School of Architecture, Civil and Environmental Engineering

Rock Mechanics Laboratory

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Master of Advanced Studies on Tunnelling
Swiss Federal Institute of Technology Lausanne (EPFL)

Attachment Report

GEOTECHNICAL HYDROGEOLOGICAL INSITU TESTING AND GEOMONITORING

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Contents **Page No**

Acknowledgement

Abstract

Table of Contents 1-2

1 Introduction 3-6

1.1 Background 3

1.2 Importance of Insitu Testing and Geomonitoring 4

1.3 Organization of the Report 6

2 Geotechnical Insitu Testing/monitoring 7-58

2.1 TRIVEC 7

2.2 Sliding Deformeter 10

2.3 Sliding Micrometer 13

2.4 Modular Extensometer 17

2.5 Reverse Head Extensometer 20

2.6 Fixed Re-Installable Micrometer 21

2.7 Electrical Displacement Transducer 24

2.8 Distometer ETH 25

2.9 Clinometer BL200B 28

2.10 CLINO – Inclinometer Chain 29

2.11 Chain Deflectometer 33

2.12 Dilatometer Measurement 35

2.13 Plate Loading Test 38

2.14 Hydraulic Fracturing Test 45

2.15 Hydraulic Jacking Test 52

3 Hydrogeological Testing 59-67

3.1 Aims and Application of the Test 59

3.2 Pumping Test 60

3.3 Water Pressure Test (Lugeon Test) 62
3.4 Double Packer (DP) Test 63
3.5 Slug Test 65

4 GeoMonitoring – System 68-78
4.1 General background 68
4.2 GeoMonitor 2 68
4.3 Trivec 2.08 Software 69
4.4 Trical 4. Software 71
4.5 Surface Extensometer 73
4.6 Inclinometer measurement 76

5 hiDCon – Elements for Tunnelling 79-83
5.1 Introduction 79
5.2 hiDCon-Elements used in tunnel invert for swelling clay 80
5.3 hiDCon beams integrated with shotcrete in squeezing rock 81

6 General Field Works 84-97
6.1 Axial Deformation Measurement 84
6.2 Dilatometer Test 86
6.3 Extensometer Installation 89
6.4 Observation and brief study of Mont Terri Rock Laboratory 91
6.5 Monitoring of the slope movement by TRIVEC 100

7 General Conclusions 102-103

References 104

Chapter 1

Introduction

1.1 Background

Master of Advanced Studies (MAS) on Tunnelling is an advanced master course on tunnel engineering provides a comprehensive academic as well as practical knowledge on tunnelling. The two months attachment as a part of the master course is an opportunity to acquire practical knowledge on an important subject of tunnelling. The authors two months attachment was with Solexperts AG. Solexperts AG is a Swiss Company reputed for Swiss Precision Geo-monitoring. Geotechnical, hydrogeological insitu testing/investigation and monitoring are the Solexperts major professionalism. As a student of tunnelling and working in the field of geological and geotechnical investigation, design and construction of underground excavation, it is very important to have a strong knowledge on geotechnical and hydrogeological insitu testing and geomonitoring.

The aim of attachment with the company is to know the know-how through practical involvement in the process of insitu testing and monitoring system. Accordingly the author has carried out several field trips to the job site and involved to perform various insitu tests and monitoring instrumentation from Solexperts. During this period the author has also carried out a brief study about various insitu testing and monitoring equipments. In this report it is also briefly described about some of those equipments.

Solexperts not only carried out the insitu testing and monitoring, it has developed and producing various insitu testing and monitoring equipments, data handling and analysis software and varieties of required accessories which are very precise and user friendly.
In the past most of the investigation, design and construction works has been done on the basis of experience and empirical approach. Predicting rock mass

quality analyzing stress induce problems in particular tunnel squeezing, rockbursting, predicting inflow and leakage often have been found extremely difficult during planning stage without insitu investigation. Considerable discrepancies have been found between predicted and actual rock mass condition resulting in significant cost and time overrun in most of the tunnelling project. Even now there are a number of underground excavation projects going on in various part of the world without proper geotechnical investigation and monitoring, where the uncertainty and risk is very high.

Since last two decades the tunnelling activities has increased considerably all over the world with rapid development and urbanization in the cities. This increased activity in tunnelling has given us the opportunity to gain knowledge on tunnelling through experiences. As well as in the field of geotechnical and hydrogeological investigation; a remarkable development has been done. Now there are several insitu investigation methods, tools and equipments are available in the domain, but selection of the proper investigation methods, monitoring system and appropriate equipment according to the site condition is very important.

1.2 Importance of Insitu Testing and Monitoring.

Proper tunnelling methodology through heterogeneous ground condition for low cost tunnelling using the maximum advantage of the self supporting capacity of the rock and soil solving all geological, geotechnical, hydrogeological and environmental problems are the main challenges for us. The detailed study of the project including the detailed geotechnical and hydrogeological insitu testing/investigation gives the clear picture of the site condition, which make it possible to build underground constructions in a more economic and safe way within the time and budget.

Now insitu testing and investigation for determination of rock mechanical properties and hydraulic parameters of the particular site are basic requirements of tunnelling and any underground space utilities projects. Characterization of rock masses and soil with mechanical and hydraulic properties provide data of structure, in order to determine project design and safe construction method. Therefore characterization the rock mass should be on the basis of insitu test data not only from the empirical calculation. As well as it is also very essential to have precise knowledge to examine and analysie of those data because the project design, selection of the construction methods, support and type of linings as the cost and safety of whole works depends directly on this point.

Some mechanical properties may be derived from laboratory tests on small specimens which can not represent the rock mass. The actual rock mass parameters can only be determined with insitu tests that affect much larger volumes of rock masses with many discontinuities and heterogeneities. In addition there are some parameters such as static formation pressure or rock stress that by nature only can be estimated by insitu test.

Underground facilities offer the new space which is not available any more on the surface. Now urban traffic is highly saturated in most of the major cities of the world and facing the problems of fast intercity transport. Now the fast inter city mass transport is only possible with a good suburban transport network. Not only suburban transport network, service utilities of the cities also required a dense suburban network and underground space.

Construction of all these entire new infrastructures below the existing dense infrastructure without disturbing to the surface is certainly a big challenge. During the construction of such suburban facilities the life at the surface must go on undisturbed. To realize such project require perfect investigation, design, planning and proactive monitoring and risk management plan. The visibility of any small damage at the surface due to suburban construction is very high. If there is not proper monitoring system, duly take care of any indication is not possible, resulting the probability of damages and consequences is very high. Therefore without proper investigation, design, proactive risk management plan and good monitoring system it should not be allowed to do any such suburban construction from the concerned authorities.

1.2 Organization of the Report

This report is organized in six different chapters. The chapter 1 gives an introduction and importance of the subject. In chapter 2, there are descriptions about various portable borehole probes available for the measurement of different geotechnical parameters and geomonitoring. The dilatometer test and Plate Loading test to identify the deformation modulus of the rock mass, Hydrofracture tests to know the stress condition and hydro jacking tests to know the minimum stress in heavily jointed rock are some major geotechnical insitu field test also mentioned in chapter 2. Chapter 3 is about the hydrogeological insitu testing and hydraulic characterizing of the rock and soil for underground excavation. The importance of monitoring and available geomonitoring system is described in chapter 4. Chapter five is about hiDCon a new invention for tunnelling through squeezing rock and swelling clay. The author has visited several job sites to carry out the insitu testing and installation of the monitoring system is described in chapter 6. An observation and brief study about various insitu investigations at Mont Terri Rock Laboratory is also mentioned in chapter 6. Finally general conclusion has been made at the end. There are several tables, figures and photographs included in the report which makes easy to understand about the subject. The references used to prepare this report are listed at the end.

Chapter - 2

Geotechnical Insitu Testing/monitoring

The design of underground openings like tunnels, subways and chambers in soil or rock was in the past almost purely a matter of experience. But now the detail investigation & insitu testing is basic a requirement of any underground project. For detailed Investigation there are various geotechnical insitu testing and monitoring equipments and methods in common practice. Some of the following instruments and investigation methods with systematic computational measurements and analysis in the field have been introduced as a powerful design aids in order to arrive at safe and economical structure.

2.1 Trivec

Trivec is developed for measurement of the three orthogonal components (x, y and z) of the displacement vector along a vertical measuring line.

TRIVEC was developed at the Swiss Federal Institute of Technology, Zurich.

TRIVEC is a portable, high precision instrument to measure in three dimensions the distribution of the displacement vectors along a vertical measuring line (borehole in soil, rock or concrete). The measuring tube to accommodate the measuring probe, consisting of measuring marks and plastic connecting tubes, is grouted into a borehole (recommended diameter 100 mm) and can follow the three-dimensional deformations free of hysteresis.

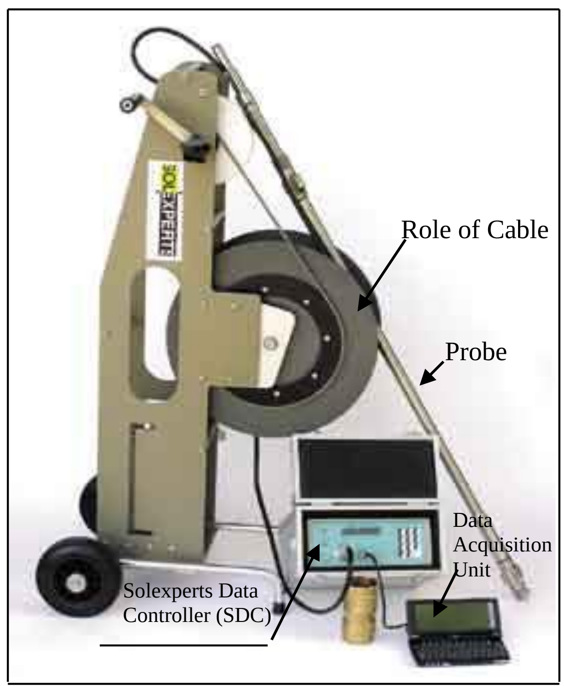


Figure 2.1 TRIVEC measuring equipment.

2.1.1 Method of measurement

The probe is introduced into the measuring tube using a guide rod and is positioned in steps of 1.0 m between two neighboring measuring marks. The two spherical-shaped heads of the probe and the circular cone-shaped measuring marks guarantee a very accurate placement of the probe. Openings in the measuring marks and in the measuring heads of the probe permit a stepwise movement of the probe in the sliding position. By rotating the probe by 45° about its axis into the measuring position and pulling the cable or the guide rod the two heads of the probe are tightened between the measuring marks. A high precision displacement transducer for the z-component and the inclinometer sensors for the x- and y-components are activated and the three measured values are transmitted to the digital data acquisition equipment SDC (Solexperts Data Controller) via the cable. For each measuring position the probe is rotated by 180° using of the guide rod. Measurement in two positions (0° and 180°) compensates the temperature influence and any systematic instrument errors.

2.1.2 Data acquisition

The measuring values can be stored in the SDC Solexperts Data Controller unit (storage capacity max. 8000 values). Field measurements are greatly simplified by using a hand-held computer, e.g. the HP Jornada with integrated recording of the measured data. The computer can communicate via the serial interface AS-232 with the data acquisition unit. Suitable software for the HP Jornada as well as for the evaluation of the data is available for IBM compatible PCs.

Technical data

Probe

- Base length : 1000 mm
- Displacement sensor : z-component
- Range of measurement : 20 mm (± 10 mm)
- Sensitivity : 0.001 mm
- Accuracy : ±0.003 mm (mean error)
- Inclinometer sensor : x- and y-components

- Range of measurement : + 14.5° from the vertical
- Sensitivity : 0.005 mm (1”)
- Accuracy : ±0.03 mm (10”)
- Operating temperature : 0°C to + 40°
- Temperature sensor : Sensitivity: 0.1°C
- Watertightness : 15 bar max.

2.1.3 Typical applications

TRIVEC can be employed in principle in any application in which the three components of the displacement vector along a vertical measuring line have to be measured.

Piles and diaphragm walls

TRIVEC is measuring the strain distribution and horizontal displacements along a vertical measuring line and subject to technical changes. Request references, literature and examples of practical applications are available.

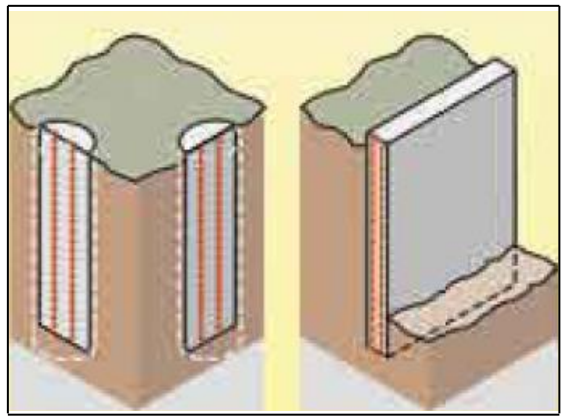
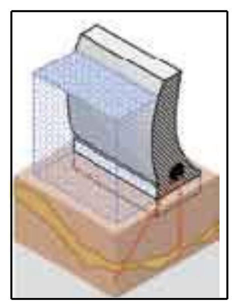


Figure 2.2 shows the positioning and use of Trivec on pile for three dimensional (X-Y-Z) deformation measurements.

Concrete dams

It is for the investigation of the interaction between the dam and the rock abutments, e.g. as a function of the reservoir level and measuring the complete distribution of the vertical strains and horizontal displacements to localized potential fissure. ***Figure 2.3 shows the use of Trivec on concrete dam.***



Tunnels and shafts

It is very useful for measurement of vertical and horizontal displacements and investigating settlement mechanisms in urban tunnelling.

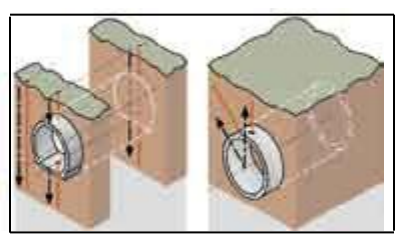


Figure 2.4 shows the use of Trivec on tunnels and shafts.

2.2 Sliding Deformeter

It is for Geotechnical Strain Profile Measurements. The Sliding Deformeter is a development of the Swiss Federal Institute of Technology, Zurich (ETHZ). Sliding Deformeter is for deformation measurements in Geotechnical applications in soil and soft rock.

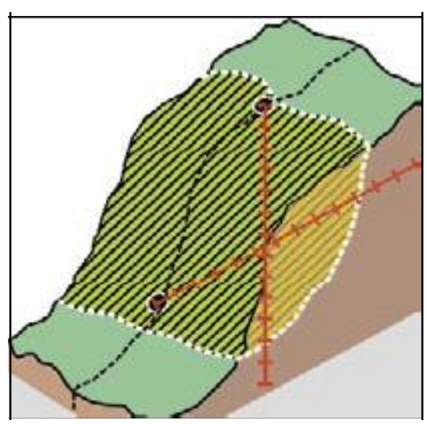
Special Features

- Precise
- Portable
- Lightweight but robust
- Reliable measurements (due to seating principle)
- Applicable in boreholes of any orientation Advantages
- Simple handling
- Comfortably carried in difficult terrain
- Cost savings due to low price and small diameter boreholes
- Visual reading and computer data acquisition of the measured values

Figure 2.5 shows a complete set of sliding deformeter.

2.2.1 Typical applications

Rock slopes and landslides



It is very useful for determination of potential slip surfaces (also in combination with Slope Indicator) in unstable rock as well as soil slope. Investigation of the landslide and to carryout the remedial measure it is very important.

Figure 2.6 shows the use of sliding deformeter at landslide slope.

Tunnels and underground openings

Monitoring of strain development and displacement along boreholes in soil and soft rock as well as it is to measure displacements in swelling rock during tunnelling and monitoring of the tunnel portals and portal slope, figure 2.7.

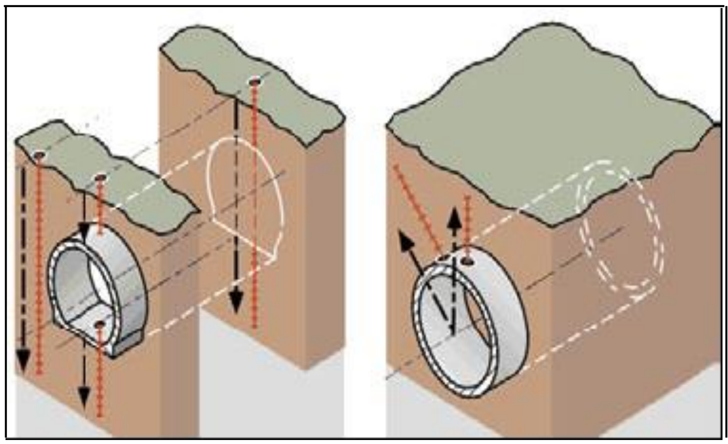


Figure 2.7 shows the use of sliding deformeter on tunnels.

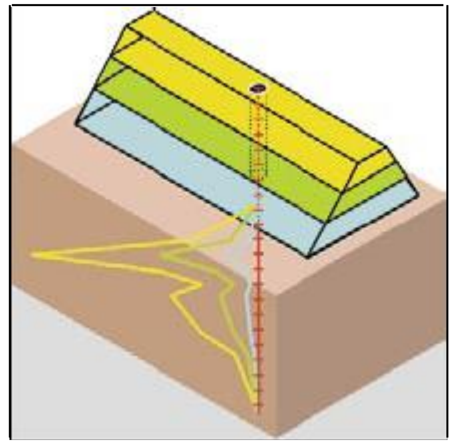


Figure 2.8 shows the use of sliding deformeter at embankment.

Embankments and dams

Monitoring of strain profiles in dams and their soil foundations during construction and it is very useful for long term behavior of the dam foundation, figure 2.8.

2.2.2 Measuring procedure

The HPVC measuring tube has measuring marks at every meter, which define the measuring line in sections of 1 m lengths. At new construction sites, the measuring tube can be easily installed during the work. At existing construction sites or in soft rock or soil, the measuring tubes are installed in boreholes and cemented with suitable cement or clay-cement slurries. The connections between measuring tube and measuring marks are compliant, allowing the measuring marks to exactly follow the displacements of the construction or sub-ground.

2.2.3 Measuring casing

A variety of measuring casings is available for the Sliding Deformeter:

- HPVC casing Ø 27/32 mm, measuring mark Ø 40 mm (Photo 1)
- HPVC casing Ø 51/59 mm, measuring mark Ø 67 mm (Photo 2)
- HPVC casing Ø 51/63 mm, grooved for combined use with Sliding Deformeter and borehole inclinometer with measuring mark Ø 67 mm.

Couplings are entirely of ABS plastic with cone-shaped measuring marks is available.

2.2.4 Calibration device

Calibration is essential to insure accuracy of the measuring system for long term deformation monitoring. To account for changes in the probe length, in case of loss of an instrument measurement can continue with a new prob, the probe is checked with a portable calibration frame, which is partly constructed of INVAR steel. Potential changes in the base length of the probe can be determined and accounted for using the calibration results. The calibration device can be used for all Sliding Deformeter types (SD27P, SD27I, SD51P and SD51I).

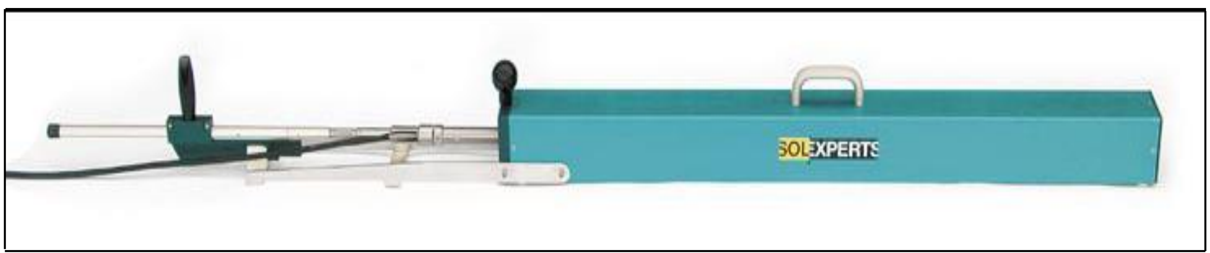


Figure 2.9 shows the complete set of calibration devices of Sliding Drformeter.

2.2.5 Readout unit

The digital readout unit is battery operated, with a serial interface (RS 232C) that allows transfer of data to a mini printer or to a PC (e.g. Notebook PC or Hewlett Packard Jornada). Optionally, the SDC can be used when using an electric displacement transducer with the probe type SD27I or SD 51I.

2.2.6 Data acquisition and analysis for the sliding deformeter

The field data acquisition equipment consists of a notebook PC or HP palmtop (e.g. Jornada). The integrated RS 232C interface and cable allow transfer of the measurement values to a PC.

For data analysis on a PC, the program TRICAL (Version 4.0) is provided, which is a menu-driven data acquisition and analysis program with built-in help functions. Graphic representations of the data can be viewed on the screen or sent to a plotter or printer. TRICAL makes possible the graphic and numeric analysis of data from the Sliding Micrometer, Trivec, Inclinometer (Slope Indicator) and the Sliding Deformeter. The software runs on Windows 95 or higher operating systems.

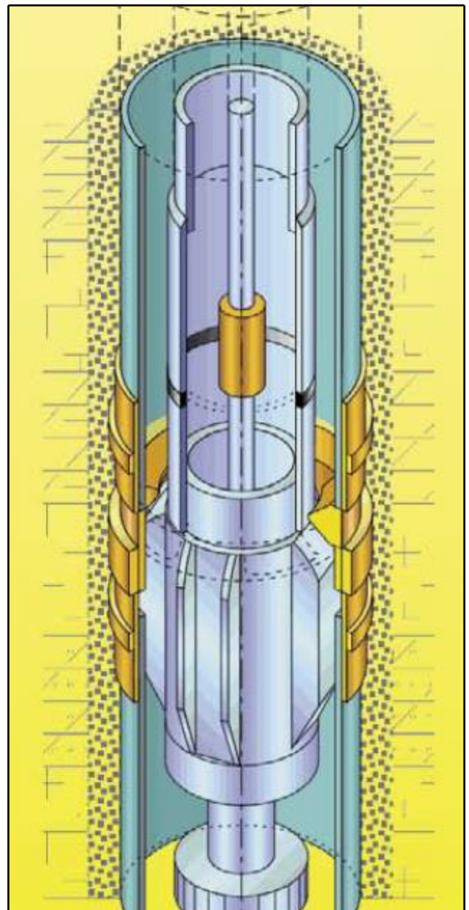
2.3 Sliding Micrometer

It is a portable device to monitor the strain distribution along a straight line with high precision. The Sliding Micrometer has been developed at the Swiss Federal Institute of Technology, Zurich.

The Sliding Micrometer is a high precision strain meter to determine the complete distribution of strains and axial displacements along a measuring line in rock, concrete or soil. Measuring casing, consisting of couplings with metallic measuring marks connected by a protective casing of HPVC, is firmly grouted in a borehole with a diameter of approximate 100 mm (or any precast tube-like opening in concrete). High precision measurements are achieved by means of the application of a cone-sphere principle for bracing the portable Sliding Micrometer in the measuring marks.

2.3.1 Measuring procedure

The probe, weighing only 3 kg, is inserted into the casing and moved in a step-by-step fashion between the measuring marks which are at 1.0 m intervals. Both the spherically shaped probe heads and the measuring marks are provided with recesses which enable the probe to slide along the casing from one measuring mark to the next (sliding position). By rotating the probe 45 and pulling back on the guide rods, the probe's two heads are tensioned between two adjacent measuring marks (measuring position). A linear displacement transducer (LVDT) inside the sensor head is activated, and the measured values are transmitted by a cable to the digital readout unit. A portable computer may be used to record the data via an RS-232 interface.



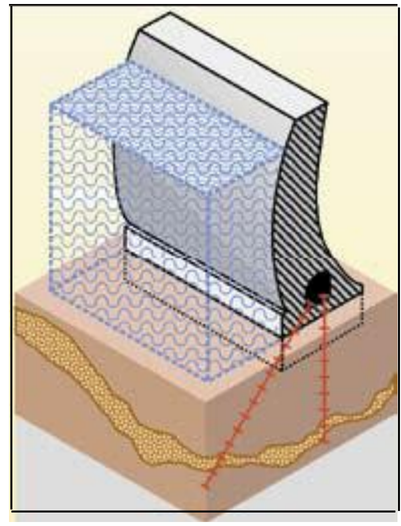
internal structure of the probe

Figure 2.10 shows complete set of Sliding micrometer and internal details of the probe.

2.3.2 Data acquisition

Field measurements are greatly simplified by using a hand-held computer, e.g. the HP Jornada. The computer can communicate via the serial interface RS 232 with the readout unit. Suitable software for the data acquisition on the HP Jornada (TRIVEC) and for the evaluation of the data in the office (TRICAL) is available.

2.3.3 Applications

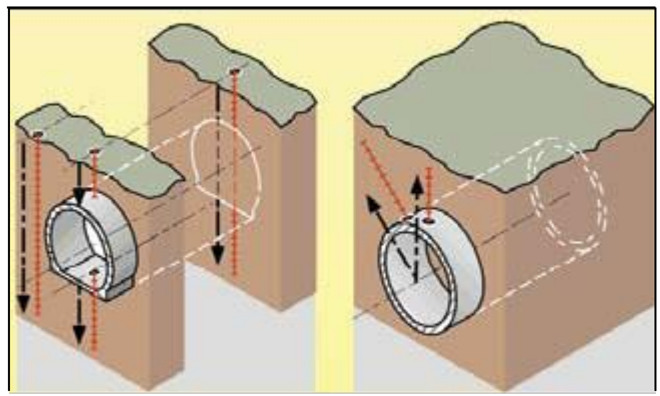


The Sliding Micrometer is used to its full advantage in cases where the complete distribution of strains and axial displacements along a straight line has to be recorded with great accuracy.

Figure 2.11 shows the use of sliding micrometer at concrete dam.

Concrete dams

Observation of the influence of loading Due to the change of water levels, changes in temperature or shrinkage of concrete. Study of interaction between abutment and rock is shown in figure 2.11.

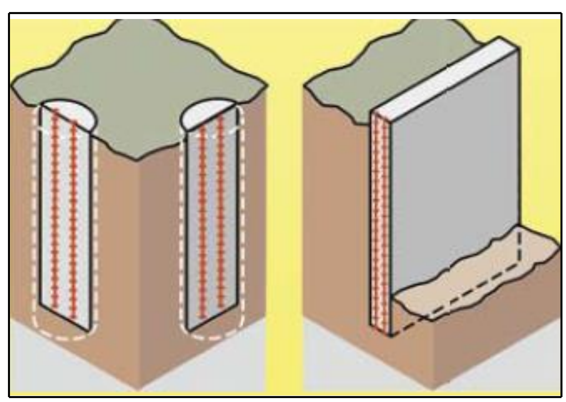


Tunnelling

In Tunnelling Sliding Micrometer is used for the determination of the loosened zone near the excavation and analysis of the swelling.

Figure 2.12 shows the application of sliding micrometer in tunnels

Piles and diaphragm walls



By observing the strains along the measuring lines on both sides of a pile or wall, it is possible to determine the curvature and with simplified assumptions to estimate the bending moment. Knowledge of the curvature along the structure also allows the determination of the deflection curve by way of integration.

Figure 2.13 shows the use of sliding micrometer at piles and diaphragm walls.

Important is the strain distribution in pile, it demonstrate the load transform to the soil along the pile/shaft with the measurement of length of the pile is determine.

2.3.4 Technical data

Probe

- Base length : 1000 mm
- Measuring range : 10 mm (+/-5 mm)
- Sensitivity : +/- 0,001 mm (SM / 0.01 SD)
- Accuracy : +/- 0,003 mm, standard deviation (σ) 0.03 SD
- Linearity : < 2% FS
- Thermal expansion : < 2% FS pro 10°C
- Working temperature : 0°C bis + 40°C
- Temperature Sensor Sensitivity : 0,1°C
- Water resistance : 15 bar

SDC (Solexperts Data Controller)

- Measuring range : +/- 10 mm
- Sensitivity : 0,001 mm
- Display : liquid crystal
- Operating temperature : 0°C to + 40°C
- Batteries : rechargeable
- Operation time of batteries: 5-10h
- External charging unit : 110 V, 220 V 150 - 60 Hz
- Serial interface : RS-232 C

Calibration device

- Base length : 997,5 und 1002,5 mm
- Temperature coefficient : < 0,0015 mm 1°C
- Temperatur Sensor : Sensitivity 0.1°C
- Empfohlene Betriebs temperature : + 18°C bis + 22°C

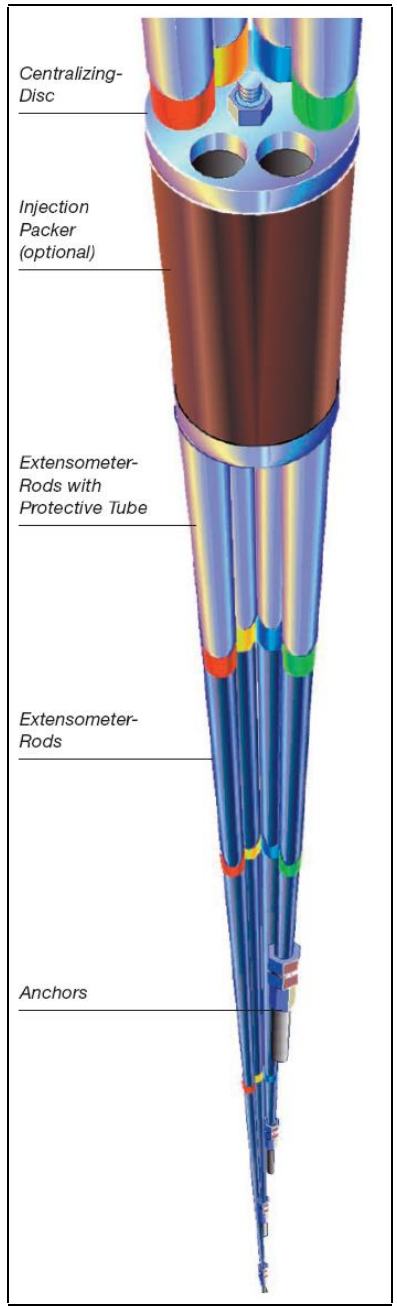
Casing

- Outside diameter : max. 60 mm, coupling 67mm
- Recommended borehole diameter : min. 100 mm

Guide rods

- Length of individual rod : 2 m or 1 m

Technical data are subject to change as per the request and site condition. Requested references, literature and examples of applications are available.



