide that via lead-through holes ends in the G-tunnel. All pressure transducers are placed in the G-tunnel to facilitate easy calibration and exchange of transducers that are out of order. The transducers are connected to the HMS system at Äspö Laboratory and it is a flexible system for changing the sampling frequency (Figure 6-2). The maximum scan frequency is every 3rd second. During periods with no hydraulic tests, preliminary the sampling (storing a value in the data base) frequency will be every 2nd hour with an automatic increase of the sampling frequency if the pressure change since last registration is larger than 2kPa. During hydraulic tests, the sampling frequency may be up to 3rd second.

Figure 6-2 *All pressure transducers are connected to the HMS system. In the G-tunnel is a computer in the HMS system where logging frequencies easily can be changed.*

6.3 Pressure sensors

The pressure in a borehole is transmitted via a plastic tube directly to a pressure transducer, see Figure 6-3.

The pressure transducers are either of the type DRUCK PTX 500 series or DRUCK PTX 600 series with a pressure range of 0 – 50 bar (absolute).

According to the manufacturer the uncertainty for these transducers is +/-0.2 % (type500) and +/-0.08 % (type 600) of full scale (F.S) for the best straight line (B.S.L.). For the 600 series types the time drift is given to max. 0.05 % F.S., while no figure is given for the 500 series types. Normally, a pressure value is scanned once every two seconds. If the change since the latest stored value exceeds a "change value" of approximately 2 kPa the newly scanned value is stored. A value is always stored once every second hour, regardless of any changes.

Figure 6-3 *Pressure transducers connections*

Figure 6-4 *Panel with pressure transducers in tunnel G*

7 Dilution measurements and water sampling

7.1 Dilution measurements

Groundwater flow rate is one part that governs the transport of solutes and thus plays a role for the hydro chemical evolution of the groundwater. Groundwater flow rate is difficult to measure in a fractured media but the available technique can provide good indications of hydraulic connections if the hydraulic stress field is changed (with a hydraulic test for example) and can also provide approximate flow rates in the rock mass.

The groundwater flow in a saturated geological formation can be estimated from dilution measurements, see for example *Halevy et al. (1967), Drost et al. (1968), Gaspar and Oncecu (1972)*. Equation 7-1 is generally used for estimating the groundwater flow (filtration velocity or Darcy velocity). It has been developed for porous media but is also used to evaluate dilution measurements in fractured rock.

$$q_{bh} = \alpha \cdot q + q_D + q_R = \frac{V}{A \cdot t} \cdot \ln\left(\frac{C}{C_0}\right) \qquad (7\text{-}1)$$

q_{bh} : Tracer dilution velocity in the borehole section (m/s)

α: Correction factor for the hydrodynamic field distortion (-)

q : Filtration velocity in the formation (m/s)

q_D : Apparent velocity due to molecular diffusion of the tracer (m/s)

q_R : Apparent velocity due to effects of vertical current, mechanical mixing etc. (m/s)

V: Dilution (water and tracer filled) volume of the borehole section (m^3)

A: The area of the dilution (measuring) volume cross-section (m^2)

t: Time (s)

C: Tracer concentration at time t (kg/m^3)

C_0: Tracer concentration at time t=0 (kg/m^3)

It should be observed that q in equation 7-1 is also called "Darcy velocity" and should not be confused with the actual transport velocity. The transport velocity is dependent of the kinematic porosity and the transport velocity can thus in crystalline rock be 100 to 10000 greater than q.