2.4 Modular Extensometer

It is very useful for measuring deformations and displacements in geotechnics, a new development based on the well proven Uni-Rod Extensometer. For automatic distance measurements often with extensometers, additional electronic displacement transducers are installed.

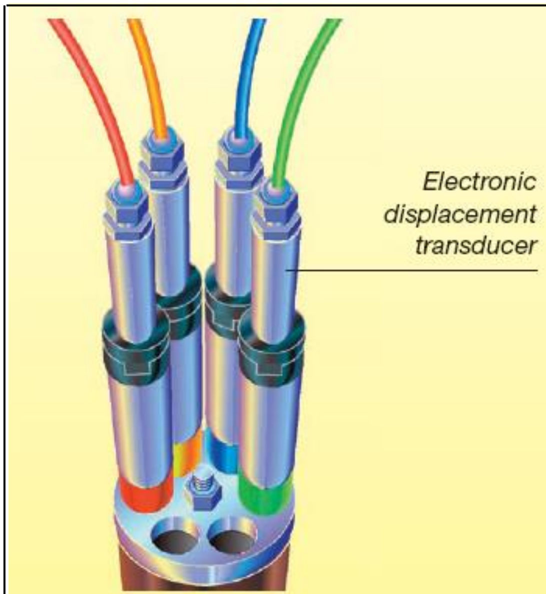
2.4.1 Extensometer measuring head

For a single measuring point it is machined of stainless steel and has a watertight protective cap. The adjustable contact bolt has a range of 130 mm, allowing measurements to be made even when deformations exceed the measuring range of the mechanical dial gauge or the displacement transducer. The transducer can be installed in the measuring head to allow measurement with the Solexperts GeoMonitor or a portable digital readout unit.

Figure 2.14 shows the details of the Modular Extensometer.

Centralizing Disc to bundle the single measuring heads into a multiple measuring head.

Extensometer Rods are made up of carbon fiber or GRP Ø7 mm and connect the anchor points with the contact bolt in the measuring head. The rods are cased within a HPVC protective tube Ø13/16 mm and thus isolated from the borehole. Custom layouts also can be changed.

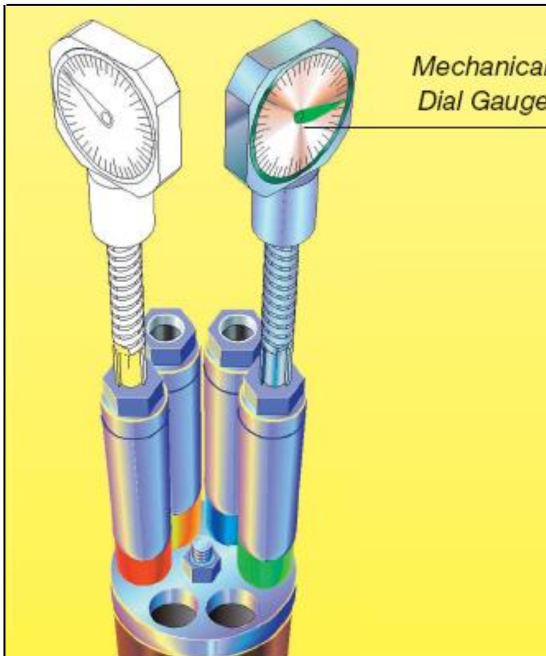


For automatic distance measurements ofthe Extensometers, electronic displacement transducers are installed.

Fig 2.15 shows the arrangement for automatic distance measurement

Extensometer Anchor Point constructed of reinforcement steel; A standard anchor with lengths of 250 mm or 500 mm, custom lengths is possible as per the requirement, diameter 17 mm.

To Ensure Free Movement of the extensometer rods, the rods can be temporarily detached from the anchors and removed to clean the annular space between the extensometer rod and the PVC protective casing.



For the manual measurement of the multi-point Extensometers, a dial gauge or the portable electronic displacement transducer with digital readout unit is used.

Figure 2.16 shows the arrangement for normal measurement of multi point Extensometers

2.4.2 Taking Measurements

1. Mechanical Dial Gauge

Measuring range: 50 mm, resolution 0.01 mm. Comes with a 3-position calibration unit and a key to adjust the contact bolt.

- ***Case*** *for the dial gauge, calibration unit.*

2. Portable Electronic Displacement Transducer with Digital Readout Unit

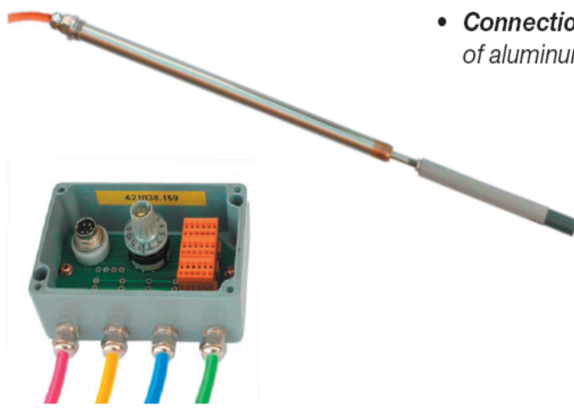
- ***Housing of stainless steel*** *with watertight displacement transducer (measuring range 25, 50, 100 or 250 mm) and 2 m long connecting cable.*
- ***Calibration and checking tool*** *made out of stainless steel.*

- ***Case*** *for the instrument, calibration unit and readout unit.*
- ***Digital Readout Unit,*** *battery operated, serial interface for transferring data to a data recording unit.*

3. Remote Measurement Unit *consists of:*

- ***Electronic Displacement Transducer*** *encased in watertight (to 15 bar) stainless steel housing along with watertight cable connection.*

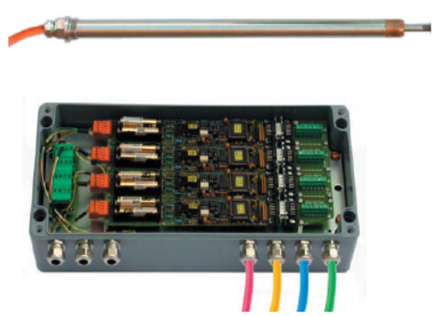
  The displacement transducer is installed directly into the measuring head after removal of the contact bolt to provide protection for the instrument. The measuring range is 25, 50, 100 or 250 mm.



- ***Connection Box*** *made out of aluminum or plastic.*

4. SOLO Data Logger

Stand-alone battery powered datalogger with connection for 6 displacement transducers. Solo has memory for 16000 measurement values and can work autonomously for many months.



- *The data transfer to PC is done with SoloWin Software through data cable or wireless modem.*
- *Solexperts GeoMonitor: automatic data acquisition system (see separate documentation).*
- *Solexperts Solo GeoMonitor: automatic data acquisition system.*

GeoMonitor

Figure 2.17 shows the other required additional accessories (from 1 to 4) for taking the measurement and monitoring.

2.5 Reverse Head Extensometer

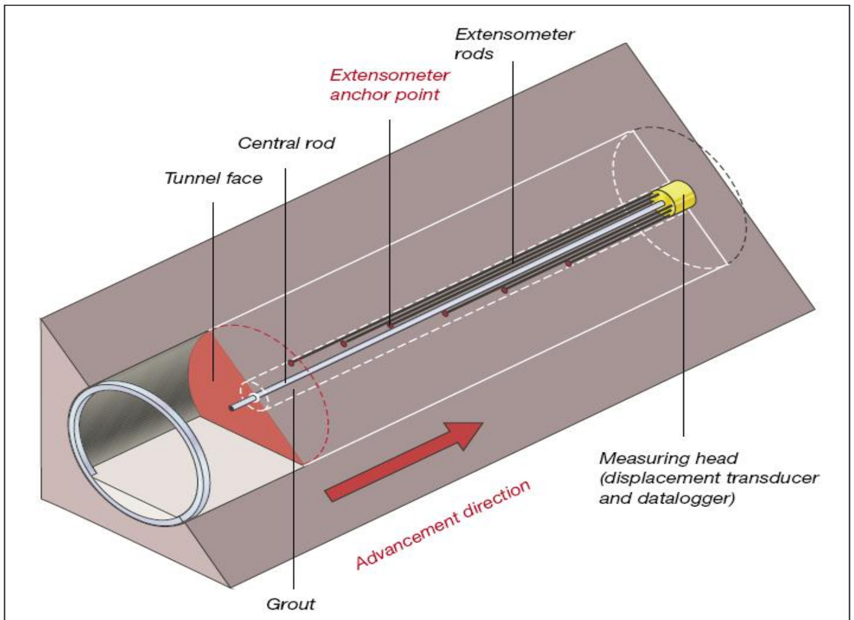
RH–Extensometer is for squeezing rock in tunnelling. The RH–Extensometer (Reverse Head Extensometer) is developed to make continuous deformation measurements particularly with regard to squeezing rock ahead of the tunnel face. As the tunnel advances the extensometer measurement sections becomes shorter as the central pipe and the anchors of the measuring points are cut away. Measurements are made even with the successive destruction of the measuring rods that occurs during the excavation procedure.

Application Alptransit Gotthard

RH-Extensometers equipped with 6 measuring points distributed over a length of 30 meters were installed in the Sedrun subsection of the Gotthard base tunnel.

The extensometer rods were removed (cut away) as the tunnel excavation advanced.

Data were stored by a logger in the measuring head and were transferred through the central rod using 2 redundant transfer systems (radio/wire).
The number or measuring points and measurement intervals can be customized.



RH-Extensometer: Displacement monitoring of the tunnel face

Readout of the frequently saved data is made at the tunnel face.

The data are extension measurements over time, showing the direct reaction of the face to excavation, anchoring and other support methods.

The rock mass in front of the face is consistently monitored by the RH-Extensometer when the installations are overlapping.

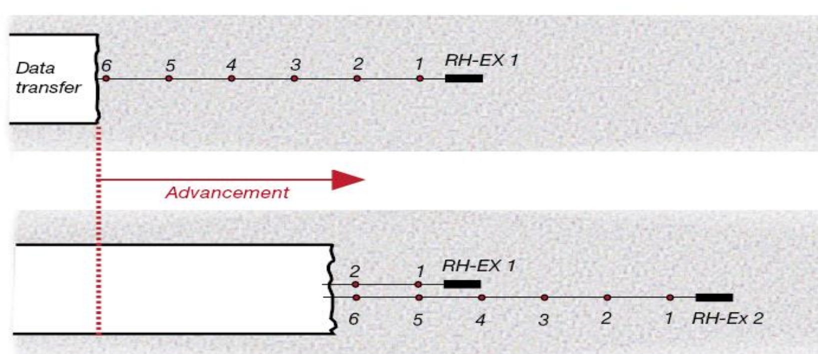


Figure 2.18 shows the application of the Reverse Head Extensometer in Alptransit Gotthard tunnel Switzerland.

Interpretation

Data can be evaluated using a number of graphical and analysis methods. Data are displacements relative to time. Classical evaluations of the displacements generally include integral or differential plots. Displacements can be displayed in relation to the tunnel advancement and distance of measurement points to the tunnel face.

This figure shows integrated displacement relative to the advancements of the face. The amount of the displacement, as the face advances, is clearly shown.

The status of the advancements is shown in relation to the installation point.

Example of an application (Gotthard base tunnel)

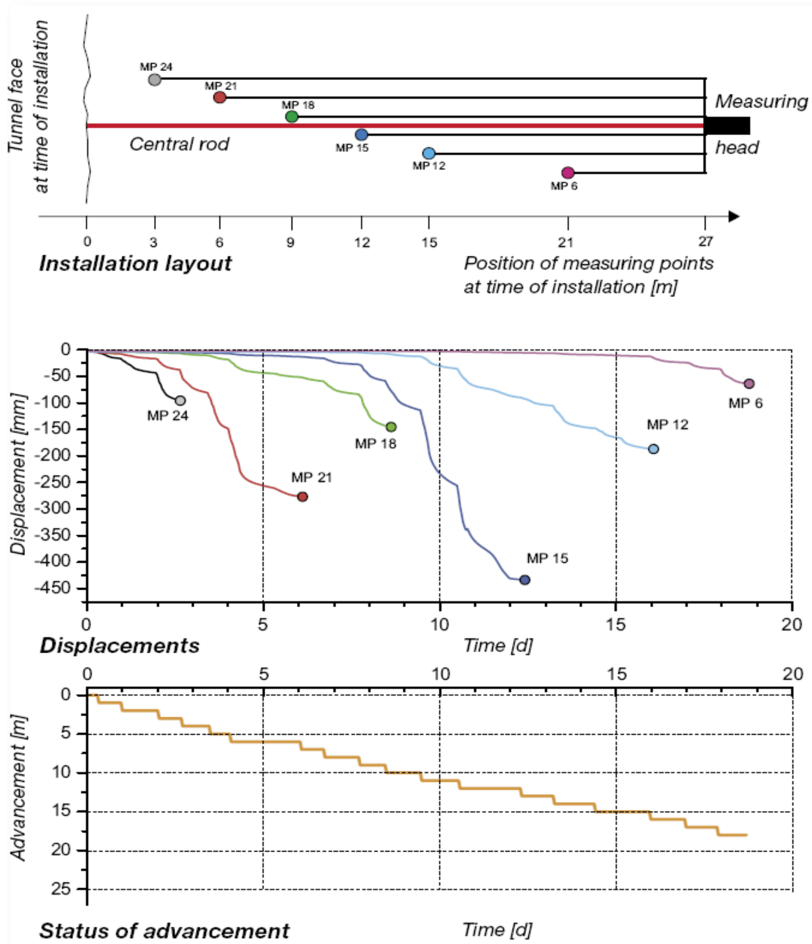


Figure 2.19 shows the application of the Reverse Head Extensometer at Alptransit Gotthard base tunnel Switzerland.

2.6 Fixed Re-Installable Micrometer

Fixed Re-Installable Micrometer is very useful to install for continuous deformation measurements along the borehole axis where sliding micrometer measuring tubes are installed.

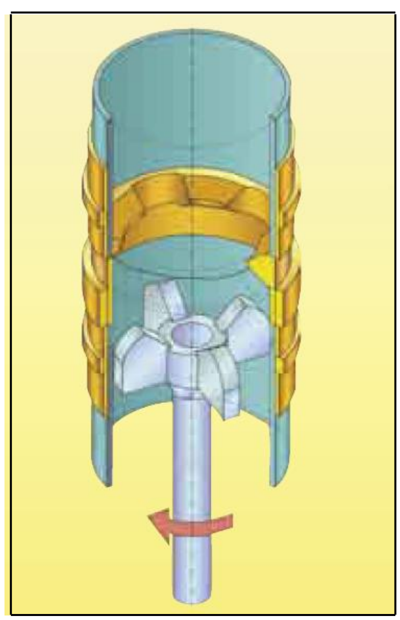


Figure 2.20 shows the internal details of fixed re-instable micrometer prob.

2.6.1 FIM - Fixed Re-Installable Micrometer

In applications where the Sliding Micrometer or the Trivec has been used, Fixed Re-Installable Micrometers (refered to as FIM) may be installed for continuous deformation measurements along the borehole axis. Each FIM is temporarily locked in place between two Sliding Micrometer or Trivec measuring marks and connected to the readout unit or data logger. When desired, the FIM may be removed from the borehole and readings at all measurement positions taken using the Sliding Micrometer or Trivec. For additional long term micrometer readings the FIM is again placed between two of the measuring marks.

Several FIMs (up to 5 elements) may be installed between measurement marks at any depth along the measuring line. Variable probe lengths allow the FIM to be placed between measuring marks of 1 to 5 meters apart. Two probes can also be installed immediately following each other. As with the Sliding Micrometer and Trivec probes, the cone-sphere principle is used to precisely locate the FIM between measurement marks. Precise location of the probe allows high precision measurements to be taken.

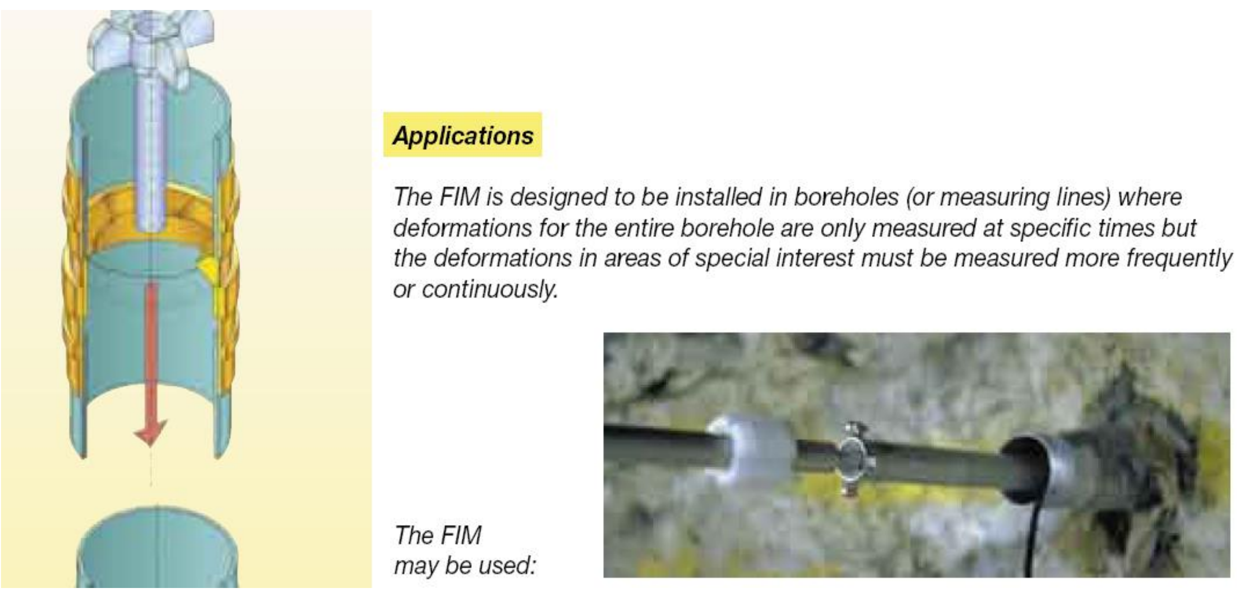
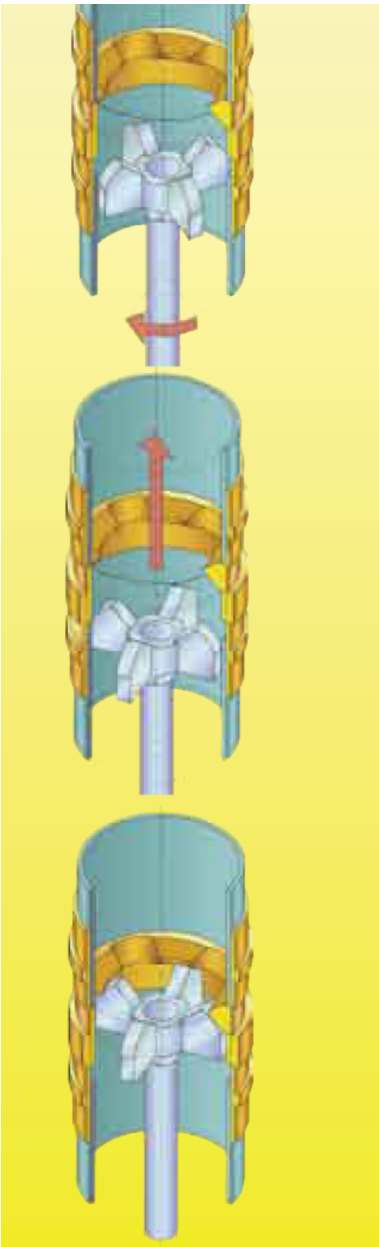


Figure 2.21 shows the application and installation of Fixed Re-Installable Micrometers in a borehole.

The FIM may be used:



- *to monitor deformations along measuring lines with limited access.*
- *or where access is only temporarily available (examples might include flooded measuring lines at reservoirs, weirs, or drifts, or measuring lines which are covered by snow).*
- *Readings from the FIM may be used to trigger alarms or other warning devices.*

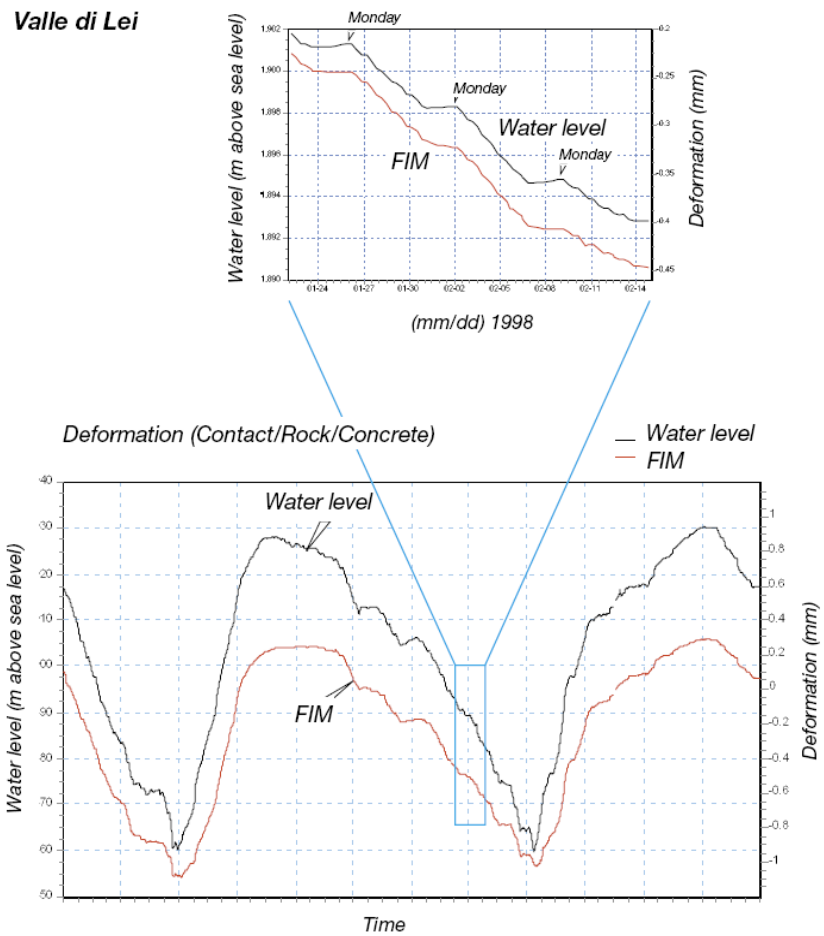


Figure 2.22 shows the other application of Fixed Re-Installable Micrometers.

Technical Data

- Base length : 1 to 5 meters
- Measuring range : ± 10 mm / ± 50 mm
- Resolution : 0.001 mm / 0.01 mm
- Sensor type : LVDT- Type displacement sensor linearity within ± 0.2% / linear potentiometric sensor
- Water tightness : tested up to 15 bar
- Cable : shielded four wire cable in protective sheath
- Optional : temperature sensor in addition to displacement sensor
- Readout units : for recording FIM data a variety of readout units and data loggers are available

2.7 Electrical Displacement Transducer

Applications

- *Where deformations and displacements have to be measured continuously and automatically and where the measuring positions cannot, or only with difficulty, be reached (e.g. for high retaining walls, rock slopes, measuring places subject to flooding).*
- *Combined with a borehole extensometer (e.g. the Solexperts Modular Extensometer) deformations, displacements, settlements or heaves can be measured along one or more measuring sections.*
- *To measure movements in one, two or three directions of joints, cracks or bearings (e.g. the movement of the bearings of bridges).*
- *With surface extensometers to measure the displacements of retaining walls, slides, bridge supports, etc.*

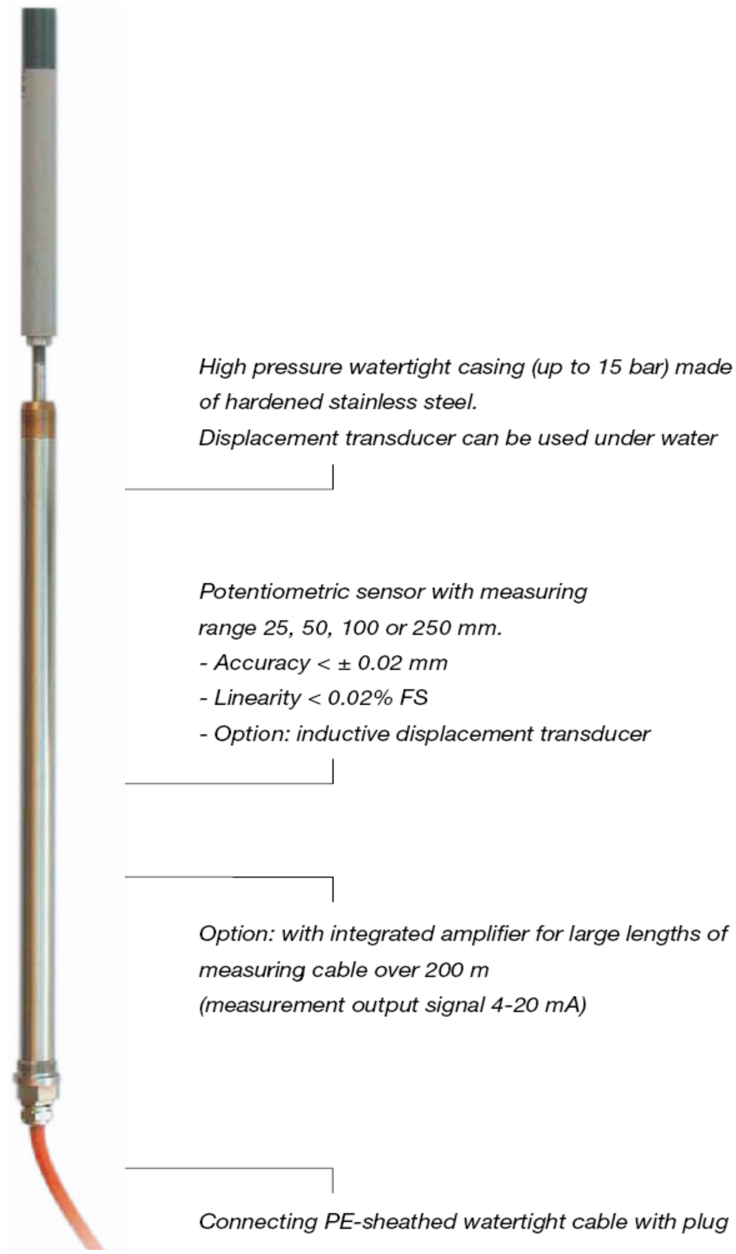


Figure 2.23 shows the instrument details of the Electrical Displacement Transducer.