The assumption made in equation 7-1 is that the groundwater flow is perpendicular to the borehole section, see Figure 7-1. The flow q_R can generally be neglected and the lower measuring limit is then governed by the molecular diffusion of the tracer. The parameter α depends on the permeability distribution around the borehole. If the permeability is constant around the borehole α=2. If the permeability is much greater within radius (r_2) of about 5 times the borehole radius (r_1) compared to outside r_2, α become about 4. If the permeability is less within radius r_2 compared to outside r_2, α may become less than 1. It is assumed that the tracer is perfectly mixed in the borehole

section. It is necessary that the circulation-flow rate (Q_m) of the tracer is much greater than $q_{bh} \cdot A$ to keep the borehole section well mixed. The time needed for a measurement can be decreased if the volume V_C decreases. By using "dummies" (massive cylindrical bodies with volume V_d) in a borehole section (with total borehole volume V) V_C decreases to V-V_d.
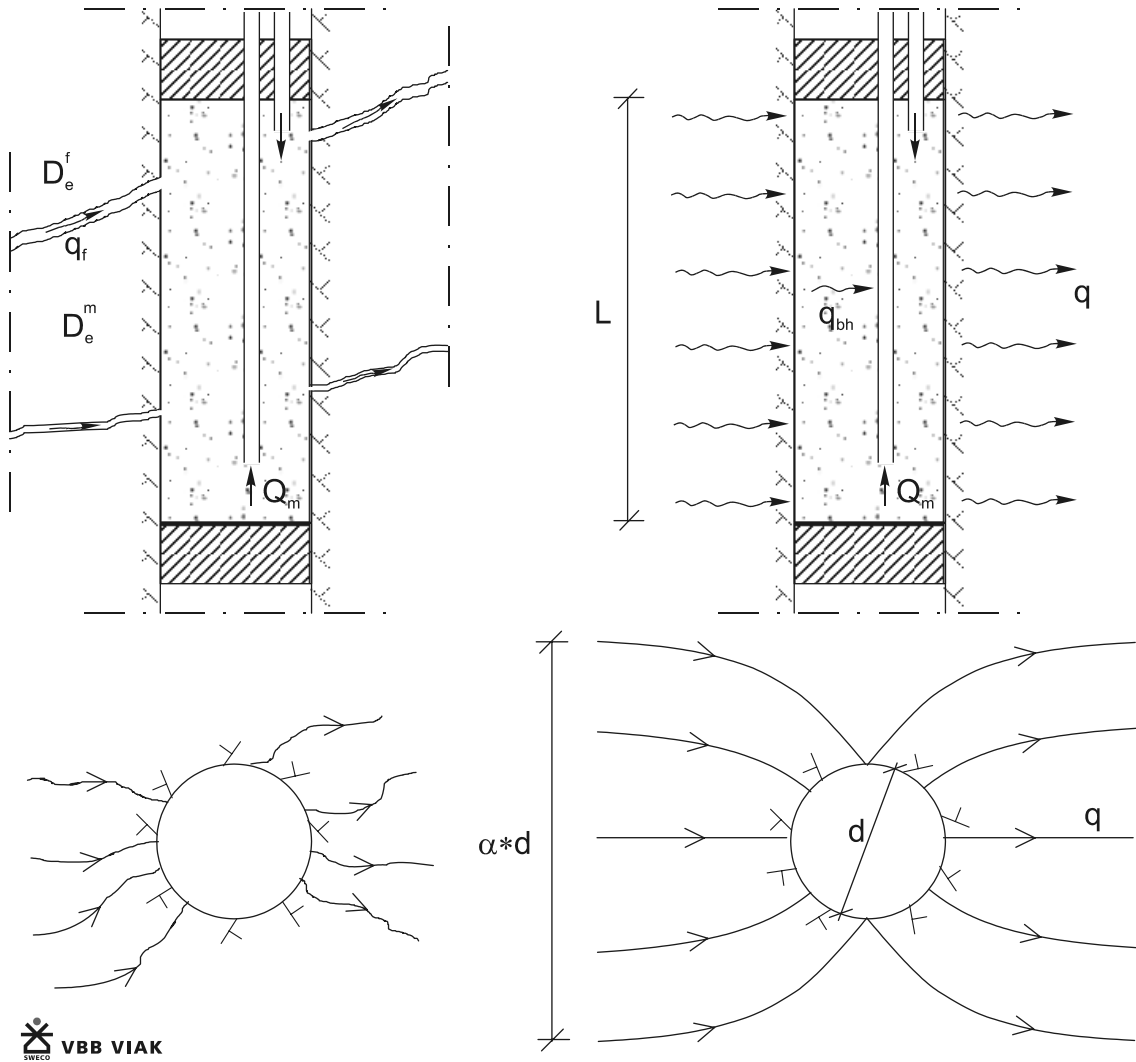
Figure 7-1 *Schematic description of dilution measurements. To the left: Flow in fractured crystalline rock. To the right: Ground water flow in a porous medium. L: length of test section. d: diameter of the borehole section. D_e^m: Effective diffusion coefficient of the rock matrix. D_e^f: Effective diffusion coefficient in the fractures.*