Technical data

Range of measurement	**:** 25, 50, 100, or 250 mm
Accuracy	**:** < +/- 0.02 mm (up to 50 mm range)
Linearity	**:** < 0.2% FS
Watertightness	**:** up to 15 bar
Ø external	**:** 16 mm

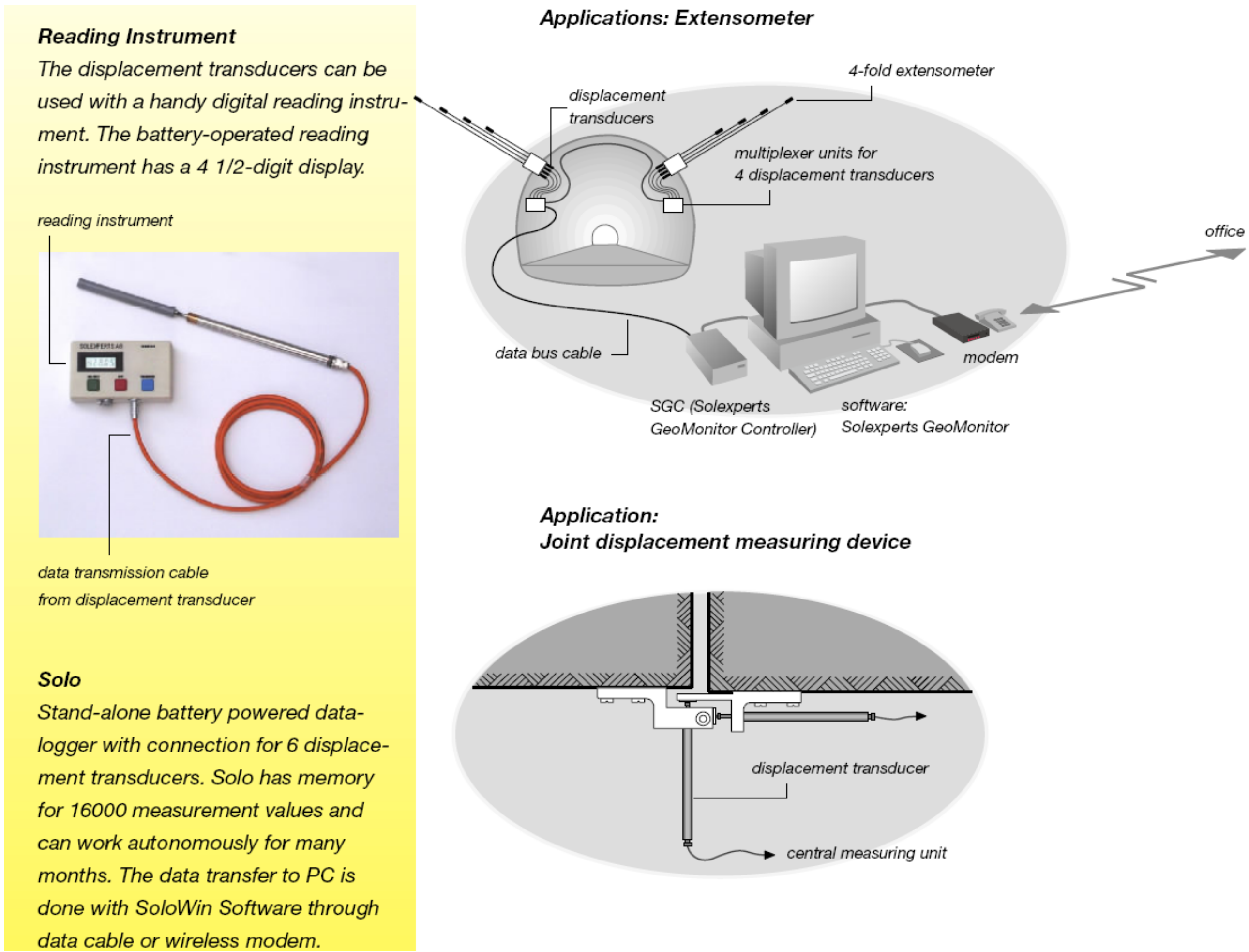


Figure 2.24 shows the Solexperts data acquisition system combined with multiple units of displacement transducer and extensometers.

2.8 Distometer ETH

Distometer ETH is developed by the Swiss Federal Institute of Technology, Zurich (ETH). This is a precision instrument for measuring length deviations using INVAR wire. The Distometer ETH is the ideal instrument for measuring convergence with high precision and reliability in situations where optical methods are not applicable. The instrument is suitable for difficult measurement conditions, poor visibility, or situations where a higher accuracy (1/10 mm) is required. The Distometer ETH has been proven in projects throughout the world - it is easy to use, robust and adaptable to many applications.

2.8.1 Typical Applications

- Deformation measurements of tunnel walls
- Monitoring wall displacement in excavations
- Deformation measurements of vaults affected by load types 1 and 2

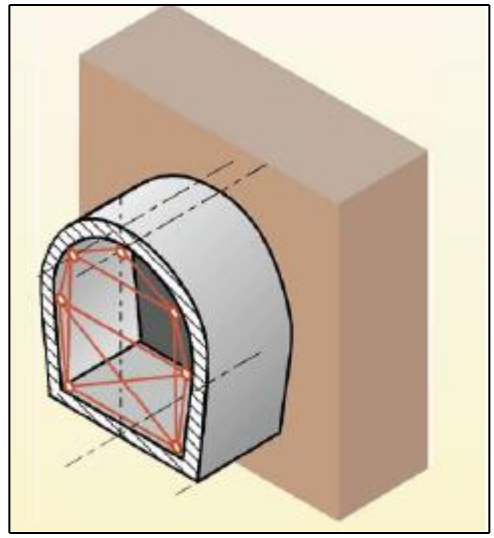
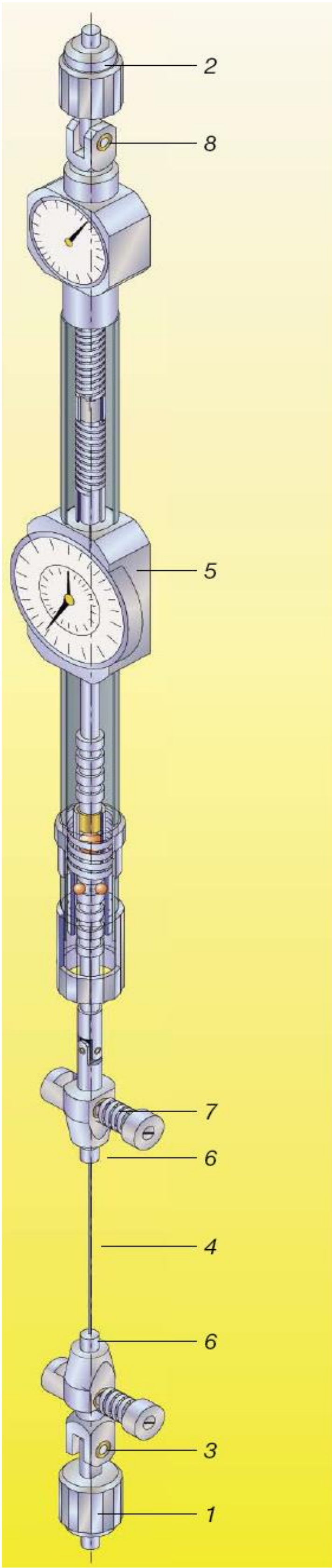


Figure 2.25 shows the application of distometer in tunnel.

2.8.2 Special Features

- Precise
- Portable, lightweight
- High measurement accuracy and reproducibility
- No electronics or electrical cable
- Lengths of any inclination can be measured (including vertical)

Figure 2.26 shows the installation of distometer in tunnel.



The «Distometer chain» consists of these main components

Invar wire

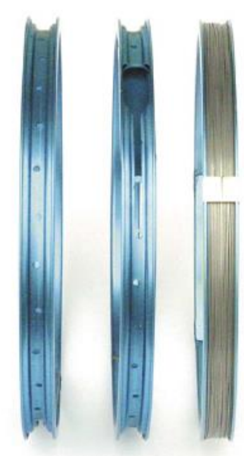
An Invar wire (4) which, under a constant preset tension, provides a stable, uniform length largely independent of temperature. The wire is equipped with two couplings (6) which attach with special adaptors (7) to swivel joints (3, 8) for precise connection to the Distometer on one end and to a secured point on the other.

Setting Bolts

Two Setting bolts (1) and (2), to secure the reference points at the objects to be measured. Various types of measurement bolts are provided. For every type of measured object there is an appropriate setting bolt for grouting or adhering to concrete, brick, etc., for welding to steel surfaces, or for use in shotcrete linings.

Tension Gauge and Displacement Gauge

A Distometer (5) which contains a Tension Gauge and a Displacement Gauge: During measurement, the tension gauge holds the invar wire under the required tension. It consists mainly of a precision steel spring whose elongation is a measure of the tension affecting the invar wire. The desired tension (elongation) can be preset to a required value on the gauge. The displacement gauge measures the distance between the distometer and the attached end of the invar wire.



The individual Invar wires of successive lengths are stored on spools in a storage case

Types of setting bolts

Figure 2.27 shows the various other accessories of Distometer.

2.9 Clinometer BL200B

This is a portable instrument for high precision measurements of the change in inclination of structures. It is a development of the Rock Engineering and Tunnelling Department of the Swiss Federal Institute of Technology Zurich (ETHZ).

The instrument

The electronic Clinometer BL 200 B is a portable handy and highly sensitive measuring device to detect inclinations. It permits to identify at an early stage exposures on structures, such as tilts so that adequate provisions can be taken in order to protect the constructions.

The Clinometer BL 200 B is especially used in the following fields:

- *Tunnelling*
- *Building Construction*
- *Bridges*
- *Concrete Dams*
- *Excavations*

Measurement Equipment

The measurement equipment consists of these components

- *portable Clinometer instrument with high-resolution "electronical" pendullum*
- *measurement console which can be hung to measurement point of KSB type*
- *transport case*

The measurements can be taken at inconvenient places thanks to LCD display which is integrated in the Clinometer.

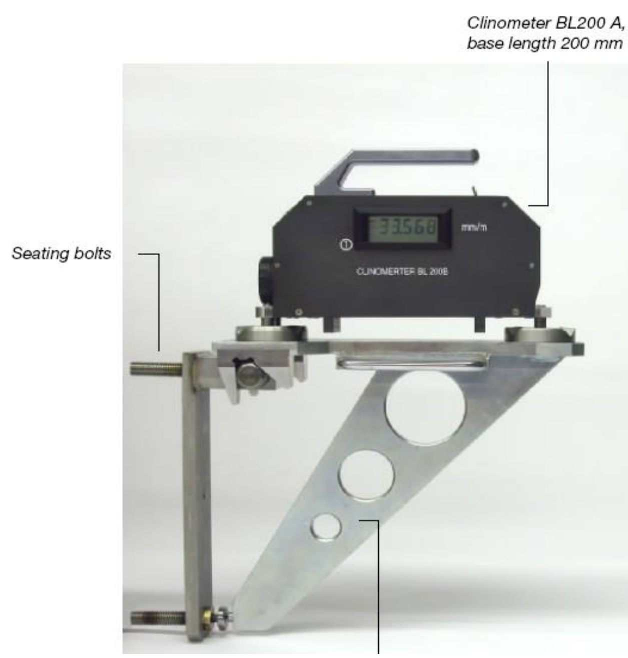
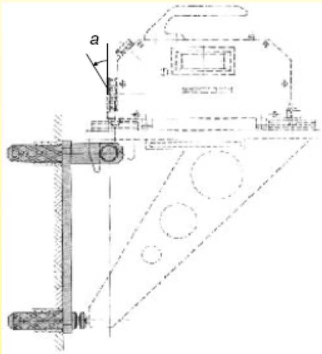
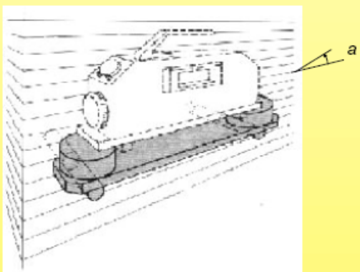


Figure 2.28 shows the instrument set up and use Clinimeter BL200B.

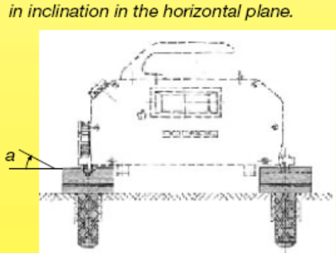
Seating bolts and bracket KSB, for measuring change in inclination in the vertical plane normal to the wall.



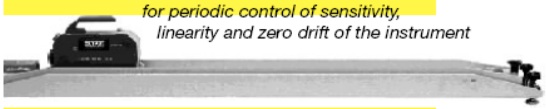
Seating bolts VB, for measuring change in inclination in the vertical plane parallel to the wall.



Seating bolts HB, for measuring change in inclination in the horizontal plane.



Clinometer calibration device KMK-1000 for periodic control of sensitivity, linearity and zero drift of the instrument



Measurement

The Clinometer is placed on special seating bolts permanently mounted on the structure to be measured. The placement of the instrument is statically determined without any constraints, enabling high reproducibility of the readings. The change in inclination of structures is determined by calculating the difference between measurement and zero reading. At every measurement, readings separated by 180 degrees are taken. The liquid crystal display shows the result about 5 seconds after the instrument is set.

Calibration device

The Clinometer calibration device is used for the periodic control of the sensitivity, linearity and the zero shift of the Clinometer. The levelling of the calibration device is achieved by a highly sensitive coincidence level, exhibiting long-term stability.

Seating Bolts

Depending on the application, various types of seating bolts are used so that rotations of a horizontal and vertical plane may be determined. The seating bolts are cemented to concrete, brickwork or rock. Steel structures require the bolts to be welded in place.
The placement of the instrument on the seating bolts is highly accurate (< + 2/1000 mm/m) as a result of the special seating principle employed

Protection of seating bolts

To protect the seating bolts against damage, protective covers made of stainless steel are used.

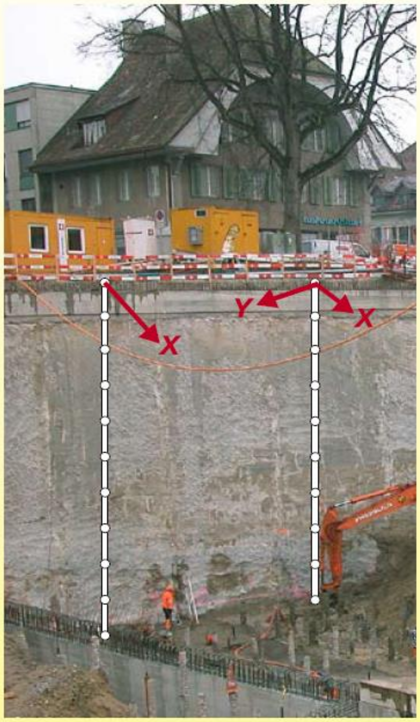
Technical Specifications

	Clinometer BL 200 B / BL 1000 B
Base length:	200 mm / 1000 mm
Measuring range:	± 17.5 mm/m (± 1°)
Sensitivity per Digit:	± 0.001 mm/m
Accuracy:	< ± 0.2% (full scale)
Linearity:	< ± 0.2% (full scale)
Operating temperature:	0° to + 40°C
Storage temperature:	+ 18° to + 22°C (Constant room temperature)
Battery life (3x1.5V):	20 to 30 hrs

Figure 2.29 shows the various application of Clinimeter BL200B.

2.10 CLINO - Inclinometer Chain

Inclinometer chains are used to monitor displacements in the structure or along the axis of vertical or horizontal borehole.

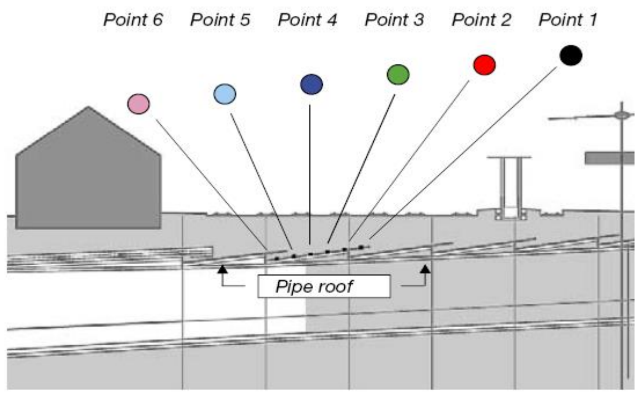


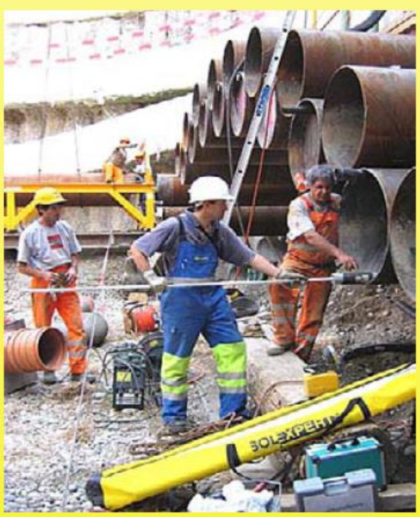
Measurement procedure

The CLINO-Chain measures transversal displacements at multiple points along a borehole axis.
The instrument is composed of sequentially mounted probes that are of variable length (min. 50 cm). These probes are connected together by swivel heads with spring-loaded wheels that guide the probe in the center of the grooved casing and fix the chain at the desired position.
Each probe includes a high-precision and highly-stable uni- or biaxial inclinometer sensor.

Applications

The Clino-Chain is often used to measure displacements in tunnels and excavation pits, especially in urban areas. Additionally, it is applied to monitor and localise vertical displacements beneath embankments and along instable slopes or earth dams.





Simple and flexible system

- *The CLINO-Chain is completely retrievable and reusable*
- *The installation depth of the chain in the borehole is easily adjusted on-site.*
- *The joint between the single elements is the support point, so the inclination is precisely measured.*
- *Only one cable is used for the entire CLINO-Chain.*
- *The measurements are directly reported in mm/m and read by a PC.*

Figure 2.30 shows the various application of CLINO Inclinometer Chain.

2.10.1 Some important features:

- Easy to install chain of inclinometers
- Innovative joints (static-determinate bearing for each probe)
- Only one data cable
- Automatic measurements of relative inclination
- Vertical measurements, uni- or biaxial
- Horizontal measurements, uniaxial
- Data directly in mm/m
- Compatible with Solexperts GeoMonitor, WebGeoMonitor and WebDavis
- Easily retrievable

Figure 2.31 an example at Base Tunnel Luzernerring

Figure 2.31 is an example at the Luzernerring tunnel passes beneath the existing St. Johann railway station (Switzerland), the SBB railway tracks and the Luzernerring Bridge. The tunnel was advanced using the pipe roofing system. The vertical displacements were monitored by CLINO-Chains installed in the pipe roof casings. The measured data were displayed graphically by WebDavis and were available on a password protected Internet site at anytime and from anywhere.

2.10.2 Measurement casings

The CLINO-Chain is installed in a casing with guiding grooves (inclinometer casing). The casing is generally installed perpendicular to the expected displacement direction. Several inclinometer casings are available to meet the project requirements:

- Standard Solexperts Inclinometer casing constructed of PVC, outer diameter 70 mm, inner diameter 58 mm, self-centering couplings every3.05 m.
- If large displacements are expected in the direction of the casing, the casing is equipped with telescope couplings.

2.10.3 Data acquisition and visualisation

A number of possibilities to monitor and present the data are available:

- Manual readout with a digital readout device.
- Autonomous data logger (Solexperts SOLO Data Logger), storage of the measurements and periodical readout on a PC with the Solexperts SOLOWIN Software.
- Real-time measurement with Solexperts GeoMonitor II and WebGeoMonitor, allowing one or more CLINO-Chains and additional sensors to be connected.
- Visualisation of all measurements on the Internet by Solexperts Web DAVIS:

2.11 Chain Deflectometer

A Development of Swiss Federal Institute of Technology Zurich (ETHZ)

2.11.1 General

The Chain Deflectometer is a multiple deflectometer used for the automatic monitoring of subsurface deformations, such as in slopes, around excavations, or beneath dams. The Chain Deflectometer is installed in a specially machined casing, normally of HPVC, which is bonded to the soil, rock or concrete by grouting. Unlike the in-place inclinometer, the Chain- Deflectometer can be installed in boreholes of any direction or inclination. The rotation between two rods of the Chain-Deflectometer is measured in two directions, x and y, by a highly sensitive electronic joint. After the Chain Deflectometer is installed in the borehole, it is connected to the Solexperts Data Controller and can be automatically monitored remotely, if connected with a personal computer. The values can then be displayed numerically and graphically. If the system is connected to a modem, the data is be transmitted to the offices of the engineers in charge.

2.11.2 Components

The Chain Deflectometer consists of heads with electronic joints, connecting rods, and heads at each end of the chain. Each head with an electronic joint holds the element which measures deflections in the x and y directions between two connecting rods. This element also includes the amplifier, the signal conditioner and the multiplexer. This arrangement enables readings of all elements of the Chain Deflectometer over one cable. The heads are connected to each other with connecting rods. The connecting rods, with lengths of 1 or 2 m (or longer) also serve as the lead-through for the signal cable. Using the Solexperts Data Controller (SDC), all the measurement values of the Chain Deflectometer can be manually read using local mode; the address of the electronic joint to be read is entered via the keyboard, and its values, x and y, are displayed on the digital display. The Solexperts Data Controller is battery operated and can be used with various other portable instruments.

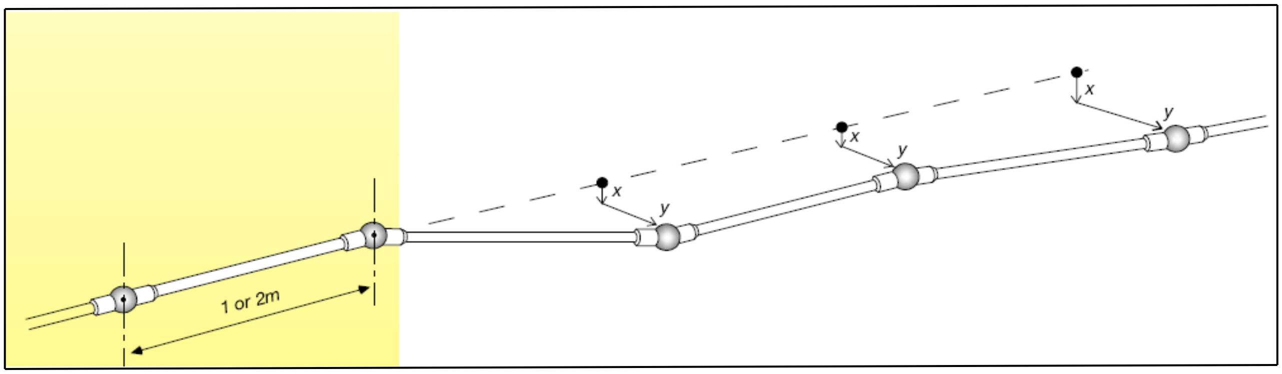
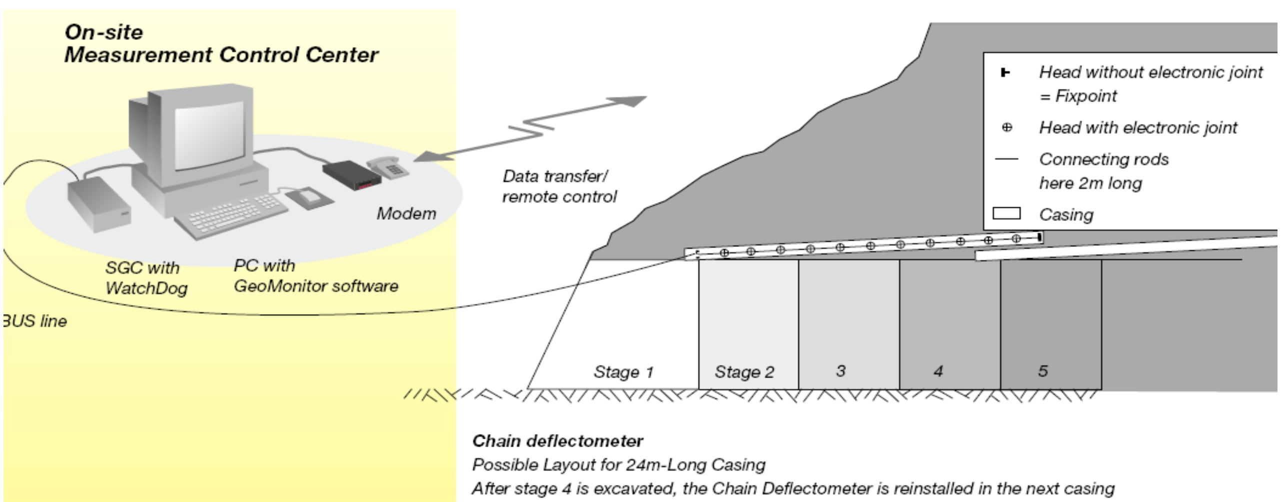


Figure 2.32 shows the function of chain deflectometer in a multiple automatic monitoring of subsurface deformation.



*The sensors within the Chain-Deflectometer can be integrated into the **Solexperts GeoMonitor**, an automatic, computerized data acquisition and monitoring system. The **GeoMonitor** system monitors up to 240 different sensors including temperature sensors, flow meters (gas and liquid), pressure sensors, extensometers, strain gauges, clinometers, etc. Separate documentation describes this system.*

Technical Specifications

Head with electronic joint

Signalhandling:	*integrated signal conditioner (amplifier) and multiplex-system*
Diameter outside:	*42 mm*
Measuring range:	
per 1m base length	*+/- 17.5 mm deviation*
**(optional double measuring range upon special request)*	
Sensitivity (one digit on SDC):	*5 m/1 m base length*
Individual calibration of every measuring head	
Linearity:	*< +/- 1%*
Water resistance:	*15 bar*

Figure 2.33 shows the application of chain deflectometer on pipe canopy at tunnel crown.

2.12 Dilatometer Measurement

To determining the in-situ deformation properties (E-modulus) of rock and soil is an important design parameter of tunnelling. Dilatometer measurements are to be performed in an exploration borehole with a borehole probe in order to determine the deformation properties of rock masses in-situ for a planned project site as the arrangement of dilatometer and other accessories are shown the diagram below (figure 2.34).

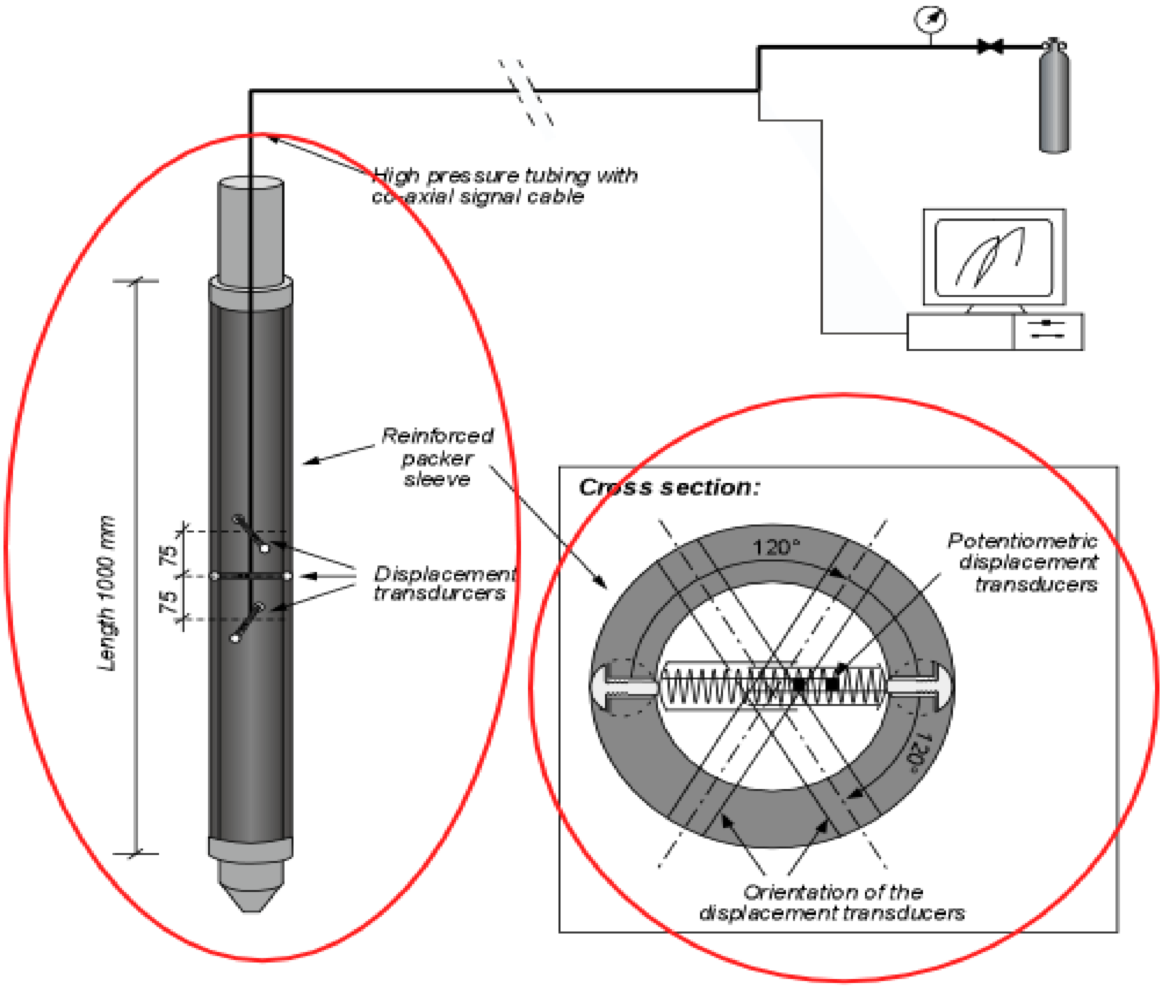


Figure 2.34 shows the internal structural details of the dilatometer probe

Dilatometer Equipment

- Dilatometer probe with 3 displacement transducers
- Coaxial cable
- Control unit
- A/D-Converter (Logger)
- Bottles with compressed nitrogen

- Available diameter of the Dilatometer probes: 93mm, 120mm, 140mm and 210mm
- Maximum pressure normally 180 bar but now it can be up to 300 bar for special case.

Figure 2.35 Installation of the dilatometer probe in exploratory borehole for Emosson pumped storage hydropower plant (Switzerland) Dilatometer probe, Sedimentation tube and Installation rods.

2.12.1 In-situ testing procedure

The probe is placed in to the borehole with a drill rig via Solexperts tubing to the desired depth (max 100m). The high pressure hose with the coaxial data transmission cable is installed simultaneously.

By expending the rubber packer with the compressed air, pressure is applied to the borehole wall in steps.

The magnitude of the steps depends on the deformability of the formation being tested. Through several cycles of applying and releasing pressure, the deformation and elasticity moduli are determined. Creep tests over several hours provide further important information about the behavior of the formation under long-term load.

Example of the test in Soil

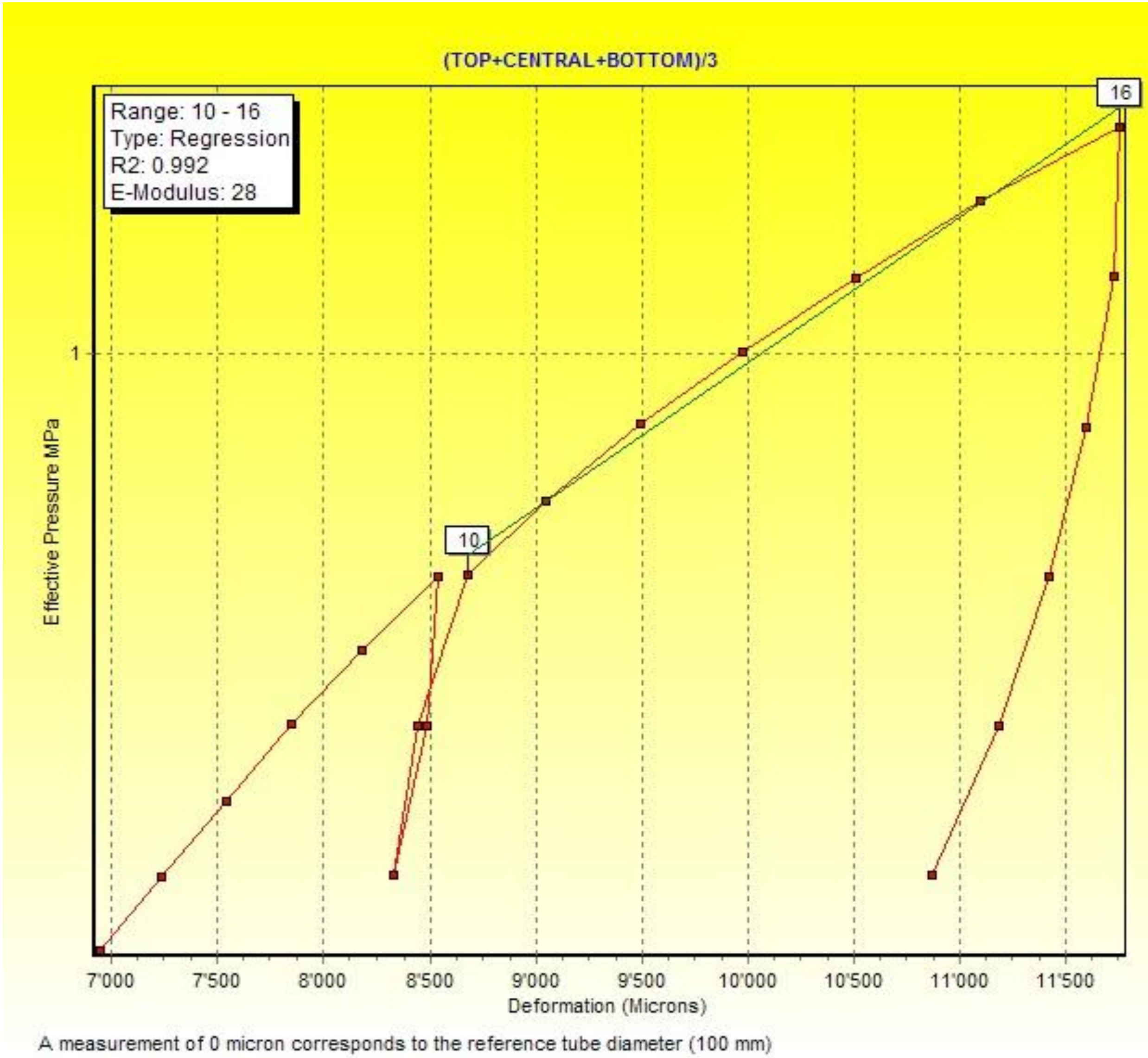


Figure 2.36 shows an example of the test result on soil.

2.12.2 Analysis of the data is done automatically by software Dilato2

The moduli are calculated based on the formula of Lame for a tubing of infinite thickness. A Poisson ratio of .33 is assumed if no laboratory measurements are available.

$$E = (\Delta p / \Delta d) * d (1+\nu)$$

Δ p = Pressure differences, *Δd = change of diameter*

d = borehole diameter, *ν = Poisson ratio*

Example of the test in Rock

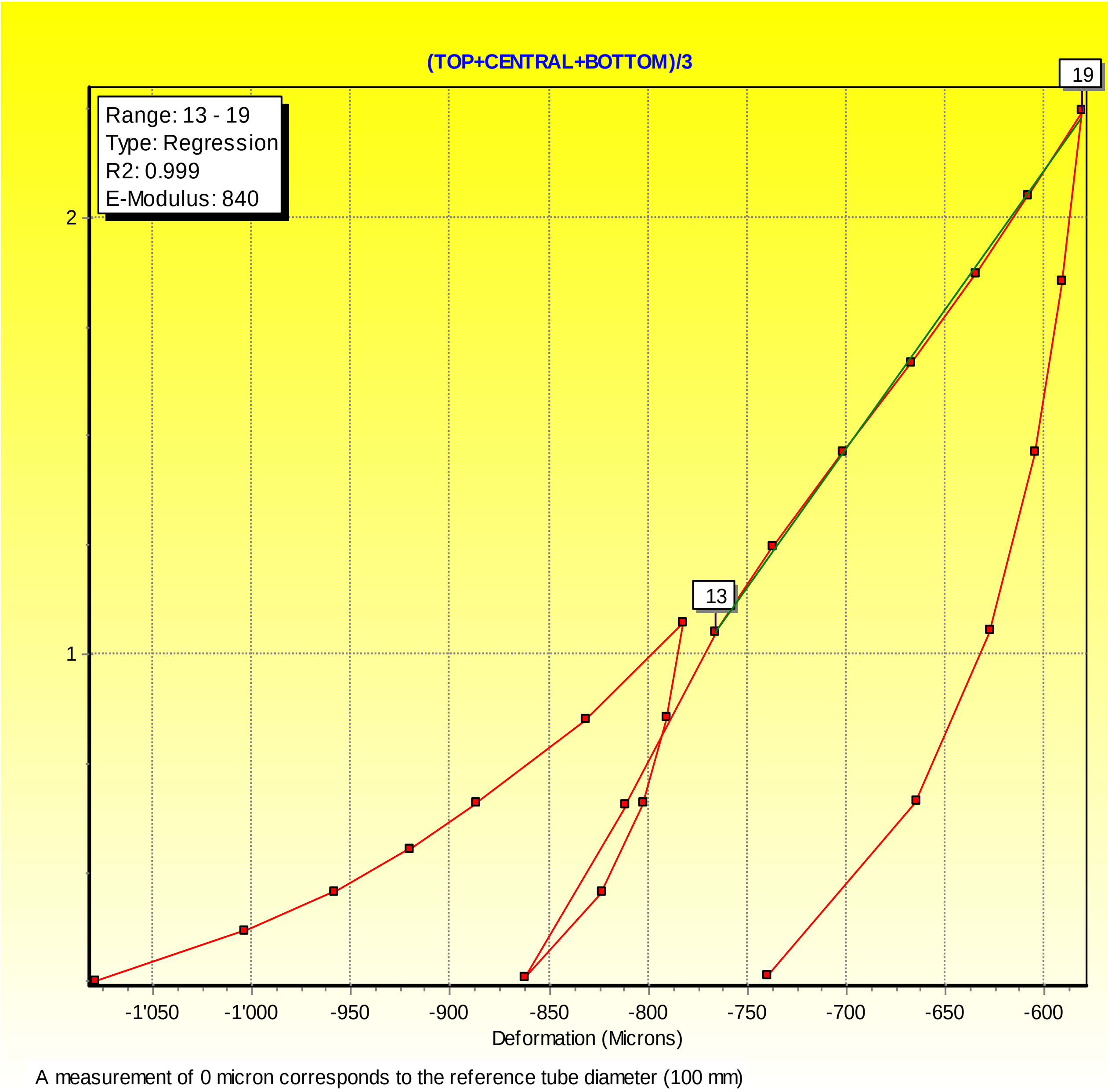


Figure 2.37 shows an example of the test result in rock.

2.13 Plate Loading Test

Plate loading tests are performed like dilatometer test for in-situ determination of deformability of the rock mass. To obtained parameters which represent jointed rock masses, the load bearing plate most cover several discontinuities. Therefore load bearing plates of 0.4 to 1.12 m in diameter are used to execute test that yield rock mass deformability values of a few cubic meter of rock. Most of these tests are configurated with two bearing plates (twin plate loading test), where the opposite face of the tunnel is used as an abutment. This geometry enables execution of two tests with the same axis simultaneously.

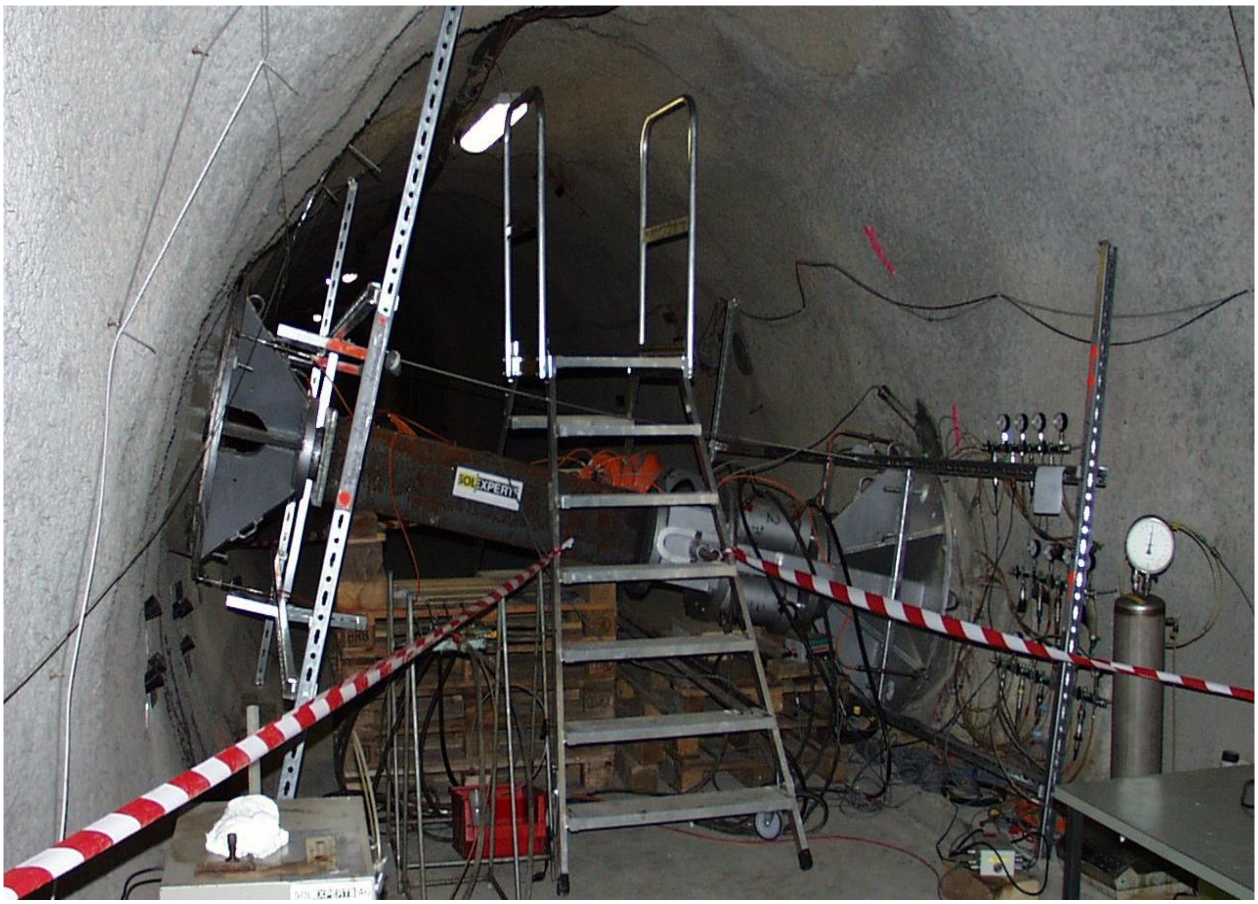


Figure 2.38 shows the final arrangement of Plate Loading test at Mont Terri Research Rock Laboratory site.

2.13.1 Equipment

Plate loading apparatus: The equipment consist of a plate loading apparatus that is assembled at site from several steel elements in order to bring both bearing plate in contact with the opposite tunnel wall.

Drum-like extinction steel elements consisting of two circular plates combined with steel ribs or heavy steel beams are used. Depending on the size of the

bearing plates and the maximum load that has to be applied, the load is generated by a single hydraulic jack or with several jacks combined.
The space between bearing plate and the rock at the tunnel wall has to be filled with small aggregate concrete. This mortar pad guarantees a proper load transmission to the rock.

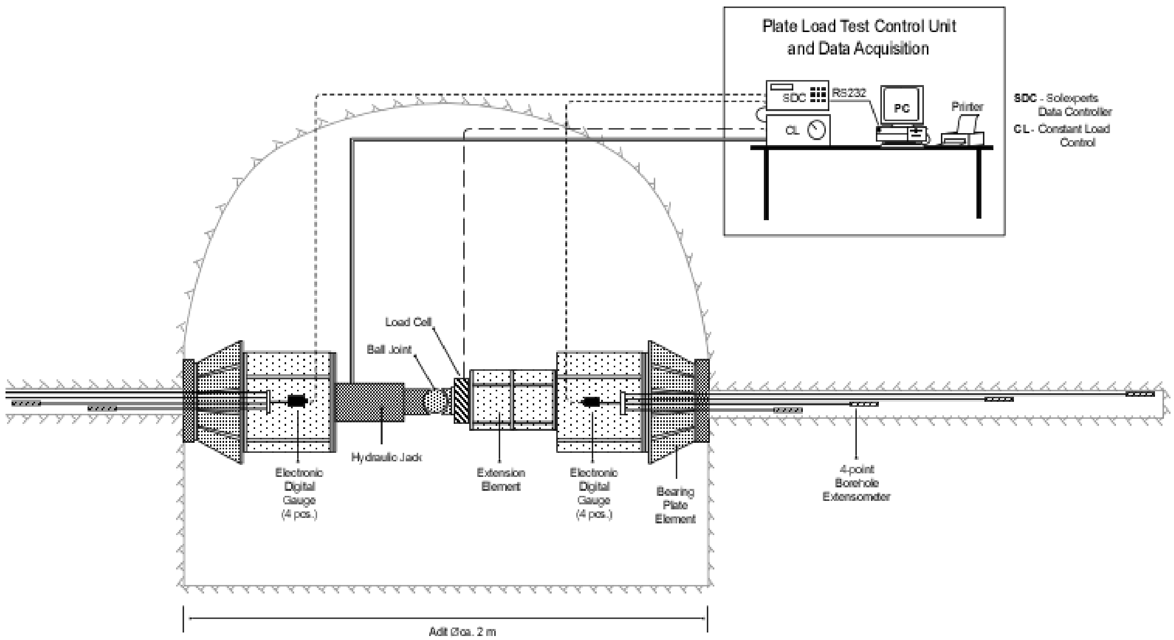


Figure 2.39 an sketch of the complete setup of the plate loading test.

Figure 2.40 shown the loading plates prepared at workshop for the plate loading test.

2.13.2 Deformation and displacement measurement

The measurement of deformation of the rock mass below the loading plates is made with two multiple-point borehole extensometers which are installed in boreholes centered below he two load bearing plates. Two 4-point compact extensometers with integrated measuring heads have proved to be best suited. The depth of the four anchors are chosen according to the diameter of the load bearing plates, usually with the deepest anchor is a distance of six diameters from the plate and other anchors within a distance of three diameters. It is recommended that displacement transducer have a range of 100 mm and a resolution of 0.001 mm. The displacement of the two plates is recorded be means of three displacement transducers on each plate. They are fixed to steel frames which are mounted to the tunnel wall outside of the zone of influence (fixation in a distance of 3-4 times the diameter of the plates from their center).

2.13.3 Load control device

The control of the load is important for proper execution of a plate loading test. A special load control devices maintains a constant pre-set pressure over an extended period of time. It consists of a hydraulic pump, a control circuit and an oil reservoir. Pressure up to 600 bar can be regulated by setting an upper and a lower pressure threshold value. A decrease of the pressure in the system below the lower threshold value activates the pump, whereas an over-pressure is released by automatic opening of an electrical valve.

A load control device is almost indispensable when carrying out he creeping tests where the system pressure tends continuously to decrease as a consequences of displacement of the bearing plate.

2.13.4 Measurement of applied load

Single jack loading equipment usually allows measurement of the load using a load cell which is installed with in the plate loading apparatus. Further, the load can be calculated from the oil pressure in the jack measured with a pressure sensor. This is the technique of regarding the applied load when working with a multiple jacks apparatus.

2.13.5 Data acquisition

A total of about 20 parameters are measured and recorded during a test. Solexperts has developed their data acquisition system for various types of application under harsh field conditions. All parameters are recorded during a test with a GeoMonitor station on an industrial computer they are stored and displayed in real-time. The system has a restart-feature which automatically restarts the program after a power failure.

2.13.6 Tests procedure

Generally, the tests are carried out according to the recommendation of ISRM (1985) with cyclic loading and unloading. For each load cycle, the load is increased stepwise to the peak load of the cycle. Then it is stepwise decreased to a base load of approximately 0.15 Mpa. As stated above, the load control devices has an important function in order to maintain the oil pressure for the hydraulic jack at a constant level.

Often creeping of the rock is an important mechanism of deformation. Therefore ISRM recommends maintaining the peak pressure of each load cycle for an extended period of time (e.g for 48 hour). With a recommended 24-hr period maintaining the base load to monitor the elastic re-deformation, a plate loading test with five cycles lasts at least 15 days.

2.13.7 Data analysis

The data recorded by the data acquisition system can easily be imported into Excel spreadsheet for analysis. The modulus of deformation from initial loading, the modulus of elasticity from unloading and the modulus of reloading are evaluated for each cycle. The moduli are calculated based on data of displacement of the **bearing plate (Δs)** and **the applied load ($\Delta\sigma$)** according to the theory of the elastic isotropic half-space:

$$E = \omega.(1-\nu 2).r.\ \Delta\sigma/\Delta s$$

Where ν **is the Poisson's ratio**, ω **is a coefficient** depending on the type of load plate (stiff or flexible) and the location of the measurement (in the center or near the rim of the plate). The coefficient ω equals p/2 for a stiff plate, but 2 for the center and 4/p at the rim of the plate in case of using a flexible plate (Mueller et.ai., 1985).

In addition the moduli can also be estimated at different depth underneath the bearing plate based on the data of the multiple-point extensometer. Unal (1997) proposed a method of estimating both the modulus of deformation and the Poisson's ratio using a least - square method with data of multiple-point extensometers. This method requires placement of at least four measuring point within a depth of two plate diameter. In our opinion it is recommended using a value of the Poisson's ratio from laboratory drill core testing and installing the extensometer according to the method of ISRM (1981) as proposed above.
Figure 2.41 shows the displacement measured at the surface of the bearing plates as a function of the applied load and the calculation deformation moduli for each load cycle. Figure 2.42 represents the displacement measured on the surface of the loading plates and with the multiple-point borehole extensometer.

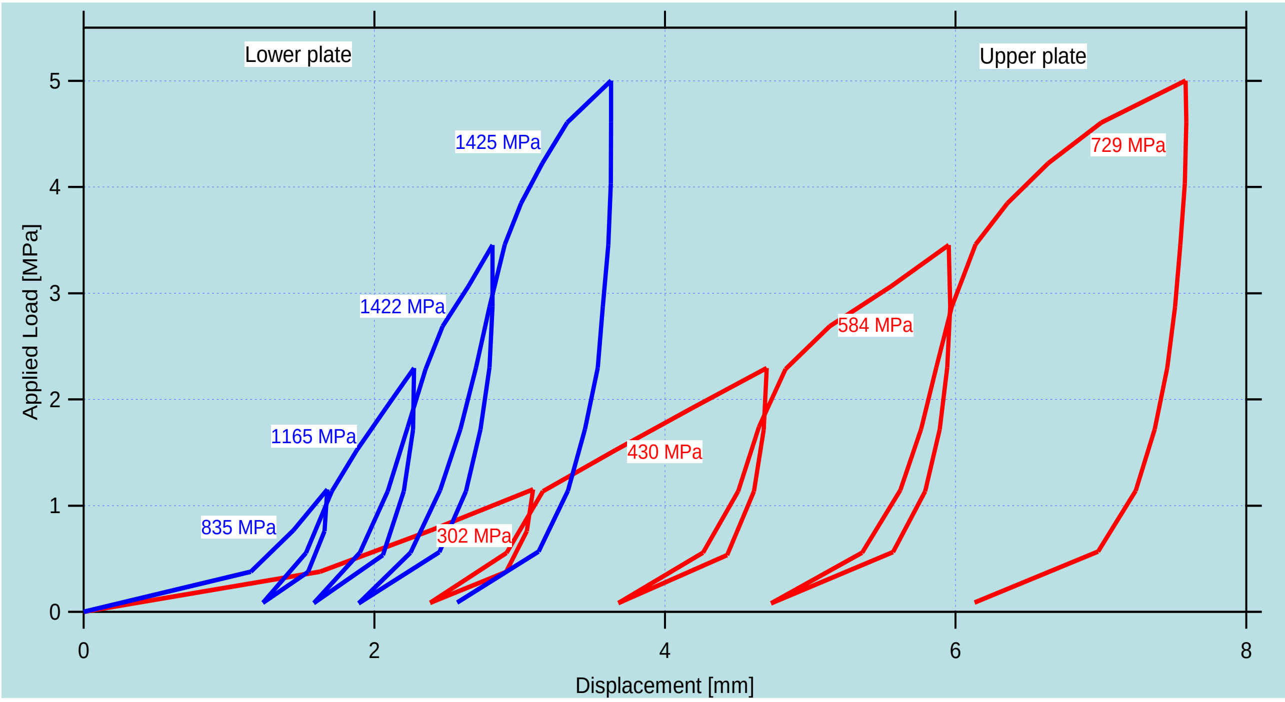


Figure 2.41 an example of plate loading test results with four cycles and corresponding value of the deformation module. A stiffening of the rock mass with increasing rock load is observed with both plates.

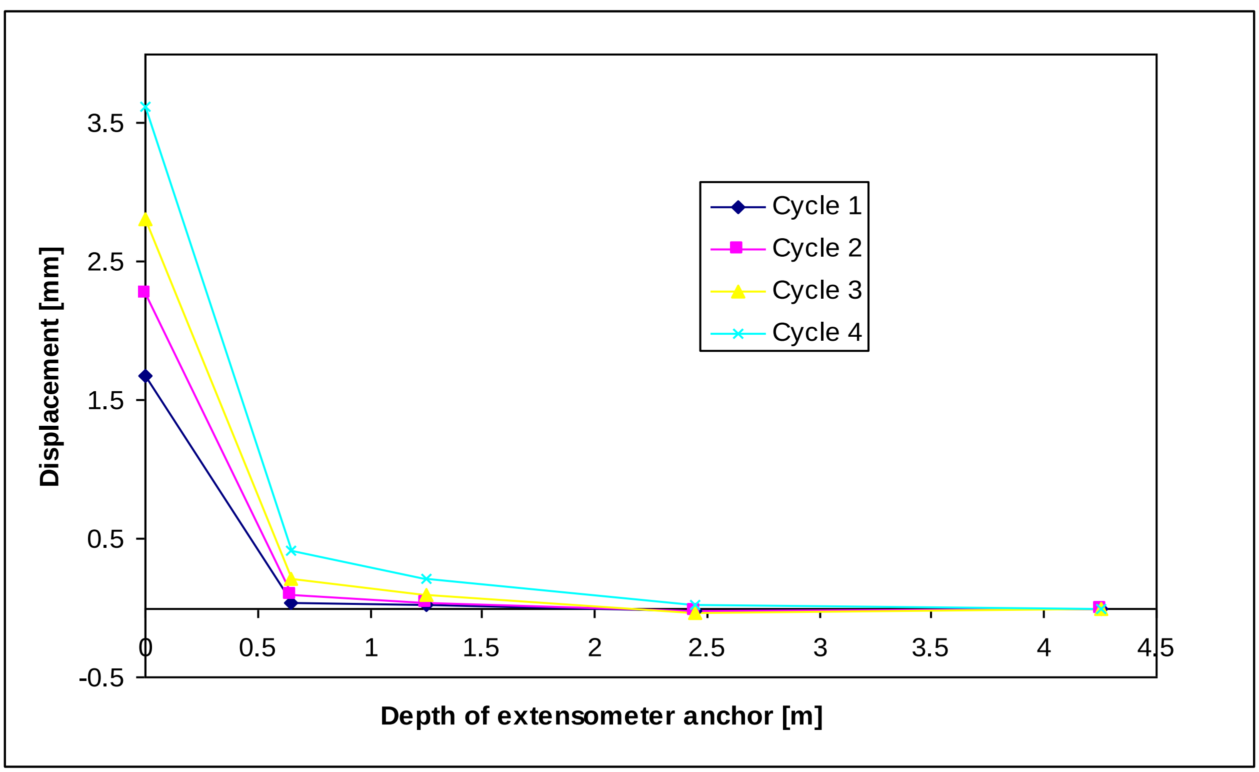


Figure 2.42 shows results of displacement measurements at the surface of the loading plate (depth=0m) and with four extensimeter underneath the loading plate (depth of anchor: 0.65m, 1.25m, 2.45m and 4.25m).

INSITU STRESS MEASUREMENT

2.14 Hydraulic Fracturing

Hydraulic fracturing is a technique for measuring in-situ stress in boreholes. For many years, a main application was determination of the minimum horizontal stress for hydropower pressure tunnels. However, this technique is more and more applied for the exploration of other underground excavations.

2.14.1 Hydraulic fracturing technique

Injection of water under high pressure in a packed-off borehole section to fracture the rock is the test technique.

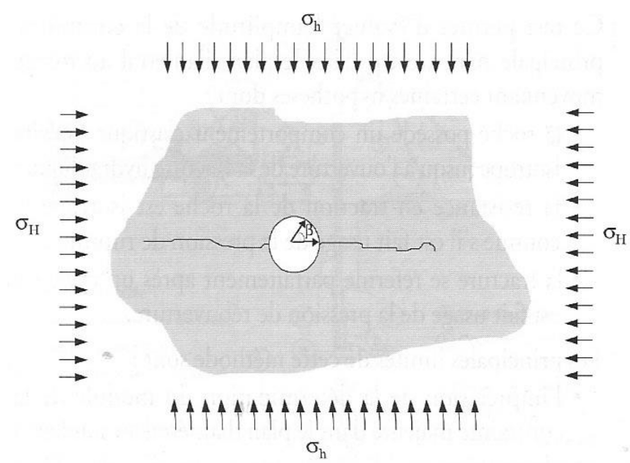


Figure 2.43 Shown the basic theory of hydrofracture test.

Theory:

Fracturing the rock perpendicular to the direction of the minimum principal stress is major theory behind it.

Hydraulic fracturing is conducted with a very robust double packer system on short boreholes intervals which are free of natural fractures (Haimson and Fairhurst, 1967). Following the setting of the packer, the interval is quickly pressurized until an axial fracture is induced. Pumping is then stopped and the interval 'flowed-back' to de-pressurized the fracture. The fracture is then subjected to several re-opening and draining cycles by injecting small fluid volumes (typically 10-40 l). The objective is to define the pressure at which the walls of the fracture are just supported by a fluid cushion. This pressure represents the rock stress component normal to the plane of the fracture, and is variously referred to as 'closure pressure' or 'Jacking pressure'.

Because of the nature of the stress field induced around the borehole during pressurization, the induced fracture will tend to be axial, and the fracture will initiate and extend in the direction of the larger of the two principle stresses that act normal to the borehole axis. Thus the normal stress acting up on the fracture plane will be the smaller of these two principle stresses.