The volume of circulation sections and connected pipes are shown in the table in Appendix 2.

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Appendix 1

Calibration levels for borehole midsections and transducers

BH:sec   Borehole name and section number

Z Transduc   Datum level of transducer

Zsecmid   Datum level of borehole midsection

BH:sec	Z Transduc (masl)	Zsecmid (masl)	BH:sec	Z Transduc (masl)	Zsecmid (masl)
KA3510A:1	-447.96	-517.48	KA3566C01:1	-445.92	-445.48
KA3510A:2	-447.96	-507.26	KA3566G01:1	-447.00	-467.47
KA3510A:3	-447.96	-494.79	KA3566G01:2	-446.78	-463.20
KA3510A:4	-447.54	-480.04	KA3566G01:3	-446.57	-459.15
KA3510A:5	-447.54	-462.38	KA3566G01:4	-446.36	-454.67
KA3539G:1	-446.93	-478.78	KA3566G01:5	-446.14	-451.32
KA3539G:2	-446.71	-473.16	KA3566G02:1	-446.56	-465.53
KA3539G:3	-446.50	-461.44	KA3566G02:2	-446.35	-460.34
KA3539G:4	-446.29	-455.60	KA3566G02:3	-446.14	-457.57
KA3542G01:1	-446.92	-469.21	KA3566G02:4	-445.93	-455.14
KA3542G01:2	-446.71	-465.78	KA3566G02:5	-445.71	-451.16
KA3542G01:3	-446.50	-462.82	KA3568D01:1	-445.49	-445.89
KA3542G01:4	-446.29	-459.00	KA3572G01:1	-446.99	-458.18
KA3542G01:5	-446.08	-453.67	KA3572G01:2	-446.78	-452.51
KA3542G02:1	-446.92	-469.37	KA3573A:1	-446.35	-447.29
KA3542G02:2	-446.71	-467.48	KA3573A:2	-446.14	-446.90
KA3542G02:3	-446.50	-465.14	KA3573A:3	-445.93	-446.68
KA3542G02:4	-446.29	-459.36	KA3573A:4	-445.71	-446.49
KA3542G02:5	-446.07	-452.56	KA3573A:5	-445.50	-446.28
KA3543A01:1	-445.42	-446.82	KA3573C01:1	-445.71	-444.36
KA3543I01:1	-445.64	-442.82	KA3574D01:1	-445.92	-444.83
KA3544G01:1	-446.07	-460.78	KA3574G01:1	-446.99	-458.33
KA3544G01:2	-445.86	-458.73	KA3574G01:2	-446.78	-454.38
KA3544G01:3	-445.65	-454.65	KA3574G01:3	-446.56	-451.28
KA3546G01:1	-446.92	-459.54	KA3576G01:1	-446.56	-458.21
KA3546G01:2	-446.71	-456.42	KA3576G01:2	-446.34	-453.14
KA3546G01:3	-446.50	-452.52	KA3576G01:3	-446.13	-450.39
KA3548A01:1	-446.92	-447.98	KA3578C01:1	-444.49	-445.47
KA3548A01:2	-446.70	-447.45	KA3578G01:1	-446.98	-457.92
KA3548A01:3	-446.49	-447.11	KA3578G01:2	-446.77	-453.28
KA3548A01:4	-446.28	-446.87	KA3578H01:1	-445.70	-442.28
KA3548D01:1	-445.43	-445.80	KA3579D01:1	-445.91	-445.45
KA3548G01:1	-445.85	-452.50	KA3579G:1	-446.56	-467.04
KA3548G01:2	-445.64	-458.00	KA3579G:2	-446.35	-461.47
KA3550G01:1	-445.85	-458.93	KA3579G:3	-446.13	-455.37