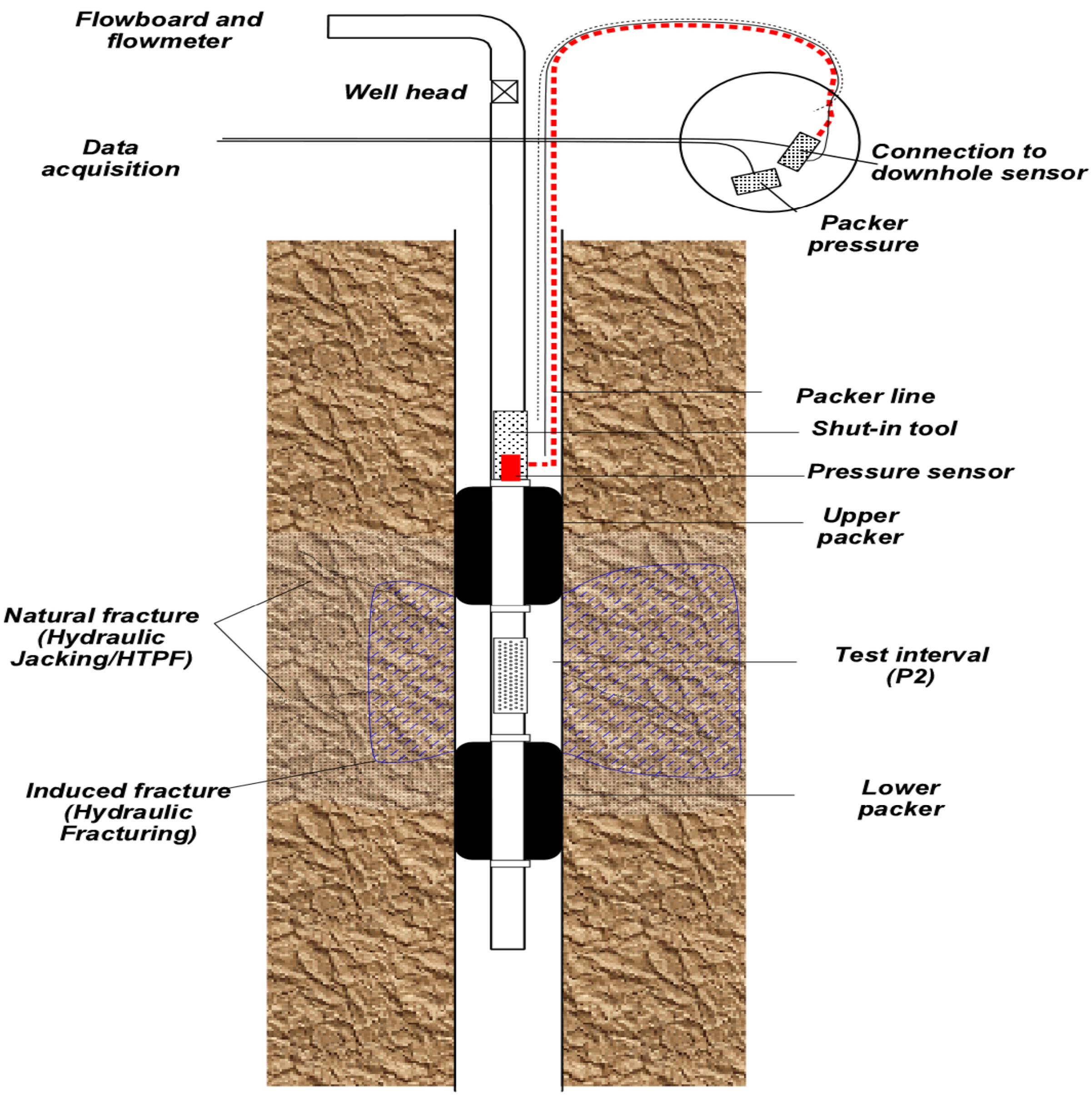


Figure 2.44 showing the arrangement of the borehole equipments and testing procedure.

By subjecting the fracture to a series of injection/during cycles, the magnitude of the principle stress can be determined to a high degree of accuracy. Analysis of the pressure at which the fracture initiates, or alternatively the interval pressure required to re-open the fracture in the later injection cycles, permits the larger of the two principle stresses acting normal to the borehole axis to be estimated, although much less accuracy then the smaller of the two. Thus the tests yields a direct measure of the magnitude of the smaller of the two principle stresses acting normal to the plane of the borehole, and an indirect measure of the magnitude of the larger of the two. The orientation of the two principle stresses is obtained by determining the orientation of the induced fracture generally using an oriented impression packer.

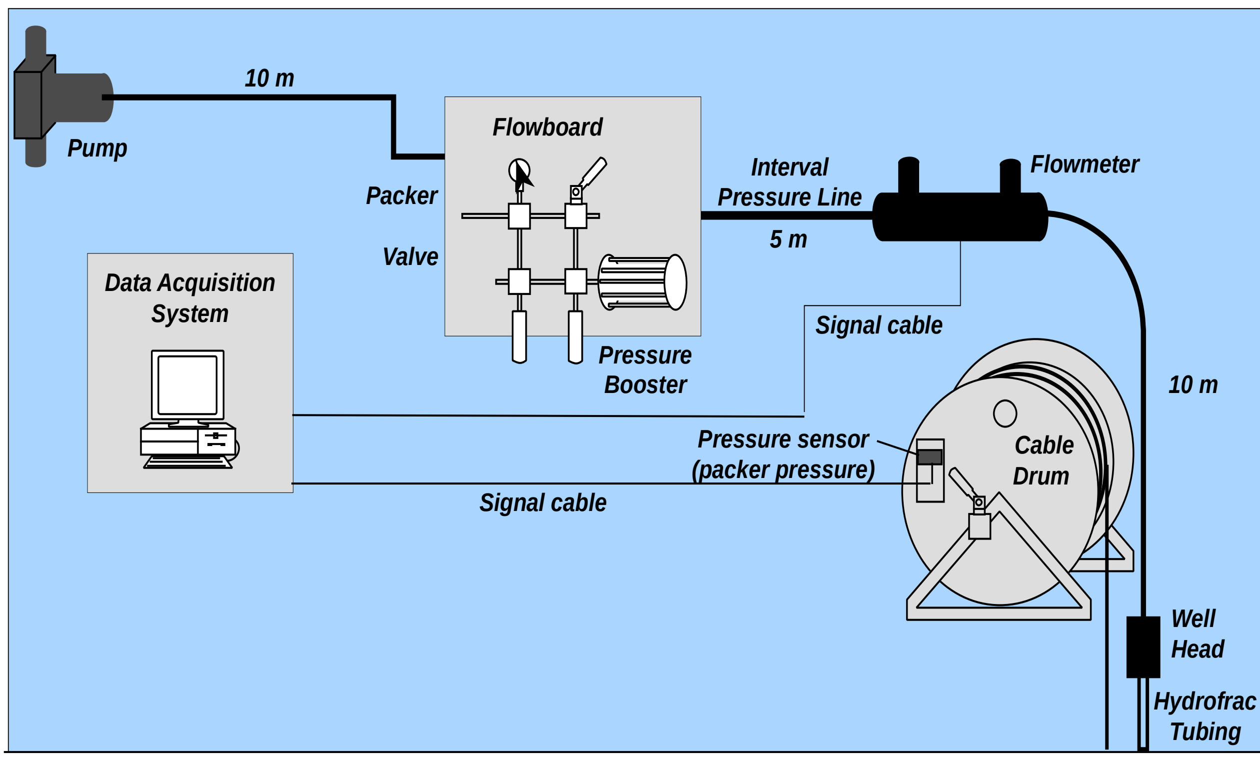


Figure 2.45 showing the arrangement of the surface equipment arrangement.

2.14.2 Test equipment

The equipment consists of a double straddle packer to isolate a test section in the borehole with a test interval length of 0.95m and the packer length of 0.85m.

The packer is lowered down to the boreholes on special high pressure 1''-rods ("hydrofractubing") of 3 m length which are used to conduct the fluid to the test section. Leakage of the coupling of this type of tubing is prevented by two O-rings. Packer inflation and electrical conductors for instrument signals are provided in an umbilical cable that is strapped to the rods. Water is injected with high pressure pumps.

Test pressures are measured down the hole in the test interval. Packer pressure, flow rate and an additional measurement of the test pressure are made on the flow-board at the surface. Data is recorded at the surface using an A/D-converter connected to a PC which provides a graphical display of the pressures and flow rates as they are recorded using a special software which allows high sampling rate during the injection phase.

The test is controlled with so called flow control bard ("flowboard"), basically a manifold system with two 60Mpa pressure sensors, three overpressure release valves, and ten pressure check values. The entire system is designed for a pressure of 50Mpa.

Impressions of the test sections are obtained using two impression packers with a soft rubber covering. A borehole compass equipped with a data logger or a borehole survey tools (multishot tool) is used to determine the orientation of the packer.

2.14.3 Testing procedure

In general Solexperts AG employs the classical hydrofracture stress measurement methodology as described by Haimson and Cornet (2003) and according to the SATM designation D 4645-87. A hydrofracture test consist of a sequence of pressurization cycles during which interval pressure, packer pressure and injection flowrate are monitored and recorded in a high sampling rate.

2.14.3.1 Preparation and pulse test

Once the hydrofracturing tool has been placed at the test depth, the packers are inflated to about 5 MPa above surface pressure. All air has to be evacuated from the test tubing and inflation lines. A permeability tests (Pulse Test) is then conducted by raising the intervals pressure by 1-2 Mpa above the ambient level and closing the shut-in valve. The objective is to ensure that permeable natural fractures are present in the test intervals, as indicated by a stable pressure level. If this is the case, the interval pressure is restored to ambient levels and preparations are made for the first pump cycles (breakdown cycles).

2.14.3.2 Breakdown cycles

Prior to injection into the intervals, a steady flow of 7-15 l/min is established through the flow-board vent valve. This valve is then closed to divert the flow into the interval. Initially, the pressure rises quickly according to a system stiffness of typically 40 MPa/l. injection is terminated as soon as breakdown is recognized and the interval is shut-in. The interval pressure and flow rate are sampled using the high sampling rate mode (ca 10 Hz). After waiting for the pressure to decline to a stable level, the interval pressure is vented through the flow-board and the return fluid volume is measured. The state of the drainage of the induced fractured is monitored by closing the shut in valve (i.e terminating venting) and observing the rebound of interval pressure.

2.14.3.3 Re-open cycles (Refrac cycle):

The fracture is then subjected to several re-open injection cycles during which the injected fluid volume is progressively increased. The ‘fracture re-opening pressure’ is a key quantity that can, under certain condition, be used to estimate the maximum principle stress acting in the plane normal to the borehole axis using the method proposed by Bredehoeft et.al (1976). The re-open pressure is taken to the point at which the pressure first deviates from the initial climb controlled by the compliance of the system.

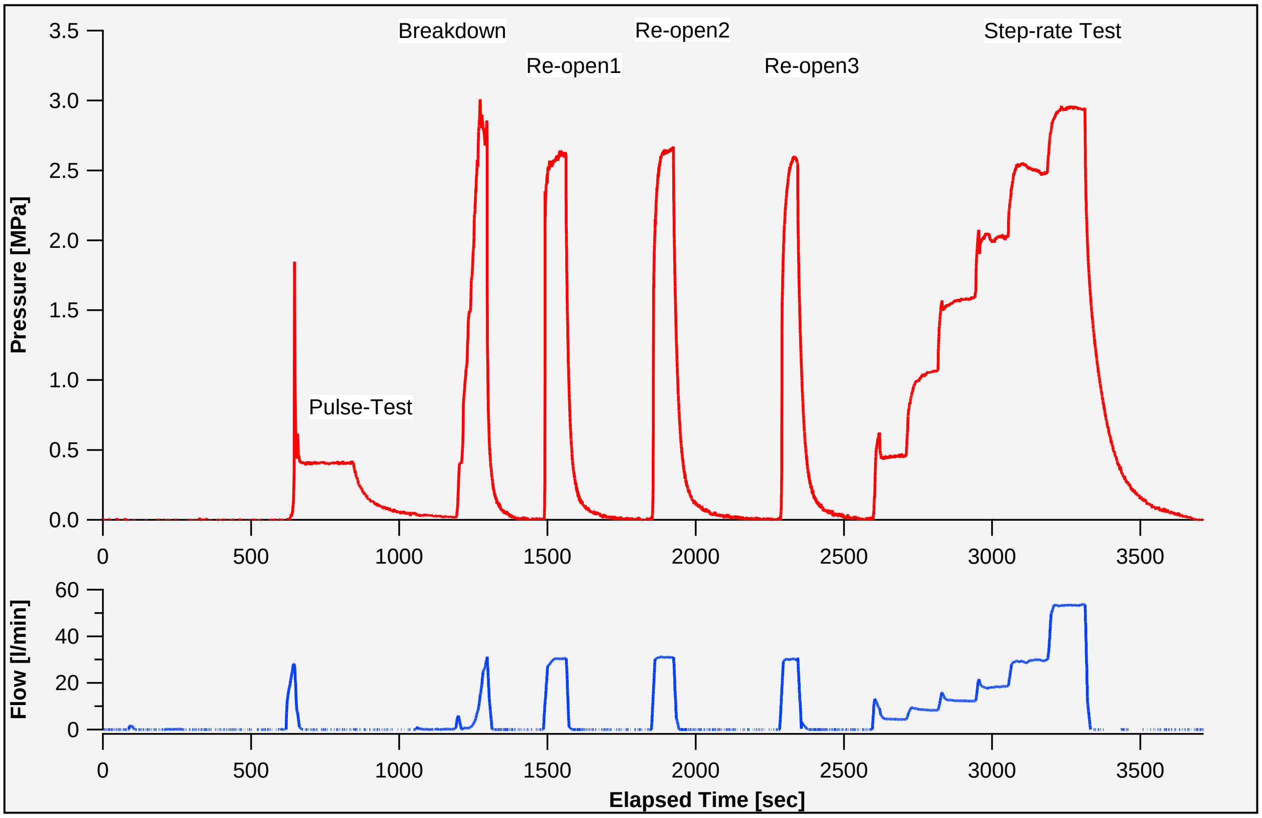


Figure 2.46 shows the results of hydraulic-fracturing test with breakdown cycle, the re-open cycles and a step-rate test.

The theory of Bredehoeft et.al (1976) assume that the fracture remains completely impermeable until the circumferential stress across the entrance to the fracture becomes tensile, at which point the fracture opens. Water injection is abruptly terminated by closing the shot-in valve.

2.14.4 Step-rate test

This test is similar to the Lugeon-type hydro jacking test, and usually conducted at the end of the test. As in the hydro jacking test, the objective is to determine the pressure at which a significant increase in transmissivity occurs reflecting fracture opening.

2.14.5 Test analysis

The minimum principle stress (σ_3) is considered to be equal to the shut-in pressure which was determined from each cycle.

$$\sigma_3 = P_{\text{Shut-in}}$$

Two methods usually can be applied to determine the shut-in pressure from the change in slope of the pressure decay graph caused by the closing of the fracture: the tangent intersection and the rate of pressure decay plotted against the pressure (Tunbridge, 1989). The tangent intersection method is not always easy to apply as the pressure decay sometimes is a smooth curve and there are no distinct segments on the curve for drawing the tangents. The rate pressure decay plotted against pressure generally produces graphs with a distinct inflection which is interpreted as the shut-in pressure. The vertical stress is calculated from the overburden weight.

The maximum Principle Stress (σ_1) can be estimated as:

$$\sigma_1 = 3P_s - P_{ro} - P_o$$

Where $\mathbf{P_s}$ is the measured average shut – in pressure, $\mathbf{P_{ro}}$ is the pressure recorded at first openings of the fracture and $\mathbf{P_o}$ is the formation pore pressure.

However there is considerable controversy in the literature concerning its interpretation based on the re-opening pressure. It appears to be more reliable to base the magnitude of the maximum principle stress on laboratory result of tensile strength of the tested rock and on the breakdown pressure.

Once the hydrofracture phase has been completed, the hydro-fracture tool is removed from the borehole and replaced by an impression packer system. This consist of an impression packer coupled to a digital downhole compass and enables impressions from the tested intervals. The system is run down the hole on the same tubing that was used for the double packer system. The packer is then inflated to the estimated level of the minimum stress, and this pressure is maintained for 25 minutes. The packer is then deflected and the tool is retrieved from the hole. After marking the traces on the packer surface, the new fractures are copied onto the transparent film. The tool is then returned to the hole to image the next interval.

Figure 2.47 Impression packer of hydrofracture test with traces of included features.

2.15 Hydraulic Jacking

The hydrojacking technique is used to estimate the minimum stress in heavily fractured rock. The objective of the test is to determine the minimum pressure at which a natural fracture or a subset of natural fractures within the formation open and become fully jacked.

A borehole section containing natural fracture is isolated be means of a robust double-packer system, after packer expansion, water is injected with stepwise increasing pressure. A steady injection flow should be attained at each pressure level before proceeding to the next level. It can be assumed that the fractures remain closed for pressure smaller then the stress acting normal to the fracture plane. At pressures higher than the fracture normal stress, the fracture opens and a considerable higher flow rate is required to keep the fracture open. The fracture re-opening is gradual and depends upon the fracture normal stiffness and effective stress inside the fracture near the borehole.

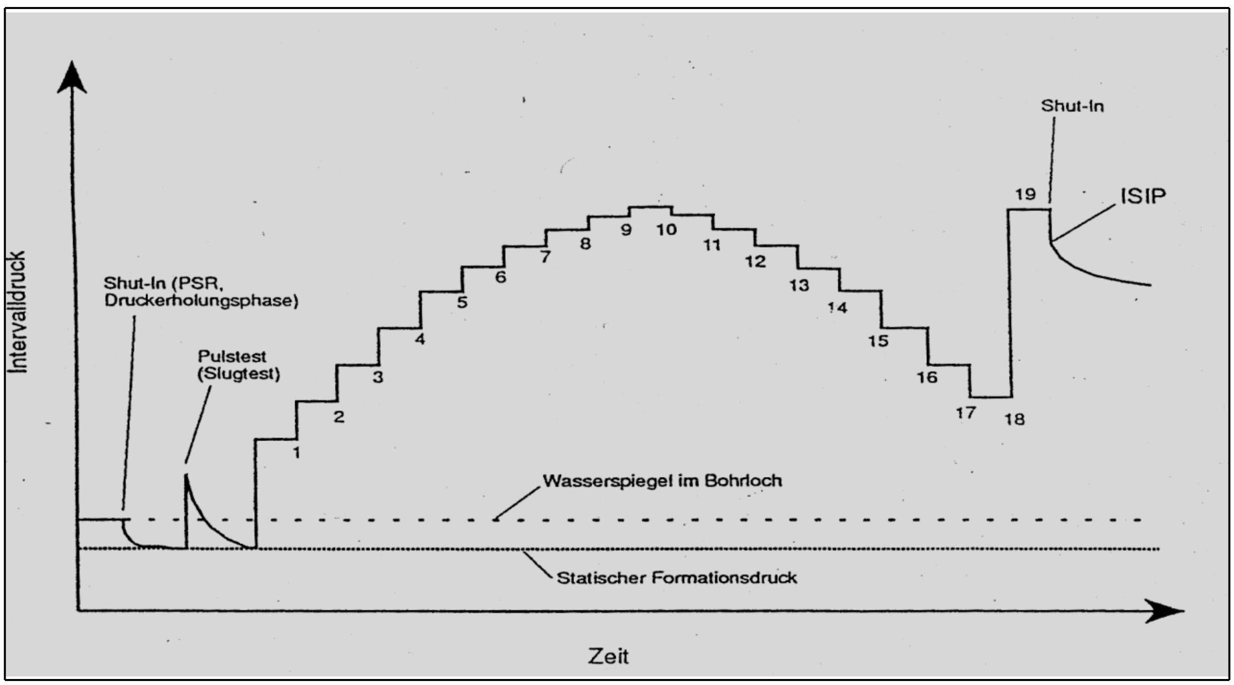


Figure 2.48 shows a typical hydrojacking test (pressure curve of stepwise injection).

The test consists of a stepwise water injection with increased flowrate in an isolated borehole section. The flow is raised until the maximum flowrate or a fixed maximum pressure is reached – for instance for safety reasons. The stepwise increase is followed by a stepwise decrease until backflow is obtained. The goal is to obtain a set of steady-state pressure/flowrate data at the end of each pressure level, which can be displayed in a p versus Q Lugeon-type plot, as in figure 2.49 and a typical hydro-jacking test plot is shown in figure 2.48.

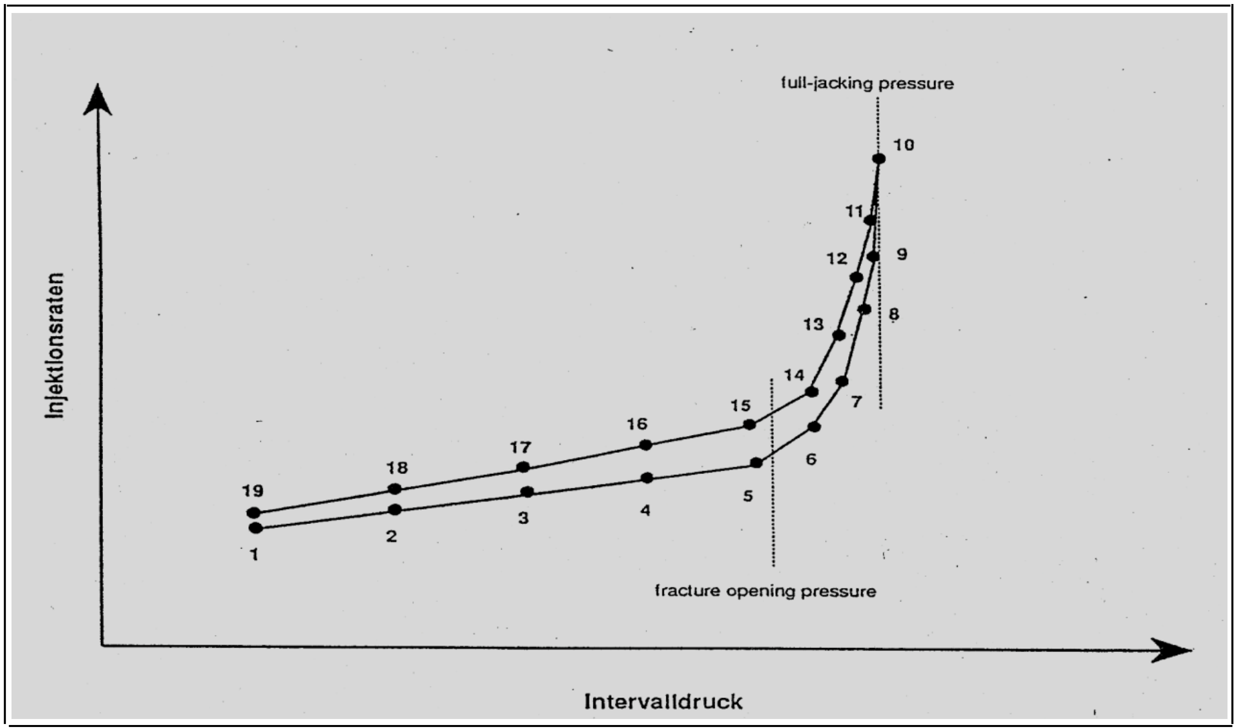


Figure 2.49 Flow rate plotted versus injection pressure of hydrojacking test.

The injection rate and pressure recorded under steady-state conditions (constant pressure and constant injection flow) are displayed in a pressure flow diagram. The data drive from lamina flow at a constant fracture opening. They result in a linear correlation. The gradient of the straight line crossing the different measuring points is proportional to the transmissivity. The pressure where the linear correlation of injection rate and injection pressure ends is called the "fracture opening pressure".

If the injection pressure is boosted, the injection rates increase non-proportionally. The highest possible injection pressure is limited by the normal stress acting onto the relevant fracture (DOE and KORBIN, 1987). This pressure is equivalent to the normal stress and called the “full jacking pressure”.

The “full jacking pressure” corresponds to the minimum principle stress if the direction of normal stress of the fracture does not deviate more than 10^0 from the direction of the minimum principle stress. This means that the “full jacking pressure” comes up to the upper limit of the minimum principle stress.

2.15.1 Test equipment

The equipment consists of a double straddle packer to isolate a test section in the borehole with a variable interval length of minimum 1.00 m and a packer sealing length of 1 m. The packer system is installed in the borehole with high pressure 1′′ –rod (“hydrofrac tubing”). These rods are used to conduct the fluid to the test section. Leakage at the couplings of this type of tubing is prevented by a double O-ring seal. Stainless steel lines for packer inflation and pressure transfer from the interval area strapped onto the rods. The injected water is pumped with an electrically driven high pressure of 200 bar.
The test is measured at the surface at the end of the steel line which reaches to the packed-off interval in the borehole. Flow rate, inflation pressures of both packers as well as a redundant injection pressure measurement are made on the flowboard.

The flow of injected water is controlled with a so called flow controlled board (“flowboard”) as well as with the pressure controller and with the frequency based speed regulator of the pump. The flowrate of injected water is measured with an ultrasonic-flowmeter. For that, two sensor heads are mounted onto a special stainless steel tube. This type of flow sensor always flow measurement over a wide range of flow rates and under high pressure.

Data is recorded at the surface using a new type of 6-channel A/D convector with USB-connection to a notebook-PC. The software developed by Solexports is especially designed for hydraulic jacking and hydraulic fracturing tests allowing data recording and graphical display with a rate of 1 Hz, 5 Hz or 10 Hz.

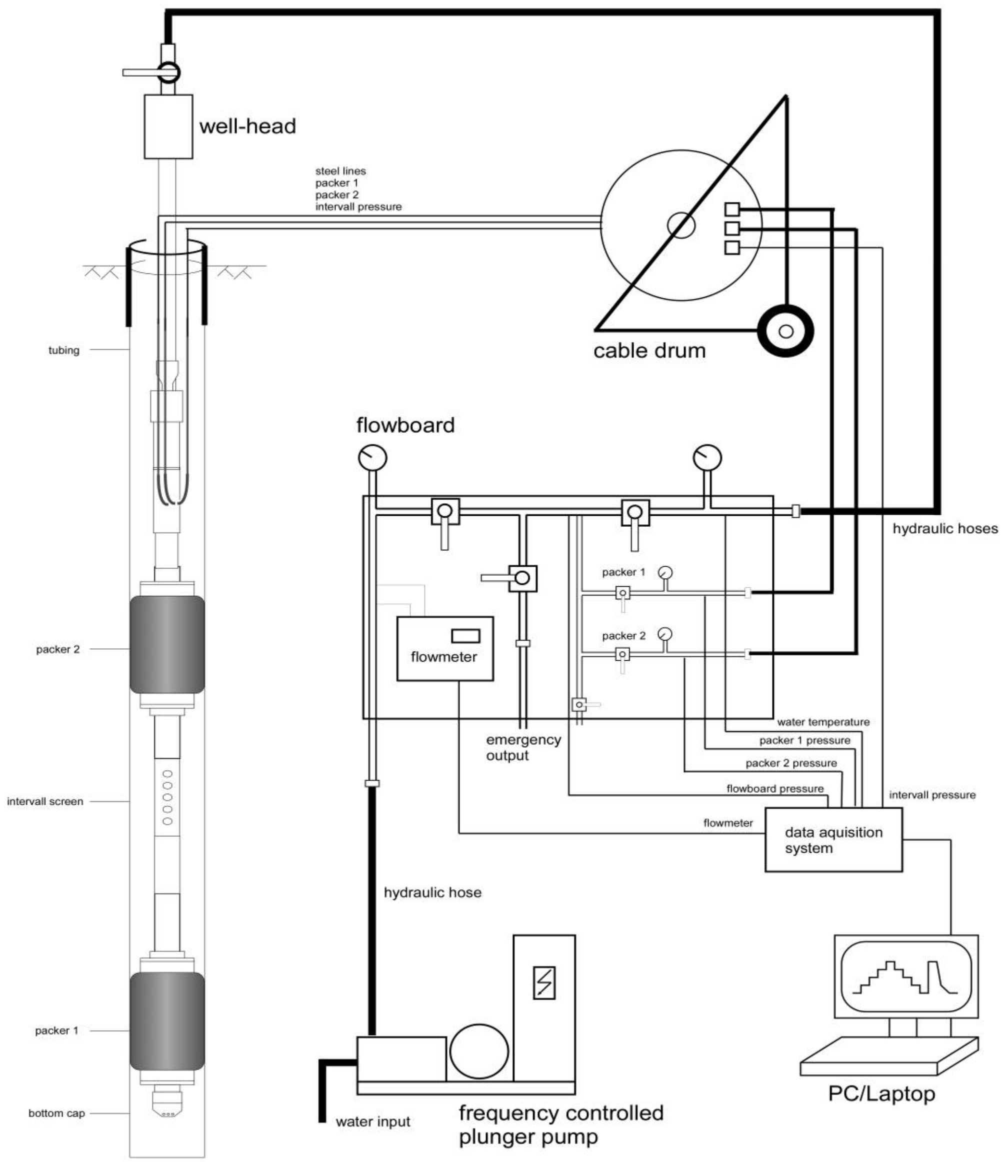


Figure 2.50 schematic overview of a hydrojacking double packer layout of the test system and the surface equipment.

2.15.2 Testing procedure

After installation of the hydrojacking packer system into the borehole, the packers are inflated up to pressure ca. 10% over the maximum injection pressure. Then the valve is closed at the well-head in order to measure the static head of the sealed borehole section. T start testing, the valve is opened and water is injected with increasing pressure steps until the capacity of the injection pump or the "full jack pressure" is reached a steady injection flow should be attained at each pressure level before proceeding to the next level. The injection pressure is increased until a linear correlation between injection rate and injection pressure is obtained. The pressure steps in the range of the "facture opening pressure" should not be too high to determine the opening pressure exactly. After reaching the "full jack pressure" or upper limit of the pump capacity, injection steps with decreasing pressure are carried out. It is recommended to perform two injection cycles. Irreversible fracture transmissivity might occur due to changes in fracture aperture as consequences of bond-breakage and perhaps shear dilatation during the first injection cycle. More reproducible Q vs P curve obtained during subsequent injection cycles indicate a largely elastic response of the tested fractures. A last pressure step with maximum pressure ("full-jacking pressure") and steady-state condition is performed after completion of the injection cycles. The value is closed at the well-head to determine the "instantaneous shut-in pressure" (ISIP).

2.15.3 Analysis

The fracture opening pressure is obtained from a Lugeon-type plot at the point where the relationship of flow rate and injection pressure starts to deviate from a straight line with increasing injection pressure steps. The full jacking pressure can be considered to be closed to the minimum principle stress if the tested fracture line within about 10% of normal to the minimum principle stress condition.

Calculation of the transmissivity for each data point in the P/Q plot

If steady-state condition (constant pressure and constant injection rate) at the end of each pressure step has been reached, the transmissivity of each data-pair can be calculated with the following equation (Thiem 1906). It has to be noted that the radius of influence is unknown. It can be calculated by applying iteration but several assumptions have to be made.

$$\mathbf{T = (Q/2\,p\Delta h)\ ln(R/r_w)}\ (m^2/s)$$

T= Transmissivity

Δh = absolute pressure

R = radius of influence

Q = injection rate

r_w = radius of the borehole

Chapter - 3
Hydrological Field Testing

3.1 Aims and application of the test

Knowledge of regional hydrogeology is required for the alignment of the tunnel path, Environmental Impact Assessment (EIA) and preparation of tender documents of any tunnelling project. Knowledge of local hydraulic conditions is required to optimize construction design parameters, for the dimensioning of the tunnel drainage system and forecast of hydraulic conditions during excavation. To obtain the all above mentioned hydrogeological information, various field hydraulic tests are required.

Particularly the field hydrological test used to conduct to obtain the following hydraulic parameters of soil and rock.

- Hydraulic characterization of subsurface units
- Assessment of hydraulic parameters:
  - Transmissivity **T** [m2/s]
  - Hydraulic conductivity **K** [m/s]
  - Hydraulic head **h** [m]
  - Aquifer storability **S** [-]
  - Evaluation of flow regimes and boundaries
- Taking ground-water samples for the analysis of the EIA

3.1.1 Various hydrological tests

The following hydrological tests are in common practice to characterize the above hydraulic parameters of the rock and soil.

1. Pump tests (single hole / interference tests)
2. Slug test
3. Water pressure test (Lugeon)
4. Double packer test

5. Tracer tests
6. Borehole dilution tests
7. Fluid logging / Impeller flowmeter/Heat pulse

3.1.2 Field of Application

- Water wells
- Dams
  - Leakage / grouting (Lugeon-tests)
- Tunneling
  - Hydraulic parameters required for support design, grouting, planning and for preparation of tender documents.
  - Environmental Impact Assessment (sources, spas).
- Contaminated sites
- Potential waste sites
- Geothermic wells
- Oil and gas exploration

3.2 Pumping Test

An aquifer test is to evaluate the aquifer by stimulating the aquifer through constant pumping and observing the aquifers drawdown in observation well to characterized the system of aquifer, aquitards and flow system boundaries. Aquifer tests are typically interpreted by using an analytical model of aquifer flow (the most fundamental being the Theis solution) to match the data observed in the real test assuming the parameters from the idealized model apply to the real aquifer.

Required equipment for the pump test

- Submersible pump
- Submersible pressure transducers
- Flow measurement device

- Flow controlling device
- Dip meter
- Data acquisition system
- Water discharge lines

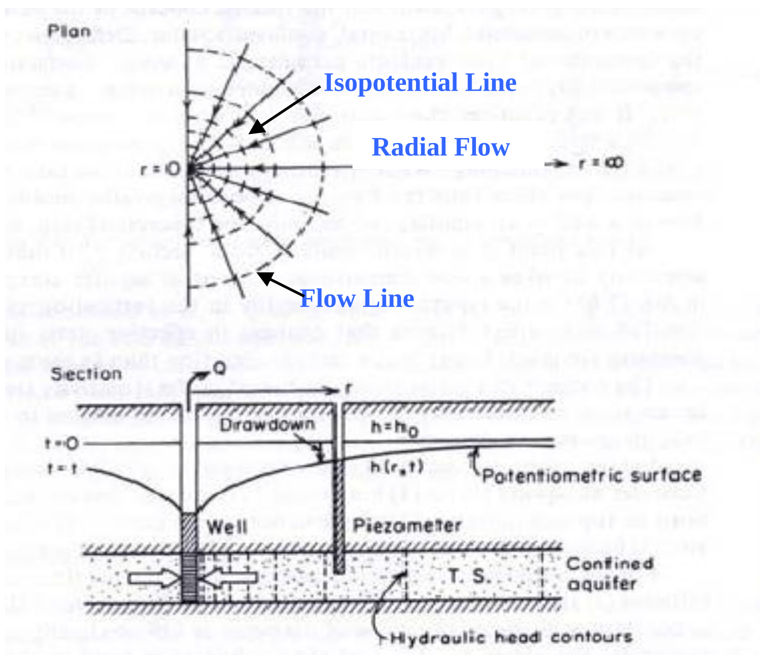


Figure 3.1 shows single well, interference test (Cross hole test).

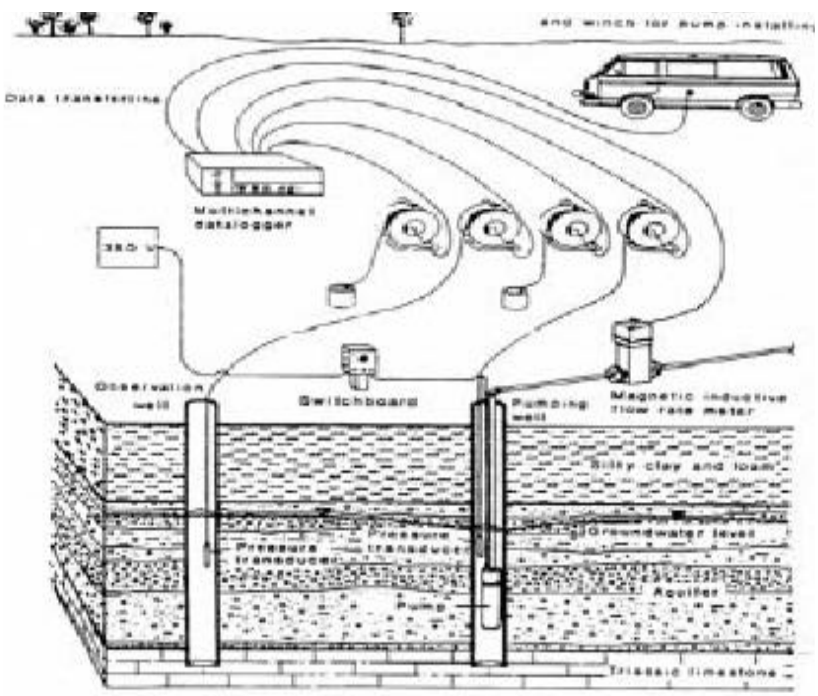


Figure 3.2 shows the complete field set up of the pump test.

3.3 Water Pressure Test (Lugeon Test)

Developed around 1932 as a method to determine grouting conditions for dams and further developed by Houlsby and now widely using in tunnelling or underground excavation to obtain the various hydraulic parameters.

- Lugeon unit = 1 liter of water taken per meter of test length, per minute, at 10 bars pressure.
- 1 Lugeon corresponds approximately to a K-value of 1E-07 m/s.
- At a "permeability" of 1 Lugeon grouting is usually not necessary.

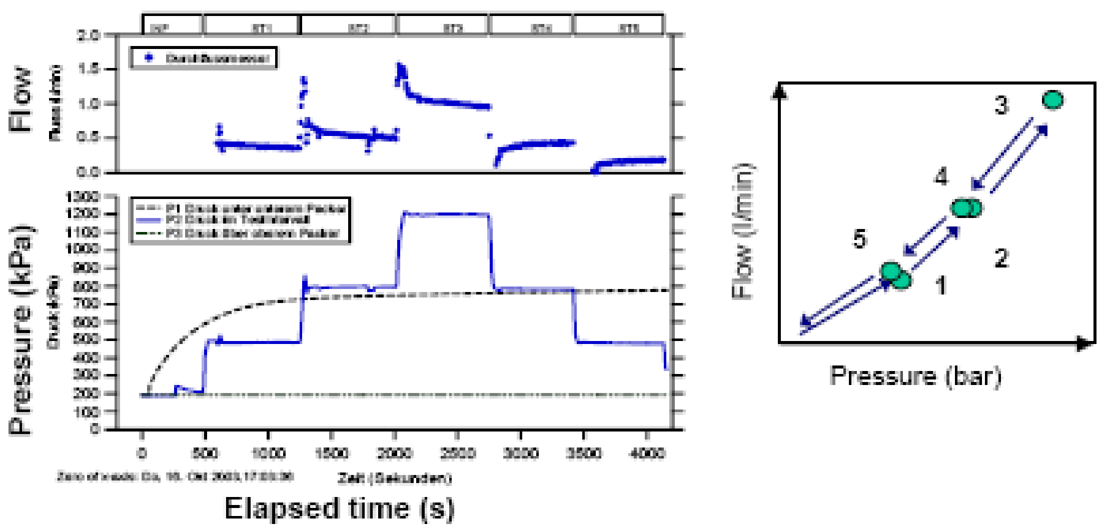


Figure 3.3 shows some examples of water pressure test (Lugeon test) results.

Figure 3.4 shows monitoring of ground water.

3.3.1 Limitations of water pressure test

- Lugeon tests are usually carried out without continuous recording of flow and pressure.
- The Lugeon values are calculated using flow and pressure values at end of each injection step, assuming steady-state flow condition (which is often not true).
- No transient analysis possible.
- No identification of flow model.
- Results may depend strongly on borehole skin.
- If pressure is measured at surface, pipe friction loss affects the result.
- Water pressure measurement only in anterior condition.

3.3.2 Alternatives

- Double packer tests
- Hydrojacking

3.4 Double Packer (DP) Test

3.4.1 Aims and applications

- Double packer tests are usually performed to investigate the vertical distribution of hydraulic parameters.
- 3D-picture of groundwater regime (if more than 2 boreholes are available for testing).
- Hydraulic characterization of subsurface units.
- Assessment of hydraulic parameters:
  - – Transmissivity [m2/s]
  - – Conductivity [m/s]
  - – Hydraulic head [m]
  - – Aquifer storability [theoretically possible, but poor accuracy].
  - – Evaluation of flow regimes and boundaries.

3.4.2 Equipment

Use of double packer testing tool for hydraulic isolation of discrete formation zones is the test strategies for low and medium permeable formations. The arrangement of equipment layout of the double packer test is presented as below.

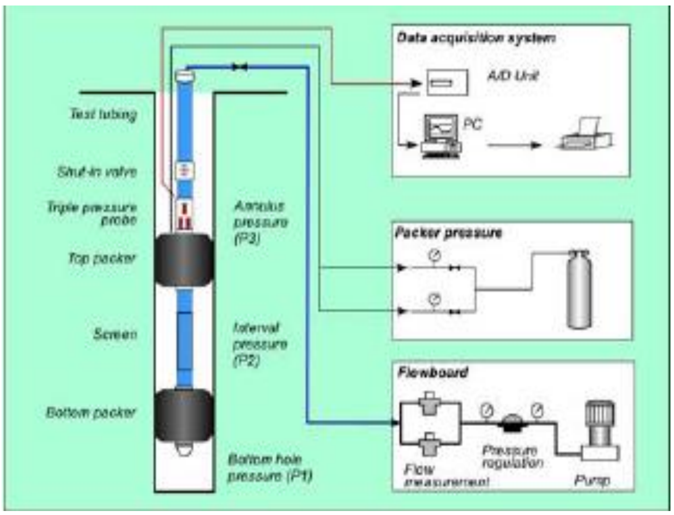
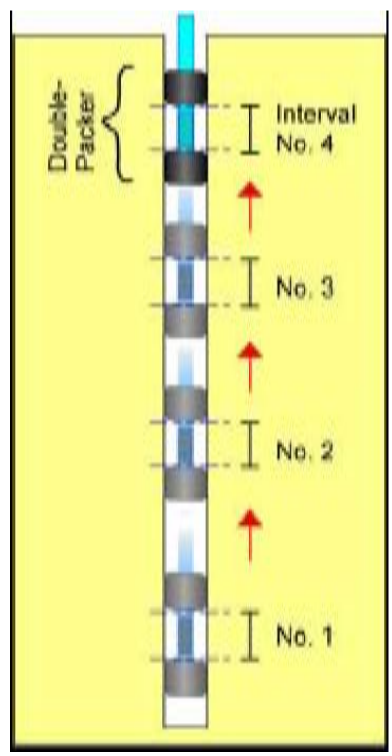


Figure 3.5 shows double packer test equipment arrangement for testing after borehole is completed.

3.4.3 Advantage:

Hydraulic conditions can be assessed for all test zones within a relatively short time period (effects of regional hydraulic trends are minimized) in a single field trip per borehole.



3.4.4 Disadvantage:

Depending on drilling duration and vertical head distribution, history effects may become important. Long periods of vertical flow in the open borehole make it difficult to sample formation specific groundwater.

Figure 3.6 shows several tests in a single borehole.

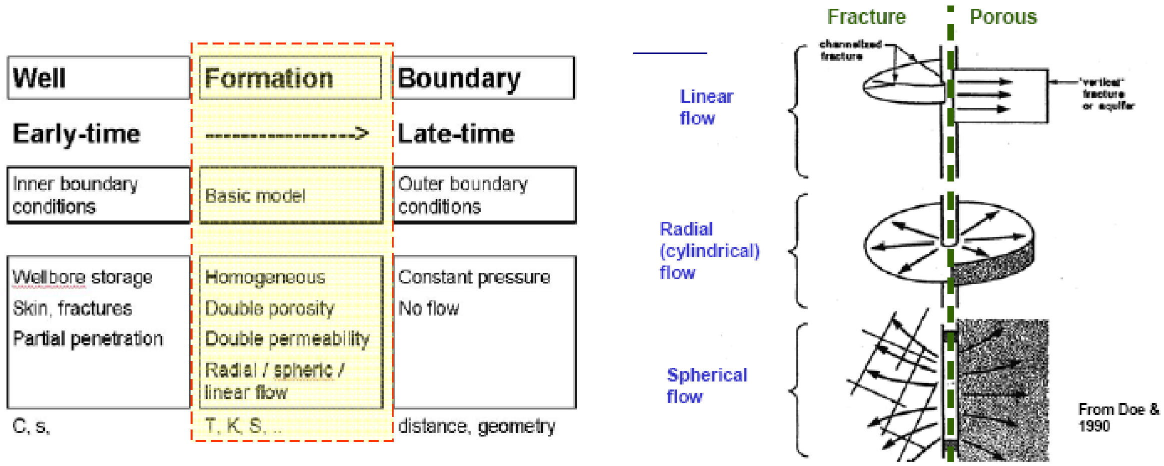


Figure 3.7 shows the flow regimes and flow model in Double Packer test.

3.5 Slug test

Slug test is ground water aquifer test where water is quickly added or removed from a ground water well, and change the hydraulic head is mentioned time to determine the near-wall aquifer characterestic. It is method used by hydrogeologist to determine the transmisivity and storativity of the underground materials.

3.5.1 Slug test method

A slug test is in contrast to standard aquifer tests, which typically involved the slug of water can either be added to or removed from the well by pumping from the well at a constant flowrate, and monitoring the response of the aquifer in near by monitoring wells.

Often slug tests are performed instead of a constant rate test, because:

- time constraints (quick results, or results for a large number of wells, are needed).
- the well does not or cannot have a pump installed on it (slug tests do not require pumping).

- the transmissivity of the material the well is completed, it is too low to realistically perform a proper pumping test (common for aquitards or some bedrock monitoring wells), or
- the general size (order of magnitude) of the aquifer parameters is all the accuracy that is required.

The size of the slug required is determined by the aquifer properties, the size of the well and the amount of time which is available for the test. For very permeable aquifers, the pulse will dissipate very quickly. If the well has a large diameter, a large volume of water must be added to increase the level in the well a measurable amount.

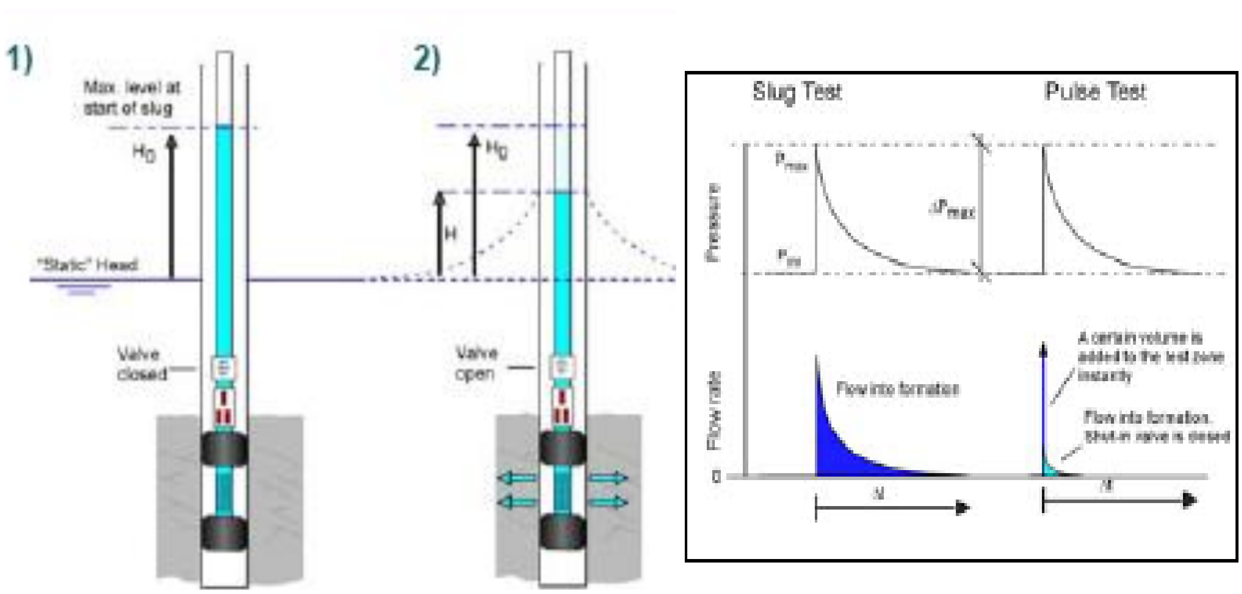


Figure 3.8 represents the principle of Slug test and Slug/pulse test.

Because the flow rate into or out of the well is not constant, as is the case in a typical aquifer test, the standard Theis solution does not work. Mathematically, the Theis equation is the solution of the groundwater flow equation for a step increase in discharge rate at the pumping well; a slug test is instead an instantaneous pulse at the pumping well. This means that a superposition (or more precisely a convolution) of an infinite number of sequential slug tests through time would effectively be a "standard" Theis aquifer test.

There are several known solutions to the slug test problem; a common engineering approximation is the Hvorslev method, which approximates the more rigorous solution to transient aquifer flow with a simple decaying exponential function.

The aquifer parameters obtained from a slug test are typically less representative of the aquifer surrounding the well than an aquifer test which involves pumping in one well and monitoring in another. Complications arise from near-well effects (i.e., well skin and well bore storage), which may make it difficult to get accurate results from slug test interpretation.

Chapter - 4
Geomonitoring

4.1 General background

Underground facilities offer the new space which is not available any more on the surface. During the construction of such suburban facilities the life at the surface must go on undisturbed. To realize such project required perfect investigation, design, planning and proactive monitoring and risk management plan. The visibility of any small damage at the surface due to suburban construction is very high. If there is no proper monitoring system, duly taking care of any indication is not possible, resulting the probability of damages and consequences is very high.

The importance of monitoring is not only during the construction of tunnels and underground facilities but is also required for a wide range of application after completion of the project. Monitoring of the rock mass behavior after completion of the cavern, shaft, tunnel and dam is equally important. Deformation of the dam structure and foundation, rock mass behavior of the dam abutments, bridge abutment and foundation, landslide, unstable slope, mass movement, surface settlement and ground water condition are the further concerning issues of geotechnical and environmental engineering which directly effect life and environment. Obtaining pre information of nay indication of risk, monitoring is only the way to minimize the potential risk.

4.2 GeoMonitor 2

GeoMonitor 2 is a package of hardware and software which allows to read hundreds of analogic and digital sensors. It is only the system that allows to integrate 20 to 50 survey instrument (totalstation) they measure simultaneously displacement of structure in X, Y and Z with an accuracy of few millimeters. Each totalstation has its logger which controls and stores the data. Within the same GeoMonitor all kinds of sensors are stored on the PC for the handling and overview of the numerous details they are transformed to the DAVIS, a visualisation software. By simple mouse click to graphic of the data are presented immediately. With this tool the engineer and geologist have a quick access to the behavior of the structure see article 4.6.3.

The Solexperts GeoMonitor System provides a practical solution for automatically monitoring many instruments and sensors and handling large amount of measurement data for complex sites. The GeoMonitor offers much more than other data acquisition system on the market; the capacity to integrate such a diversity of instruments, a single databus cable connecting all interface to the data acquisition center, sophisticated alarms, remote operation via modern automatic calculations and reports, and geodetic net analysis. This flexibility, robustness and convenience of the system make it the ideal solution for monitoring structures concerning of geotechnical and hydrogeological issues of all sizes projects.

Additional GeoMonitor system by using some of the following equipments and softwares are described below

4. 3 Trivec 2.08 (software)

Field Data Recording Software for Handheld PC or portable PC for Solexperts for following linewise measurement instruments:

TRIVEC - Sliding Micrometer - Sliding Deformeter - Inclinometer

Solexperts use different linewise measurement instruments to gather data in field. In order to use only one program for all the instruments, Solexperts developed a field data acquisition program Trivec 2.08. The program Trivec 2.08, which can be used with various linewise measurement instruments as mentioned above. This program provides field measurements as well as calibration of probes before and after field measurements. The calibration of measurement instruments is done to determine a conversion factor from Digits to Millimeters, as well as to observe the zero-point in long-term period.

Figure 4.1 shows the monitoring system how the data is received directly to the office computer and analysis by another program TRICAL4.

Features of Trivec 2.0 Software

- assists with instrument calibration
- data transfer and continuous data recording during field measurement

- project-specific information is included in data files, such as:
  - project name
  - borehole designation
  - measurement number
  - number of measurement positions
  - measurement equipment
  - Comments
- displays measurement direction Down/Up and measurement position.
- displays the current Down/Up measurement.
- displays the reference measurement.
- displays the difference between the Up measurement and the Down measurement.
- allows user to repeat or resume measurement of a previous position.
- manual entry of measurements is possible, as an alternative to automatic data acquisition.
- data files can be viewed on-screen.
- data transfer to the PC for analysis (with separate analysis software TRICAL 4.0).

Note; The TRIVEC software was developed for the handheld's PC's and palm, but can also be used on a PC (e.g. notebook) with the following configuration:

- **Window 95 / 98 / 2000 / NT / XP**
- **at least one available serial port**

4. 4 Trical 4.0 Software

Data Analysis Software for Solexperts linewise measurement instruments for PC in the office.

TRIVEC - Sliding Micrometer - Sliding Deformeter - Inclinometer

The program is built according to the most important logical steps of data evaluation.

1. Choose or open a new file for the corresponding borehole.
2. Transfer of measurement data from handheld computer to desktop PC.
3. Editing the new data with calibration results.
4. Computation of deformations (up to 10 measurement episodes can be compared).
5. Graphical and numerical data interpretation with print-out.

Many further features as azimuth consideration, export of graphs to EMF format for use in other applications make the Trical comprehensive software.

4.4.1 Features of TRICAL 4.0 software:

General

- Easy, chronological operation
- English, German and French user languages
- Simple configuration

Data Management

- Create new data files
- Transfer data from the field computer (HP handheld) to the office PC
- Manual data input is also possible

Editing

- View raw data and reference values
- Enter calibration data
- Individual graphic and list options
- Graphical evaluation of up to10 measurements per graph
- Take azimuth into account in the evaluation

- Select the fixed and the end points; profiles may be split at specific comments

Output

- Graphical and numerical on-screen display
- Output results to a plotter or printer

4. 5 Surface Extensometer

Use of surface extensometer for geomonitoring, deformations and displacements can be measured with a single surface extensometer or group of surface extensometers (referred to as a chain" of extensometers).

4.5.1Typical applications

The surface extensometer provides continuous precise displacement measurements for projects with difficult to access measurement locations. For example: bridges, mines, slope movement, caverns and tunnels. Figure 4.2 shows the monitoring of the various structure and slope by using surface extensometer.

4.5.2 Readout unit

The digital readout unit has a display for viewing the displacement transducer measurements. The unit is battery power and contains an RS232 interface for connection to surface extensometers (the same readout unit works with the Sliding Deformeter equipment). The readout unit is in an aluminum watertight case and comes with a 3-meter cable with watertight connections.

4.5.3 Monitoring system

There are two options to automatically record surface extensometer measurements:

- Data can be recorded with the SOLO Data Logger and downloaded to a pc by the SOLOWIN data transfer software.

- Surface extensometer measurements are monitored in real time by the GeoMonitor 2 data acquisition system.

The SOLO Data Logger can record up to 6-potentiometric displacements transducers. Data transfer to the pc may be via a Logger to PC cable or, optionally by a wireless data transfer module. Up to 8 SOLO Data Loggers can be housed in an aluminum watertight housing with watertight cable connections, feeder clamp and RS232 interface.

4.5.4 General technical data

The construction can be customized to the required project specific needs.

Extensometer base length: from 0.5 to 5-meters. Longer lengths are possible as per requirement of the site.

Displacement transducer: surface extensometers may be fitted with transducers that have a measurement range of: 50, 100 or 250 mm. Measurement precision within <0.02% FS, linearity within <0.2% FS. a signal output of V/V or 4-20 mA.

Watertight: up to 15-bars.

Temperature measurement: (optional) the displacement transducer can include an integrated temperature sensor (PT100 or PT1000 sensor).

Measurement rods: steel, invar-steel, fiberglass or carbon fiber reinforced plastic.

Protection of measurement rods: with or without steel telescopic tubes.

Figure 4.2 showing the general application of the surface extensometers in various places and structures for monitoring.

4. 6 Inclinometer Measurement (manual)

In Geotechnics, Inclinometer measurements are employed for a variety of applications. The measurement method employs the highly-developed tilt measurement technique to monitor structures such as deep excavations, as well as the stability of slopes.

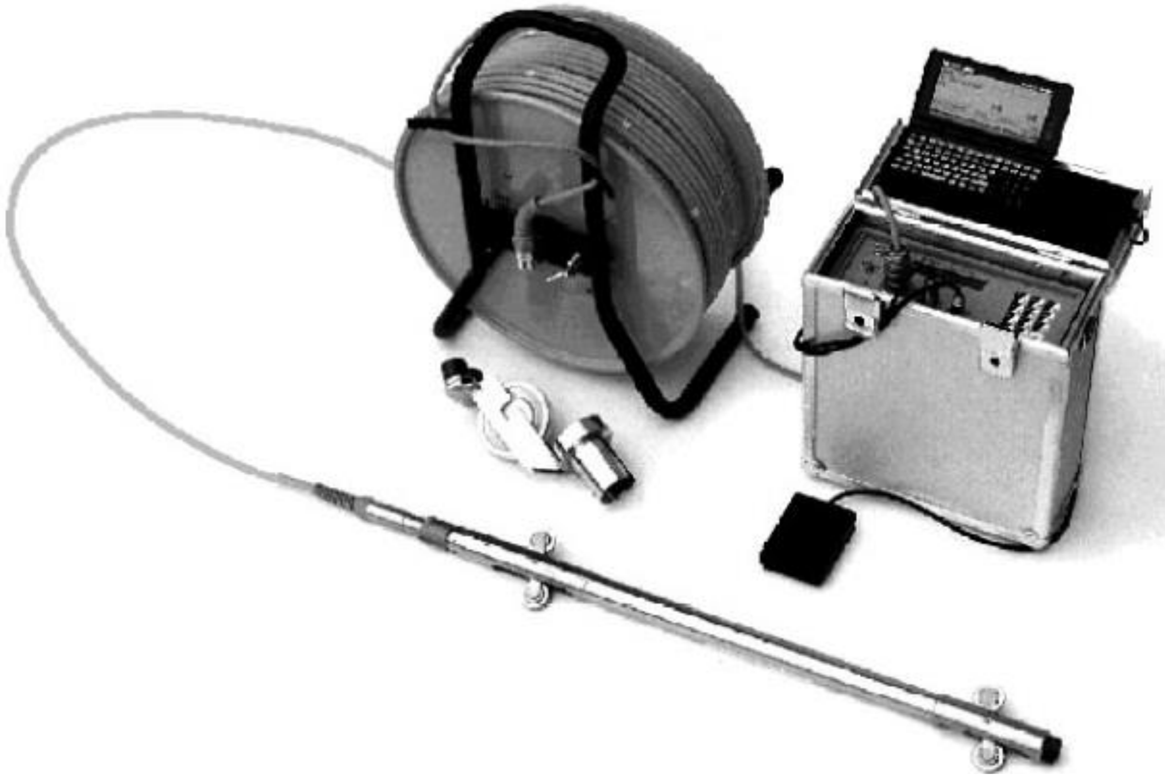


Figure 4.3 shows a complete set of inclinometer.