KA3550G01:2	-445.64	-455.02	KA3584G01:1	-446.98	-457.75
KA3550G01:3	-445.43	-451.77	KA3584G01:2	-446.77	-451.45
KA3550G05:1	-446.07	-451.21	KA3588C01:1	-445.91	-442.15
KA3551G05:1	-446.28	-451.21	KA3588D01:1	-445.70	-445.28
KA3552A01:1	-445.64	-446.69	KA3588I01:1	-445.91	-442.15
KA3552G01:1	-446.92	-458.30	KA3590G01:1	-446.98	-464.18
KA3552G01:2	-446.70	-453.97	KA3590G01:2	-446.78	-455.76
KA3552G01:3	-446.49	-451.20	KA3590G01:3	-446.56	-450.69
KA3552H01	-445.64	-442.82	KA3590G02:1	-446.98	-467.36
KA3553B01	-445.43	-447.36	KA3590G02:2	-446.77	-461.58
KA3554G01:1	-446.92	-468.35	KA3590G02:3	-446.55	-456.87
KA3554G01:2	-446.71	-465.37	KA3590G02:4	-446.34	-452.13
KA3554G01:3	-446.49	-461.43	KA3592C01:1	-445.49	-445.15
KA3554G01:4	-446.28	-455.20	KA3593G:1	-446.98	-475.25
KA3554G01:5	-446.07	-450.78	KA3593G:2	-446.76	-471.55
KA3554G02:1	-446.92	-467.21	KA3593G:3	-446.55	-463.58
KA3554G02:2	-446.71	-461.86	KA3593G:4	-446.34	-452.99
KA3554G02:3	-446.50	-458.75	KA3597D01:1	-445.70	-445.02
KA3554G02:4	-446.28	-456.84	KA3597H01:1	-445.91	-442.07
KA3554G02:5	-446.07	-452.71	KA3600F:1	-446.98	-446.96
KA3557G:1	-446.92	-471.12	KA3600F:2	-446.76	-446.81
KA3557G:2	-446.71	-456.51	KA3600F:3	-446.55	-446.47
KA3563A01:1	-445.49	-446.10	KA3600F:4	-446.34	-445.91
KA3563D01:1	-445.93	-470.85	KG0021A01:1	-447.00	-431.30
KA3563G:1	-445.93	-470.85	KG0021A01:2	-446.79	-433.24
KA3563G:2	-445.72	-460.02	KG0021A01:3	-446.58	-434.38
KA3563G:3	-445.94	-454.60	KG0021A01:4	-446.36	-437.11
KA3563G:4	-445.72	-450.91	KG0021A01:5	-446.15	-441.67
KA3563I:1	-445.70	-442.30	KG0048A01:1	-447.00	-431.95
			KG0048A01:2	-446.79	-434.47
			KG0048A01:3	-446.58	-436.43
			KG0048A01:4	-446.36	-439.07
			KG0048A01:5	-446.15	-442.40

Appendix 2

Dilution measurements and water sampling

Heading in the table below includes

Borehole	Borehole name
Section	Section with packer chainage, secup and seclow
Net section volume, Vs	The total available volume within a specified section when reduction of volume has been done regarding tubes, cables and other equipment
C tube volume, Vc	Total volume within the tube or tubes from section to valves designated for circulation measurements
HC tube volume, VHC	Total volume within the tube from section to valve designated for Hydro Chemical sampling
F tube volume, VF	Total tube volume within the tube from section to valve designated for flowing