4.6.1 Typical applications

Inclinometer measurements assist in determining magnitude and direction of displacement in potential or active landslides. Inclinometer measurements are frequently used to check calculations and monitor safety upon completion of excavations. Under embankment dams for roads and railway lines, and for soil consolidation (e.g. consolidation tests), vertical displacements under the embankment can be measured with horizontal and vertical borehole inclinometers. With these measurements, settlement and horizontal displacement are monitored and accurately localized. During Tunnel construction, especially in urban areas, Inclinometer measurements provide crucial information about displacement. In addition, borehole Inclinometer measurements prove useful during excavation beneath grout shields and collars. Ground freezing projects require frequent measurement of displacement is another typical application for the borehole Inclinometer.

4.6.2 Optimization

In many cases, it is beneficial to measure axial displacement Z in addition to the horizontal displacements X and Y. For this situation, Solexperts has developed measurement casing in which both the Sliding Micrometer and Inclinometer can be employed.

4.6.3 Data visualization

For complex construction and monitoring sites, Solexperts **DAVIS software** provides a comprehensive overview of data from a variety of instruments and sensors. The Inclinometer measurements can be entered along with other measurements (manual or automatic) for easy display and analysis. The program provides a comprehensive overview of the site and the measured parameters, as well as offering advanced plotting and calculation options.

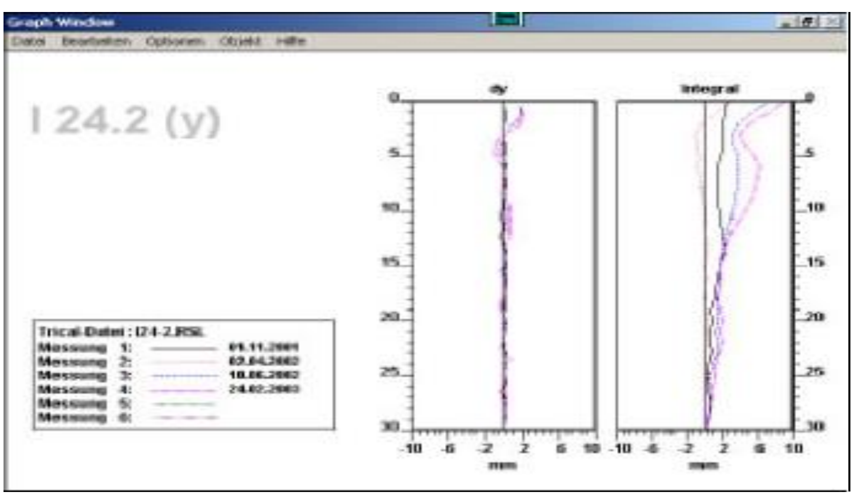


Figure 4.4 Solexperts DAVIS software provides comprehensive overview of data.

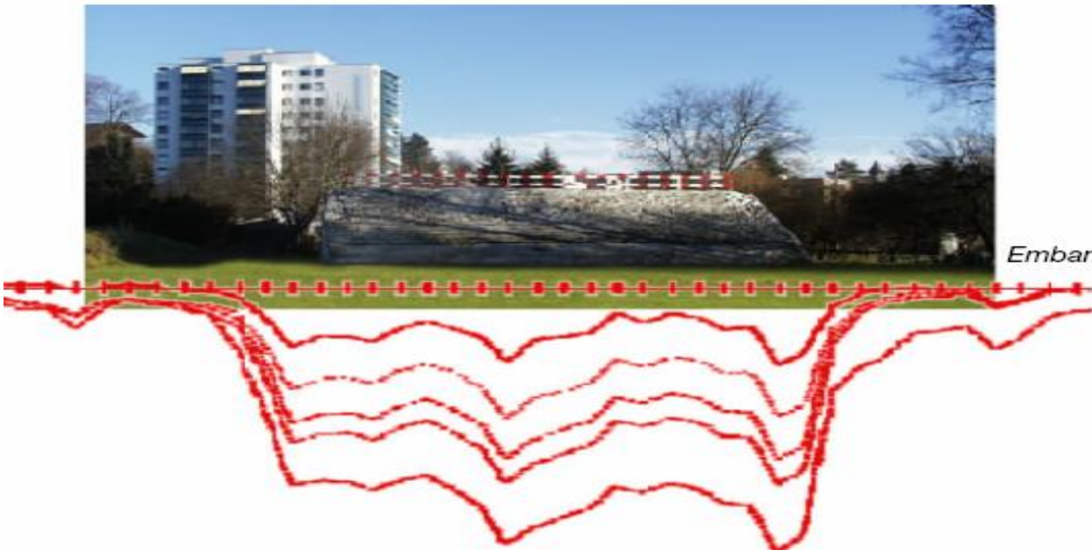


Figure 4.5 showing the application of the inclinometer measurement in several different condition and different places.

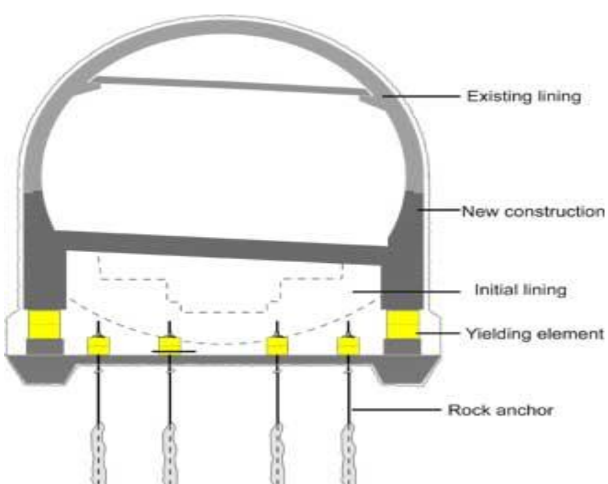
Chapter – 5

hiDCon–Elements for Tunnelling

5.1 Introduction

High Deformable Concrete **(hiDCon)** Elements is precast special concrete element with defined constant resistance for application in tunnels in squeezing and swelling condition of rock and clay. It is the "Modular Yielding Support" concept developed by Prof. Dr. K. Kovári (Zürich) in association with Solexperts AG after reviewing numerous alternatives for swelling rock. It is found a best solution for squeezing and swelling ground condition. It has been used first time in Chienberg road tunnel near Basel at tunnel invert for swelling gipsy kenper and Lötschberg Base Tunnel in squeezing carbonate rock integrated in shotcrete lining.

Figure 5.1 shows the application of this method in a schematic manner. The existing bottom lining was removed in stages and the tunnel profile was extended to form a flat base. The newly concreted sidewalls of the tunnel were supported by hiDCon-elements (ø 90 cm, h=100cm) placed on a foundation.



a) Lining concept of “Modular Yielding Support”

b) Implementation of “Modular Yielding Support”

Figure 5.1 a and b shows the application of hiDCon in swilling and invert heave tunnel floor.

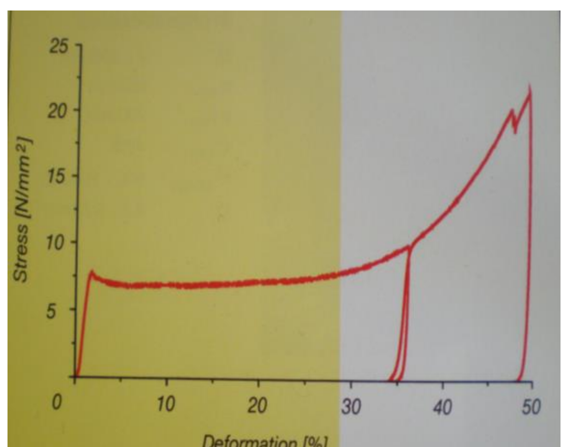
5.2 hiDCon-Elements used in swelling Clay

The hiDCon foundation-elements reduce the swelling pressure on the tunnel lining and simultaneously allow a limited amount of heave in the bottom of the tunnel. Pre-stressed 25 m long anchors with tensile strength of 1750 kN were built into the flat tunnel base at Chienberg road tunnel near Basel (Switzerland). Cylindrical hiDCon - elements were placed between the natural rock and the anchor plates to permit the floor to heave in a controlled manner shown the application on figure 5.1.

a) Load test of hiDCon foundation elements in protection sleeve Ø=900 mm, and H=1000 mm

b) Load test of hiDCon foundation elements ε= 25% σ=7.4 N/mm^2

c) Load test of hiDCon foundation elements ε= 50% σ=21.8 N/mm^2



d) Stress strain diagram of a hiDCon foundation element

Figure 5.2 a, b, c, and d shows test result of deformability constant resistance for application in squeezing and swelling rock soil in tunnels.

Rock containing swelling clay minerals and anhydrite increase in volume (swell) due to water absorption. The swelling results in a build up of pressure in the bottom of the tunnel lining.

Under low overburden conditions (10-50 m) pressures at the bottom of the tunnel lining could cause the tunnel to heave, resulting in vertical displacements at the ground surface above the tunnel. Additionally, damages to the tunnel lining could occur because of varying degrees of heaving along the tunnel axis (primarily in the lower part of the cross section).

Significant heave in the 60 and 370 m sections of the Chienberg road tunnel near Basel (Switzerland) occurred before the tunnel was even finished. The observed heave rates and resulting heave damage on the tunnel lining were so serious abandonment of the tunnel project was discussed. Finally hiDCon element were used (figure 5.1) during the reconstruction of the Chienberg road tunnel. Corresponding to the overburden (20-60m) hiDCon foundation element with load capacity of 1550 – 10500kN were used. The hiDCon - elements had a load resistance of 600 to 1500kN, figure 5.2 shows the test results and behavior of the hiDCon elements.

5.3 hiDCon beams integrated with shotcrete in squeezing rock

Beam shaped hiDCon-elements are used when tunneling in squeezing rock zones. A load bearing and deformable lining is created by installing shotcrete shells with integrated hiDCon-elements between steel arches with sliding connections. The resulting tunnel lining significantly helps to reduce rock pressures.

The application of bearing yet yielding shotcrete shells is based on the engineering principle: In squeezing rock, the rock pressure decreases with increasing rock deformation.

a) Beam shaped hiDCon-element for shotcrete lining

b) Details of installed hiDCon-elements in shotcrete e in squeezing

d) Partly deformed hiDCon-elements inside shotcrete

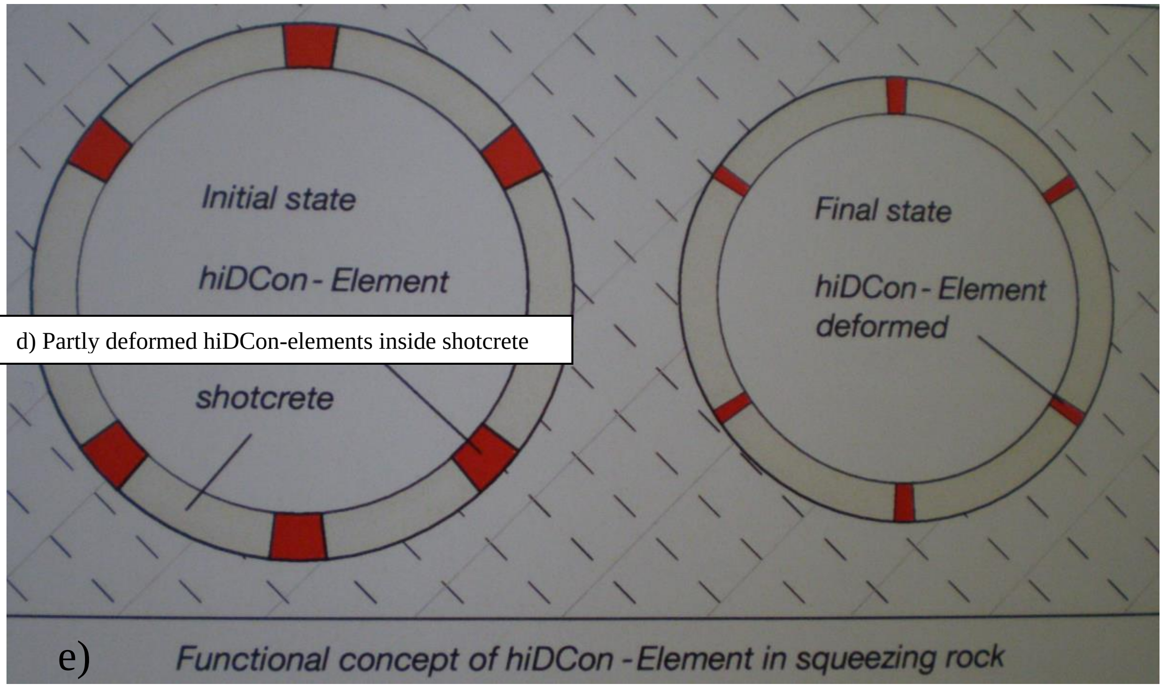


Figure 5.3 a, b, c, d and e shows clear concept of the use of hiDCon-Elements in tunnelling with shotcrete for squeezing rock condition.

An implementation of this principle in tunnel linings is made up of shotcrete shells with integrated deformable hiDCon-elements. The result is a bearing yet yielding lining that reduce rock pressure allowing the squeezing of rock.

The shape and number of hiDCon-elements per cross section depends on the amount of permitted radial deformation. The hiDCon elements resist the shotcrete lining with a predetermined bearing capacity so the shotcrete does not become overstressed. The hiDCon-elements are designed so that after exhausting their working range only small additional deformations develop. The lining resists these (small) deformations with the full bearing capacity of the shotcrete shells.

Figure 5.3 shows the shotcrete lining with integrated beam shaped hiDCon - elements in the Lötschberg Base Tunnel. hiDCon-elements incorporated in the shotcrete lining permit controlled convergence of the rock mass while maintaining a substantial high lining resistance. The amount of the maximum convergence is defined by the size and number of hiDCon-elements in the cross section. The shape and size of the elements may be customized as needed.

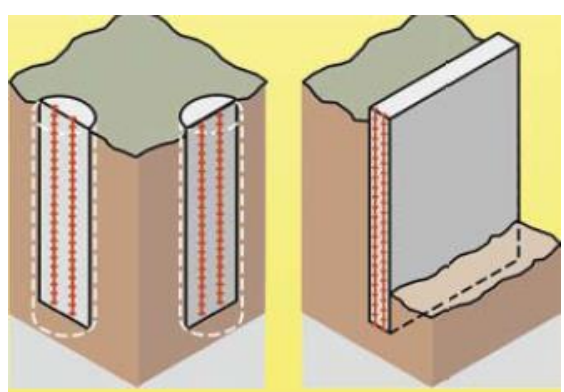
Chapter - 6

General Field Works/ Case histories

6.1 Sliding Micrometer at Zurich Highway Test Pile

A part of the highway passing through the Zurich city is planed to be covered to avoid the disturbance to either side residence/market as well to make available the free open space above the highway. The preliminary concept is to construct the pile foundation either side wall and RCC covered above the highway. A load test was carried out on the test pile as well as the sliding micrometer was installed to observe the axial deformation at the pile

To observing the axial deformation (strains) along the measuring lines on both sides of a pile or wall, it is possible to determine the curvature and with



simplified assumptions to estimate the bending moment.

Figure 6.1 positioning of the sliding micrometer

The main scope of the strain distribution measurement is to check if the pile length is sufficient to resist to the applied load.

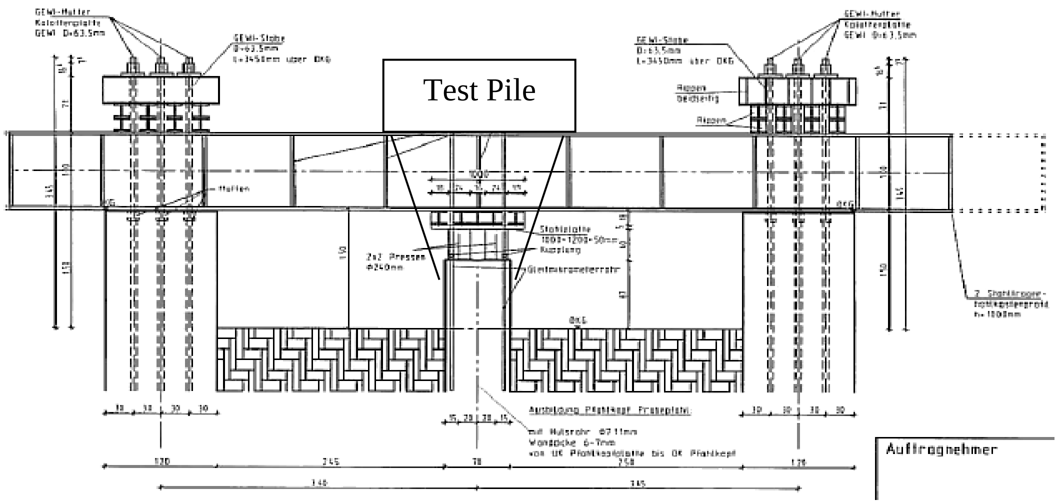


Figure 6.2 shown sketch of pile load, the test was carried out on central pile

Figure 6.3 shown testing proceduer and deformation measuring on PC in the field.

The pile was 24 m deep and the axial deformation measurement was carried out in each one meter interval of the pile fig 6.1 shown the positioning of the measurement of the pile and fig 6.2 the sketch of the test scheme and the central pile is the testing pile.

stellt.

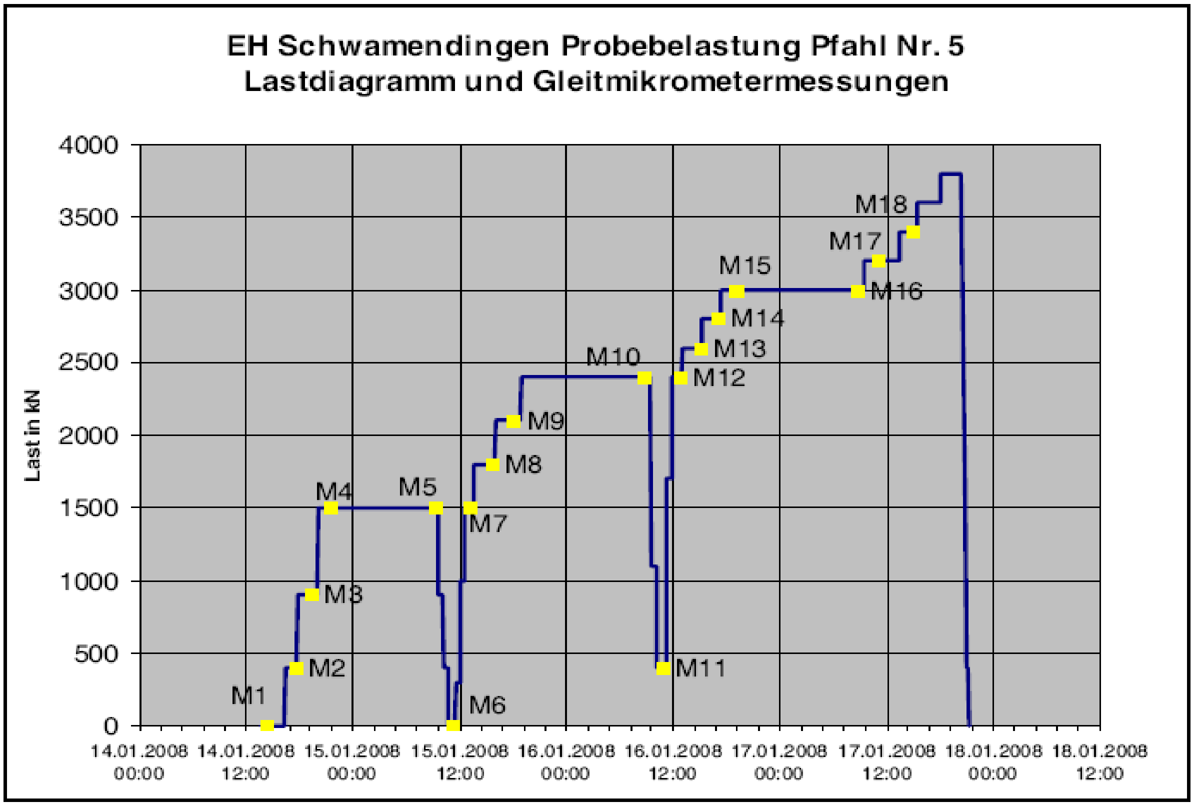


Figure 6.4 shown test results sliding micrometer, axial deformation during load test.

6.2 Dilatometer Test at Tunnel de Choindez

Location; Project 1797 Tunnel de Choindez (an investigation adit).

Dilatometer test was carried out in a 8 m deep borehole drilled at the invert of the test adit tunnel to find out the deformability of the rock mass. Three test was carried out first at the bottom of the hole, second at the middle of the hole and third near the surface of the hole. Each test was carried out in three loading, on-loading and reloading cycles.

The probe is placed in to the borehole manually by means of installation rods. The high pressure hose with the coaxial data transmission cable is installed simultaneously. By expending the rubber packer with the nitrogen gas, pressure is applied to the borehole wall in steps. The magnitude of the steps depends on the deformability of the formation being tested. Through several cycles of applying and releasing pressure, the deformation and elasticity moduli of the geological formation are determined.

Used equipments/accessories

1 Dilatometer probe

2 High pressure delivery hose

3 Nitrogen Gas

4 Calibration devices

5 Pressure regulation devices

6 Data acquisition cable

7 Data acquisition system

8 Data analysis software and PC

9 Other various tools and supporting accessories

Calculation of the E modulus is carried out on the basis following question

$$E = (\Delta p / \Delta d) * d (1+\nu)$$

Δp = Pressure differences, *Δd = change of diameter*

d = borehole diameter, *ν = Poisson ratio*

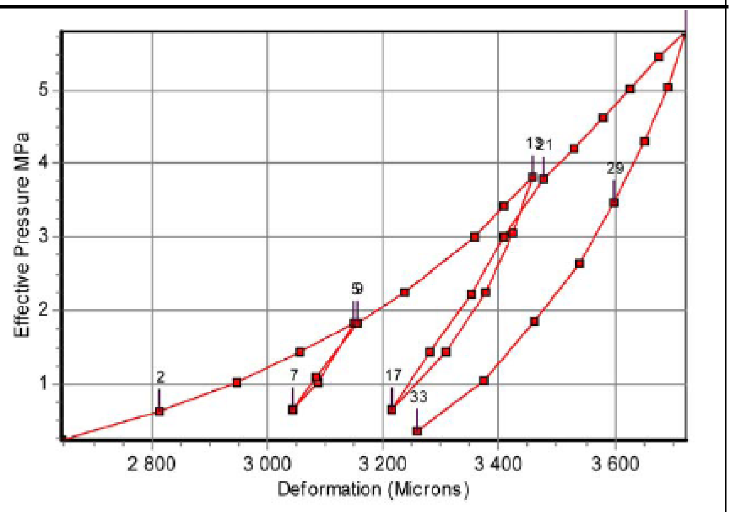
Project: Choindez Tunnel
Test Date: 19/01/2008 12:12:00

ANALYSIS RESULTS

Borehole: Bohrloch1
Test Depth (m): 4.5

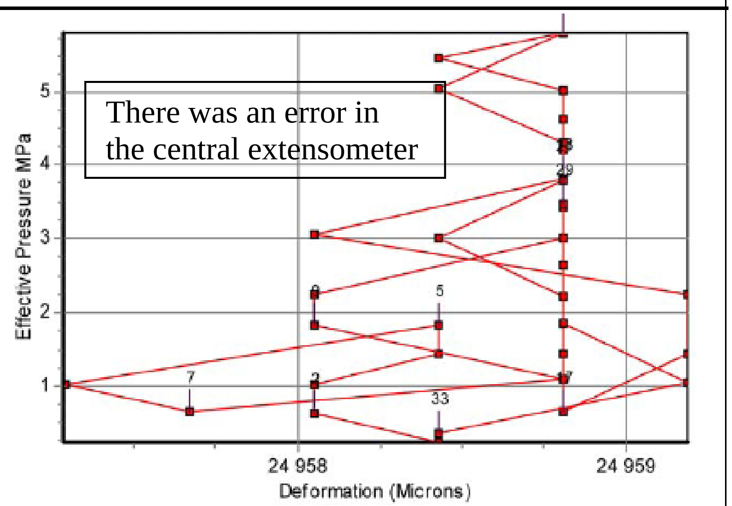
Top Extensometer

Range Start - End	Fit Type	E-Modulus MPa
2 - 5	R	480
5 - 7	S	1450
7 - 9	R	1370
9 - 13	R	890
13 - 17	S	1740
17 - 21	R	1620
21 - 26	R	1110
26 - 29	S	2530
26 - 33	S	1580



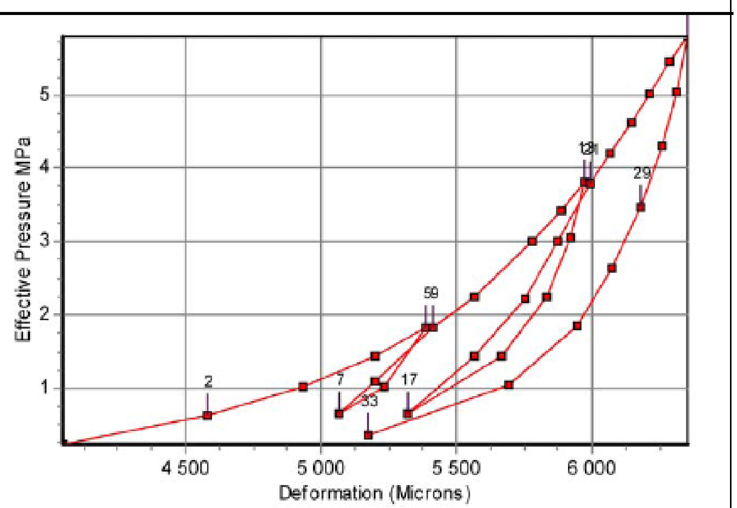
Central Extensometer

Range Start - End	Fit Type	E-Modulus MPa
2 - 5	R	347000
5 - 7	S	205000
7 - 9	R	758000
9 - 13	R	287000
13 - 17	S	0
17 - 21	R	0
21 - 26	R	0
26 - 29	S	0
26 - 33	S	1925000



Bottom Extensometer

Range Start - End	Fit Type	E-Modulus MPa
2 - 5	R	200
5 - 7	S	480
7 - 9	R	450
9 - 13	R	480
13 - 17	S	660
17 - 21	R	640
21 - 26	R	750
26 - 29	S	1840
26 - 33	S	620



Program: Dilato2
Solexperts AG [Man]

27/ 1/2008 14:24:06
File: S:...Choindez\Messdaten\430-VRa\choindez_4.5_1.D2I

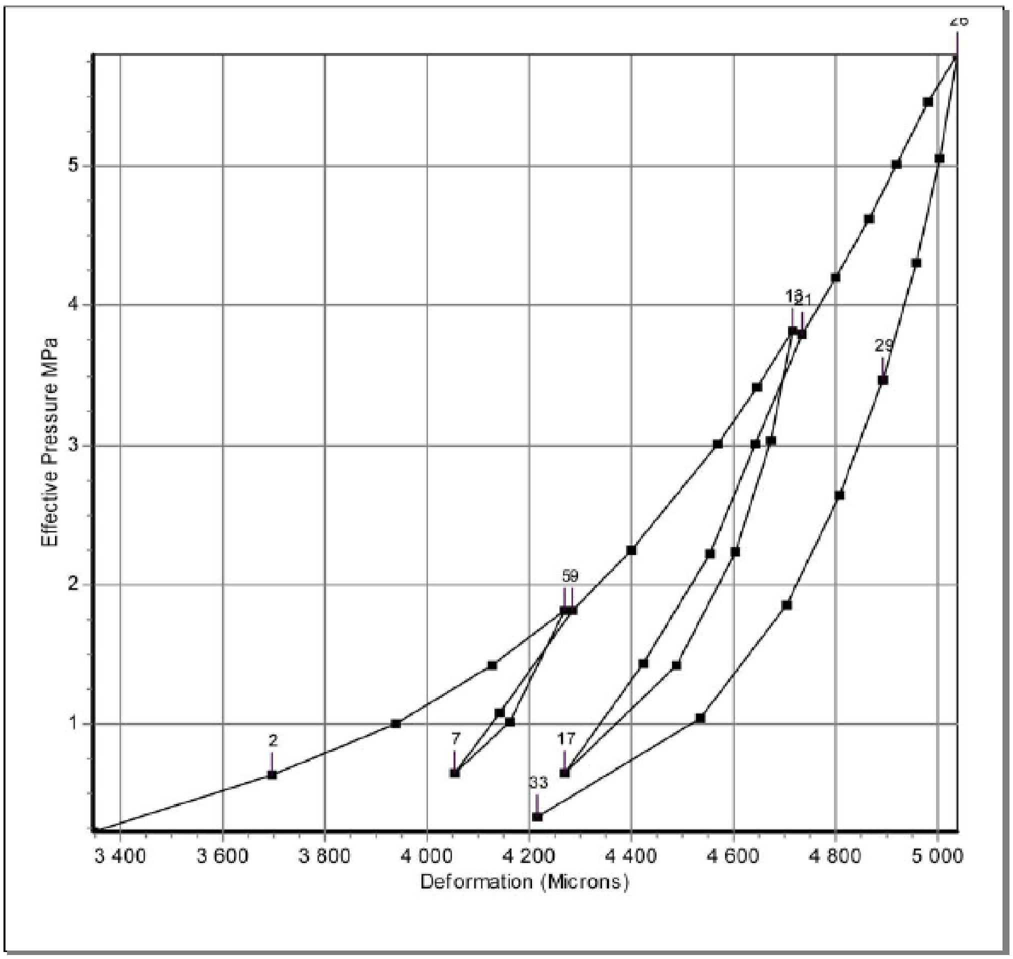
Project: Choindez Tunnel
Test Date: 19/01/2008 12:12:00

ANALYSIS RESULTS

Borehole: Bohrloch1
Test Depth (m): 4.5

(TB)/2 Extensometer

Step Nr.	Range Start-End	Fit Type	E-Modulus MPa	Step Nr.	Range Start-End	Fit Type	E-Modulus MPa
1	2 - 5	R	280	2	5 - 7	S	720
3	7 - 9	R	680	4	9 - 13	R	630
5	13 - 17	S	950	6	17 - 21	R	920
7	21 - 26	R	900	8	26 - 29	S	2130
9	26 - 33	S	890				



Program: Dilato2
Solexperts AG [Man]
27/ 1/2008 14:24:28
File: S:...Choindez\Messdaten\430-VRa\choindez_4.5_1.D2I
SOLEXPERTS

The above presented chart and data is an example of the dilatometer test result at the depth of 4.5m.