Borehole	Section	Net section volume, Vs (dm3)	C tube volume, Vc (dm3) (2 tubes)	HC tube volume, VHC (dm3)	F tube volume, VF (dm3)	Total volume Vtot (dm3)
KA3600F	43.0 - 50.1	31.9	-	-	-	31.9
	40.5 - 42.0	1.29	-	0.42	-	1.71
	20.0 - 39.5	79.3	-	-	-	79.3
	3.4 - 18.0	58.8	-	-	-	58.8
KA3593G	25.3 - 30.02	21.53	-	-	-	21.53
	23.5 - 24.2	0.99	-	0.35	-	1.34
	9.0 - 22.5	54.7	-	-	-	54.7
	3.0 - 7.0	15.6	-	-	-	15.6
KA3590G02	25.65 - 30.01	19.4	-	-	1.34	20.74
	15.35 - 23.65	33.4	-	-	-	33.4
	12.05 - 13.35	1.24	-	0.29	-	1.53
	1.65 - 10.05	33.5	-	-	-	33.5
KA3590G01	16.0 - 30.0	63.2	-	-	-	63.2
	7.0 - 15.0	32.4	-	-	1.2	33.6
	1.5 - 6.0	17.5	-	0.26	-	17.76
KA3584G01	7.0 - 12.0	22.3	-	-	-	22.3
	1.4 - 5.0	14.2	-	-	-	14.2
KA3579G	14.7 - 22.65	35.7	-	-	-	35.7
	12.5 - 13.7	4.32	-	-	-	4.32
	2.5 - 11.5	36.3	-	-	-	36.3
KA3578G01	6.5 - 12.58	27.2	-	-	-	27.2
	4.3 - 5.5	1.18	-	0.28	-	1.46
KA3576G01	7.87 - 12.01	18.4	-	-	-	18.4
	3.87 - 5.87	1.48	-	0.28	-	1.76
	1.37 - 2.87	5.48	-	-	-	5.48
KA3574G01	8.0 - 12.03	17.9	-	-	-	17.9
	5.1 - 7.0	7.21	-	-	-	7.21
	1.8 - 4.1	1.54	2.34	-	-	3.88
KA3573A	26.0 - 40.07	63.5	-	-	-	63.5
	21.0 - 24.0	11.8	-	-	1.5	13.3
	14.5 - 19.0	17.7	-	-	-	17.7
	10.5 - 12.5	7.41	-	-	-	7.41
	3.4 - 8.5	19.7	-	-	1	20.7
KA3572G01	7.3 - 12.03	21.1	-	-	-	21.1
	2.7 - 5.3	1.63	2.15	-	-	3.78
KA3566G02	19.0 - 30.01	49.6	-	-	-	49.6
	16.0 - 18.0	1.46	2.48	-	-	3.94
	12.0 - 14.0	7.42	-	-	-	7.42
	8.0 - 11.0	11.4	-	-	-	11.4
	1.5 - 6.0	17.3	-	-	1.05	18.35
KA3566G01	23.5 - 30.01	29.2	-	-	-	29.2
	20.0 - 21.5	1.29	2.58	-	-	3.87
	12.0 - 18.0	23.6	-	-	-	23.6
	7.3 - 10.0	10.2	-	-	-	10.2
	1.5 - 6.3	18.5	-	-	1.05	19.55
KA3563G	15.0 - 30.01	67.8	-	-	-	67.8
	10.0 - 13.0	11.8	-	-	-	11.8
	4.0 - 8.0	15.8	-	-	-	15.8
	1.5 - 3.0	1.29	2.24	-	-	3.53

Borehole	Section	Net section volume, Vs (dm3)	C tube volume, Vc (dm3) (2 tubes)	HC tube volume, VHC (dm3)	F tube volume, VF (dm3)	Total volume Vtot (dm3)
KA3557G	15.0 - 30.04	67.88	-	-	-	67.88
	1.5 - 14.0	51.39	-	-	-	51.39
KA3554G02	22.0 - 30.01	35.99	-	-	-	35.99
	15.9 - 21.0	20.58	-	-	-	20.58
	13.2 - 14.9	6.37	-	-	-	6.37
	10.5 - 12.2	4.97	2.42	-	-	7.39
	1.5 - 9.5	30.3	-	-	-	30.3
KA3554G01	25.15 - 30.01	21.7	-	-	-	21.7
	22.6 - 24.15	4.26	2.72	-	-	6.98
	14.0 - 21.6	30.43	-	-	-	30.43
	5.0 - 13.0	30.54	-	-	-	30.54
	1.5 - 4.0	9.72	-	-	-	9.72
KA3552G01	7.05 - 12.0	22.1	-	-	-	22.1
	4.35 - 6.05	4.88	2.27	-	-	7.15
	1.5 - 3.35	6.55	-	-	-	6.55
KA3550G01	8.3 - 12.03	16.57	-	-	-	16.57
	5.2 - 7.3	6.55	2.29	-	-	8.84
	1.8 - 4.2	8.72	-	-	-	8.72
KA3548G01	6.0 - 12.0	26.85	-	-	-	26.85
	2.0 - 5.0	11.79	-	-	-	11.79
KA3548A01	21.5 - 30	38.21	-	-	-	38.21
	11.75 - 20.5	35.79	-	-	1.22	37.01
	8.8 - 10.75	5.8	2.28	-	-	8.08
	3.0 - 7.8	17.89	-	-	-	17.89
KA3546G01	9.3 - 12.0	11.9	-	-	-	11.9
	6.75 - 8.3	4.27	2.35	-	-	6.62
	1.5 - 5.75	16.02	-	-	-	16.02
KA3544G01	11.65 - 12.0	1.24	-	-	-	1.24
	8.9 - 10.65	5.1	2.38	-	-	7.48
	3.5 - 7.9	16.61	-	-	-	16.61
KA3542G02	28.2 - 30.01	7.86	-	-	-	7.86
	25.6 - 27.2	4.48	2.8	-	-	7.28
	21.5 - 24.6	11.46	-	-	-	11.46
	9.0 - 20.5	44.24	-	-	-	44.24
	2.0 - 8.0	24.39	-	-	1.09	25.48
KA3542G01	27.0 - 30.0	13.26	-	-	-	13.26
	21.3 - 26.0	18.92	-	-	-	18.92
	18.6 - 20.3	4.84	2.63	-	-	7.47
	10.5 - 17.6	27.03	-	-	-	27.03
	3.5 - 9.5	22.55	-	-	-	22.55
KA3539G	18.6 - 30.0	51.37	-	-	-	51.37
	15.85 - 17.6	5.1	2.56	-	-	7.66
	10.0 - 14.85	18.38	-	-	1.19	19.57
	4.0 - 9.0	18.66	-	-	-	18.66
KA3510A	125.0 - 150.0	113.06	-	-	-	113.06
	110.0 - 124.0	57.65	-	-	2.26	59.91
	75.0 - 109.0	139.02	-	-	-	139.02
	51.0 - 74.0	93.17	-	-	-	93.17
	4.5 - 50.0	183.7	-	-	-	183.7
KG0021A01	42.5 - 48.82	26.38	-	0.16	-	26.54
	37.0 - 41.5	18.06	-	-	-	18.06
	35.0 - 36.0	0.43	1.14	-	-	1.57
	19.0 - 34.0	59.97	-	-	-	59.97
	5.0 - 18.0	51.5	-	-	-	51.5
KG0048A01	49.0 - 54.69	23.56	-	0.19	-	23.75
	34.8 - 48.0	54.23	-	-	-	54.23
	32.8 - 33.8	0.43	1.09	-	-	1.52
	13.0 - 31.8	75.87	-	-	-	75.87
	5.0 - 12.0	27.4	-	-	-	27.4