***Figure 6.5 shown testing borehole location and measuring on PC in the field*.**

6.3 Installation of Extensometer at Tunnel de Chondez

A four point extensometer was installed in the same borehole drilled at the invert tunnel de Choindez where the dilatometers test was carried out. Extensometer is for measuring deformations and displacements which is very common and reliable. In the geotechnical field it is a new development based on the well proven Uni-Rod Extensometer.

For automatic distance measurements often extensometers, electronic displacement transducers are installed.

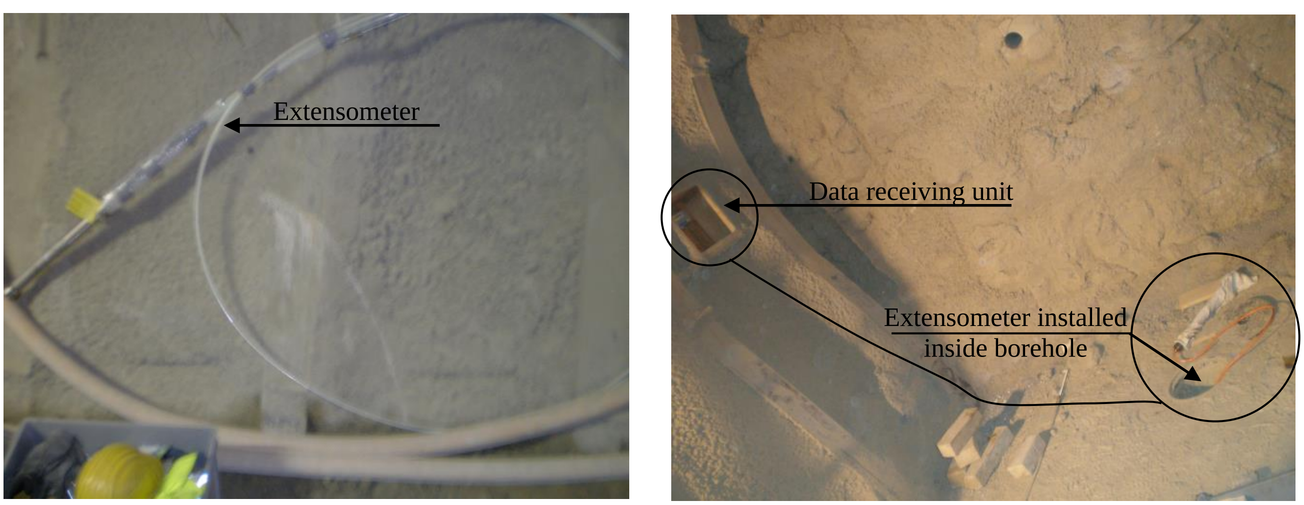


Figure 6.6 a and b shows the installation of the extensometer in the borehole.

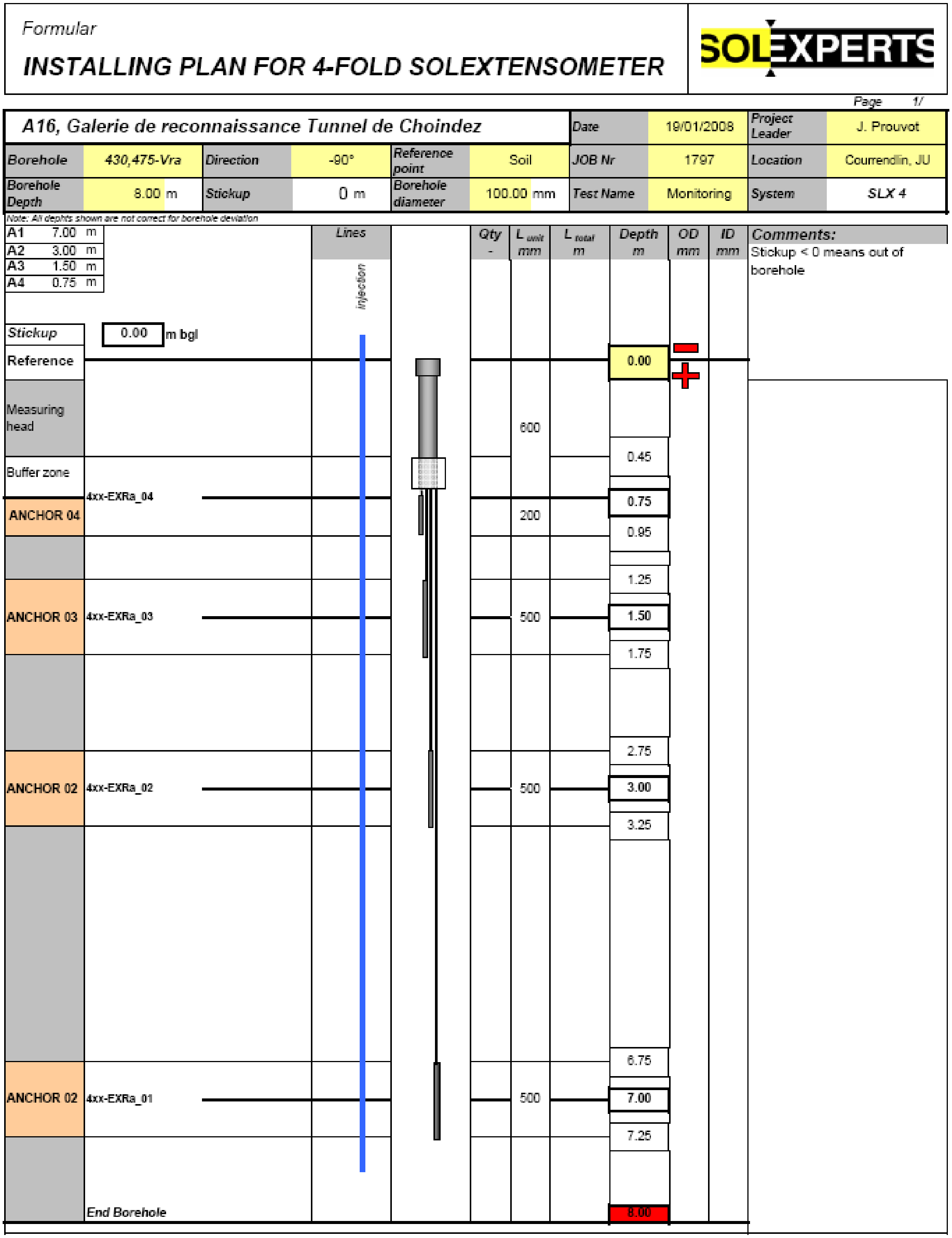


Figure 6.7 an installation plan of four point extensor meter in the 8m deep borehole.

6.4 Observation and brief study of Mont Terri Rock Laboratory

Observation and brief study about the investigation and research work of the Mont Terri Underground Rock Laboratory is an important opportunities for a student of tunnelling and rock mechanics. Mont Terri Rock Laboratory is an underground research laboratory is being conducted by nine organizations. The organizations are **Swiss National Cooperative for the Disposal of Radioactive West (nagra**) with other five from Europe and Nuclear Cycle development Institute Japan, figure 6.8 is a plan view of laboratory.

Members of Nagra

- Swiss Federal Government (Representative by the Development of the interior)
- BKWFMB Energie AG Berne (Nuclear Power Plant/NPP Muhleberg
- KKW Gosgen-Daniken AG, Daniken (NPP Gosgen)
- KKW Leibstadt AG, Leibstadt (NPP Leibstadt)
- Nordostschweizerische Kraftwerke Baden (NPP Beznau I & II)
- Engine Ouest Suisse, Lausanne

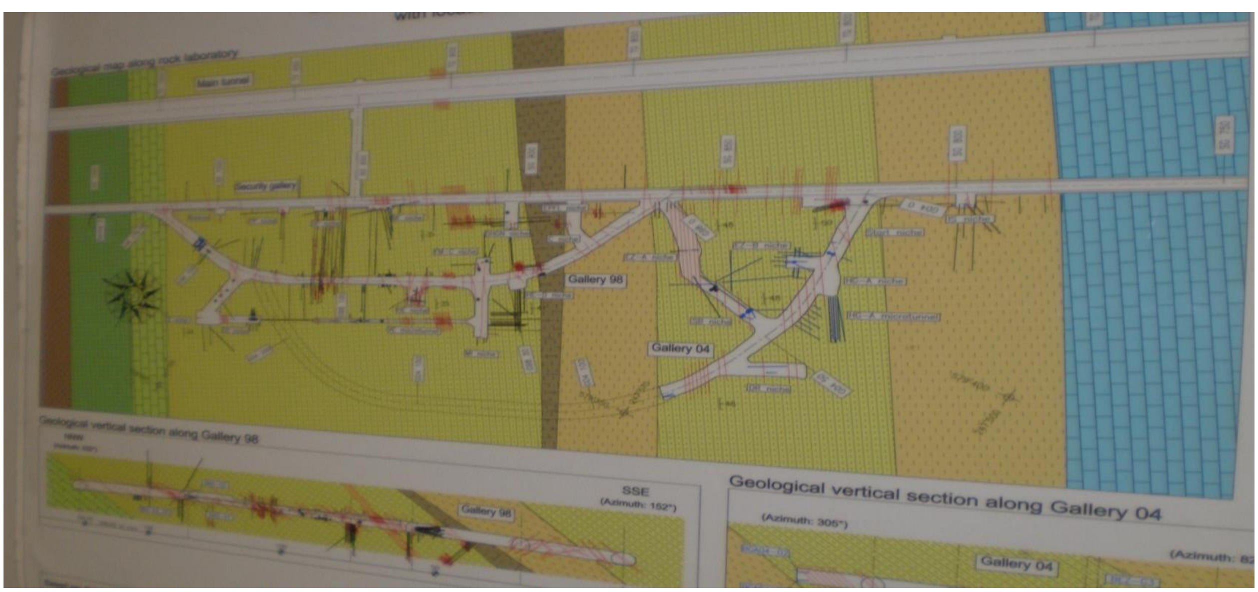


Figure 6.8 Shown the plan of the underground Mont Terri Rock Laboratory.

Aims of the Research

The aim of the research is the study of potential geological formation in view of its geotechnical behaviour and development of deep geological disposal of radioactive west for environmentally safe and long term isolation inside a potential host rock, Opalinus Clay of Zura Mountain (Switzerland).

Present Research at Mont Terri

For confirmation of the present knowledge and optimization of the proposed disposal system with regards to the construction, operation and long term safety, the following research activities are in progress as a part of the international research project at Mont Terri.

- Diffusion and retention of radionuclides.
- Gas migration.
- Evolution with time of the Excavation Disturbed Zone (self sealing of fractures).
- Geochemical and hydrochemical properties of Opalinus Clay.

6.4.1 Location and Geology

The rock laboratory is located in and alongside the reconnaissance gallery of the Mont Terri motorway tunnel in North-western Switzerland. The 3962 m long tunnel crosses the northernmost anticline of the Jura Mountains, the Mont Terri anticline, which was folded during the late Miocene to Pliocene period about 10 million years ago.

The Mont Terri Rock Laboratory is located in the Opalinus Clay, a shale formation. The present overburden is 250 m to 320 m. The reconnaissance gallery intersects a 243 m long section of the Opalinus Clay which dips from 20 to 60^0 to the south-east. The apparent thickness is about 160 m However, thrust faulting may have led to accumulation of the Opalinus Clay; thus the true thickness might be less than apparent thickness. A simplified NW-SE geological profile through the Mont Terri anticline is shown on figure 6.9.

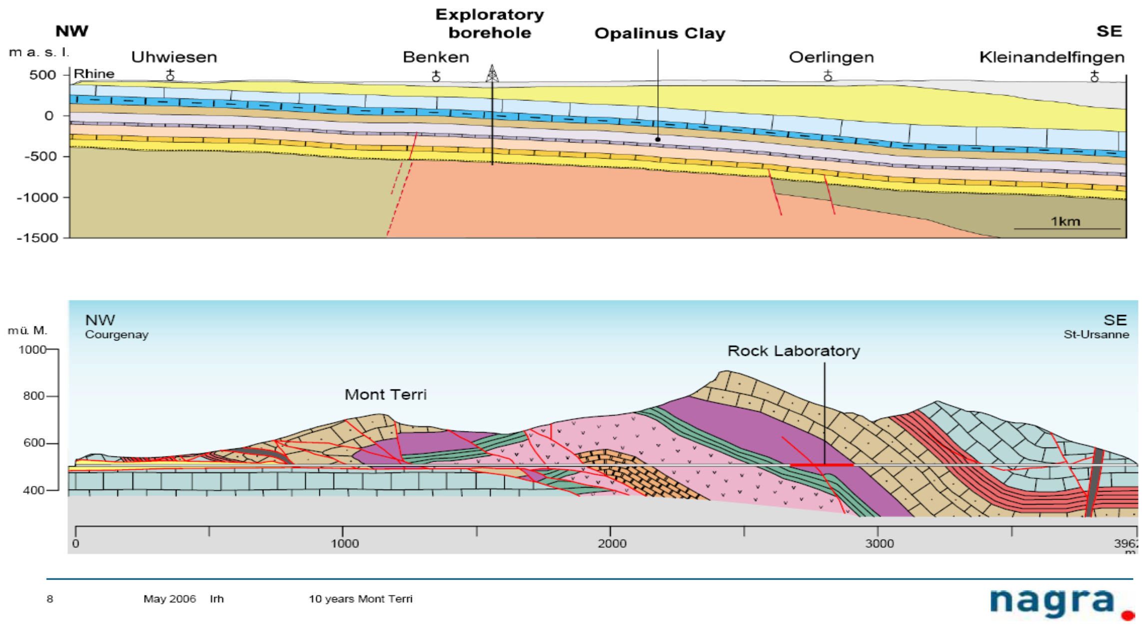


Figure 6.9 a simplified NW-SE geological profile through the Mont Terri anticline.

The profile line is placed along the Mont Terri motorway. The southern limb of the Mont Terri anticline exhibits a simple geometry with gently to moderately SE dipping strata and without major tectonic discontinuities. Due to the over thrusting of the northern fold limb on to the Tabular Jura. The geological structure of the Mont Terri anticline is complicated and at least four thrust sheets diverge from the basal detachment and dissect Triassic and middle Jurassic formations, which locally leads to inverted strata.

6.4.2 Investigation Drillings

The majority of the experiments at Mont Terri were performed in boreholes. In two drilling campaigns 42 boreholes with a total length of 540 m were drilled. Adequate drilling techniques and new type of techniques and new type of drilling equipments were developed in order to successfully address such concerns as quality of the drilling and overcores, borehole stability, smoothness of boreholes wall and prevention and handling of swelling. Most of the boreholes were drilled dry (air drilling), but some were drilled with drilling fluids.

Core barrels

Core barrels with diameter up to and 600 mm (see figure 6.10) were used for laboratory testing. Borehole with small diameter (35 and 46 mm) drilled normal to the bedding planes, could not be drilled due to core disking, and in these cases destructive drilling was applied. Three different types' of core barrels were used single double and triple. Single core barrels used only one steel barrels containing drill bite and its front. In double core barrels, a second steel tube is introduce into the first barrel and rotates freely within outer barrel. The inner tube takes up the core. In triple core barrels the core is encased by a plastic liner which lies within the inner steel tube. The liner and core stay together until the core is mapped. The triple core technique delivered the best core quality especially when coring tectonised zones. In the undisturbed Opalinus Clay, drilling with double core equipment was sufficient.

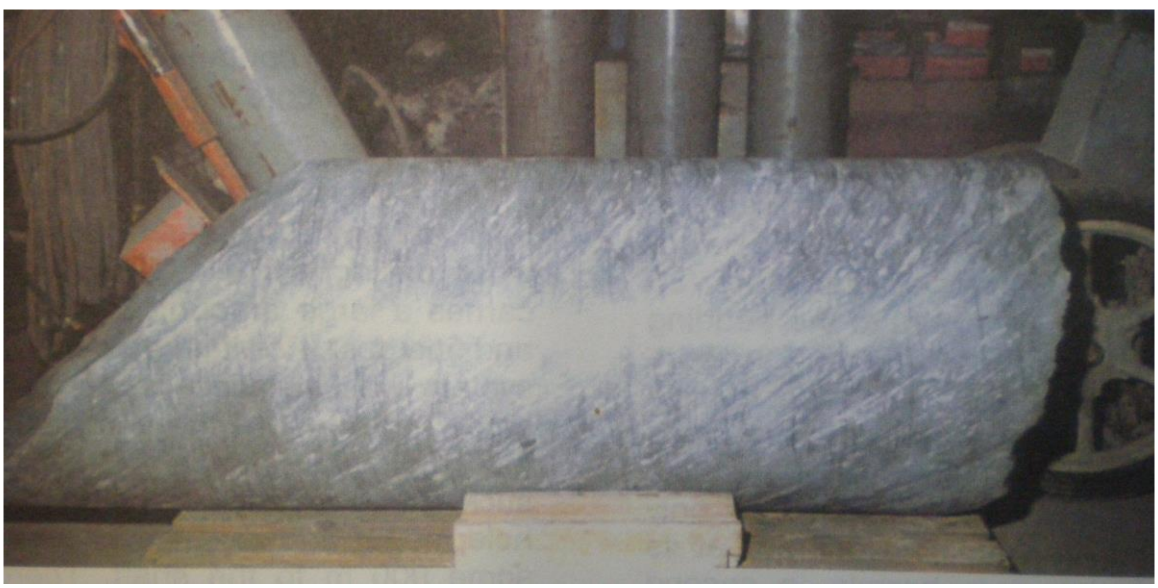


Figure 6.10 Shown a 2.5 m long 600mm diameter double core barrel sample.

Overcoring

Two overcoring diameters were used; 252 mm and 600 mm. Both diameters were drilled with air and double core barrels. Each overcoring was proceeded by a small diameter pilot borehole in the centre of the planed overcoring borehole.

Core mapping and borehole logging.

Systematic core mapping was performed to

- create a complete documentation of lithological and structural features.
- obtained information about rock quality.
- assemble a complete overview of sample taken from the cores.

The cores were mapped using with six parallel columns. 1) lithology, 2) meter scale, 3) Structures, 4) abbreviation for structure, 5) references for sample, 6) ordered from the core.

The number of total discontinuities and artificial discontinuities is indicated at the bottom of the every mapped meter. The RQD (Rock Quality Designation) value indicates the quality of rock. If required the apparent orientation of the discontinuities was also determined and later re-oriented to its true orientation. The interpretation of the tectonic and artificial structures observed in the core is based on the detailed structural mapping.

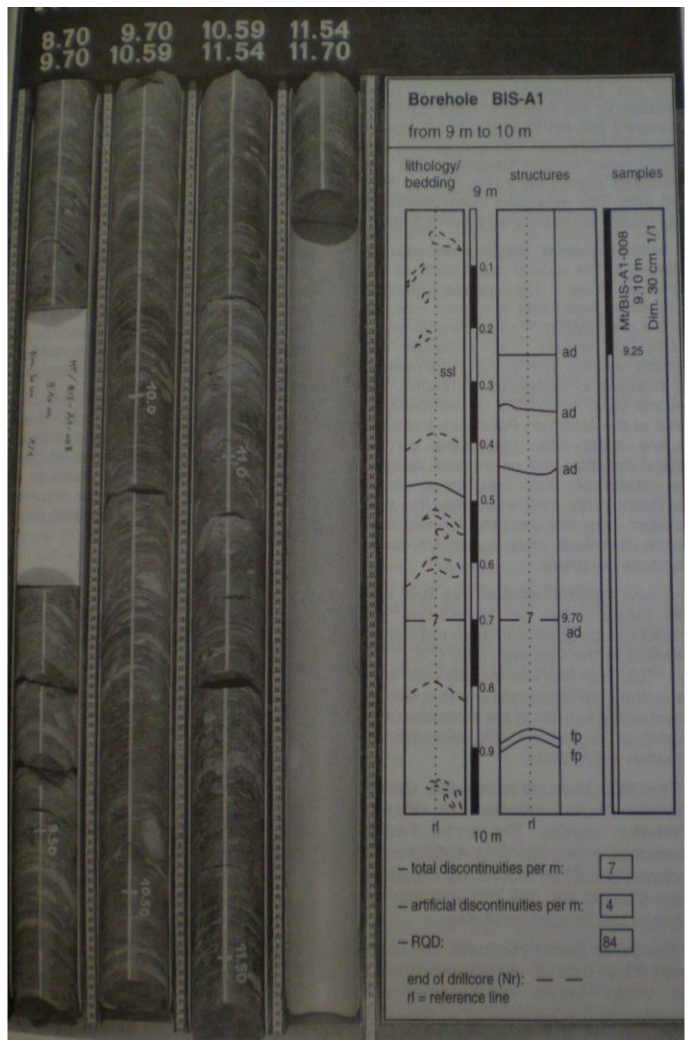


Figure 6.11 shows the careful handling and systematic arrangement of the drill core before logging.

6.4.3 Investigations on Excavation Disturbed Zone (EDZ)

6.4.3.1 Rock Mechanical Experiments on EDZ

During the construction of the underground facilities the primary stress fields is altered and a secondary stress field develops around the openings. Depending the host rock properties, this stress redistribution may lead to the development of a plastic zone around the tunnel (non-linear deformation occurs) and creation of discontinuities (unloading fractures), such a zone is termed as Excavation Disturbed Zone (EDZ).

In the EDZ volume increase (unloading fractures) and convergence of the tunnel are the major effects of the stress redistribution. The degree of disturbance depends up on the other factors, on the method of excavation, the stress field, the rock properties, the geometry of the opening and time. The geometry of the EDZ and the resulting secondary stress field are also dependent on the magnitude and orientation of the initial stress field.

Knowledge of insitu initial stress field is an important parameter for studying and long term behaviour of underground openings. Measuring the stresses in argillaceous rock is a delicate operation because of the non elastic behaviour of such rock.

Insitu stress measurement

In Mont Terri project two different testing methods have been applied to evaluate the insitu stress;

- Insitu stress measurement based on borehole slotting (IS-B) but not very successful.
- Insitu stress measurement based on undercoring/overcoring technique (IS - A).

Plate Loading Test

A plate loading test was conducted (Buhler et al. 2004) at the EH experimental site and demonstrate that the mechanical loading of the EDZ will additionally contribute to the reduction of the EDZ transmissivity

6.4.3.2 Hydraulic Experiments on EDZ

Area around underground excavation affected by excavation process are generally called excavation disturbed zone (EDZ). There is an international consensus to relate the definition of the EDZ with processes which are important for the long-term safety of a repository for the geological disposal of radio active waste. It is important to differentiate the two zones with regard to their flow and transport characteristics, admitting that area of hydro-mechanical and geochemical modifications with major changes in flow and transport properties (EDZ) should be distinguished from those without negative effects on the long term safety.

Most of the hydraulic experiments at Mont Terri were performed in boreholes. The rock mass in the direct vicinity of the tunnel and caverns, the so-called excavation disturbed zone (EDZ), may exhibit variable hydraulic properties due to stress redistribution following the construction of such openings. The aim of the hydraulic testing was to characterized the distribution of hydraulic parameters at different radial distances from the existing reconnaissance gallery using various methodologies. The following various hydraulic test was carried out to identify the EDZ.

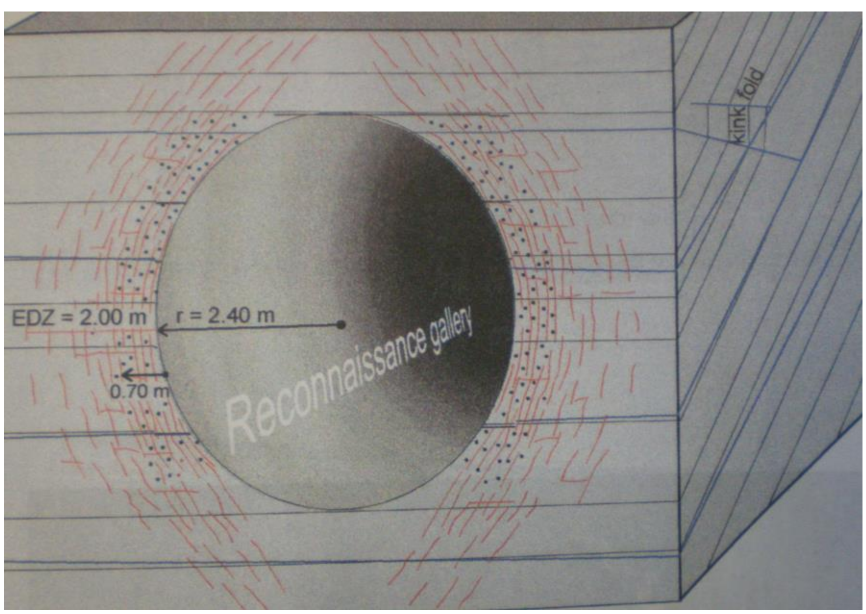


Figure 6.12 Shown a model of excavation disturbed zone (EDZ).

Measurement with the SEPPI

Hydraulic test with SEPPI probe is a specific tools developed by the LGM Laboratory of Nancy France. The test was performed in two sub-horizontal boreholes diameter of 86mm and 5m long.

Hydraulic testing with the MMPS equipment

The MMPS (Modular Mini-Packer System) equipment was specifically designed for hydraulic testing in the excavation disturbed zone in the direct vicinity of the tunnel. To minimize the influence of the exploration borehole on the properties of the excavation disturbed zone itself, the borehole diameter for the MMPS test was limited 50 mm. The length of the borehole varied between 2.2m to 3.2 m.

Porewater Pressure Experiment

The aim of the porewater pressure experiment was to develop and validate a technique and procedure to measure porewater pressure in formations with varies low hydraulic conductivity and very low free-water contents.

6.4.4 Hydraulic and Gas Testing (GP)-

The aim of the hydraulic and gas testing was to identify the hydraulic parameters and formation pressure in matrix and faults.

- Detection of a discrete water-conducting features (fault & fracture zone along the borehole).
- Hydraulic characterization of this zone.
- Hydraulic characterization of the Opalinus Clay matrix.
- Hydraulic characterisation of a fault zone in the Opalinus Clay.
- Characterisation of the two phase properties by means of gas threshold pressure test.
- Performance of an extended gas threshold pressure test in order to determine the pressure at which gas starts to flow into the Opalinus

Clay, and to obtain the data which could be used for assessing two-phase flow parameters through modelling.

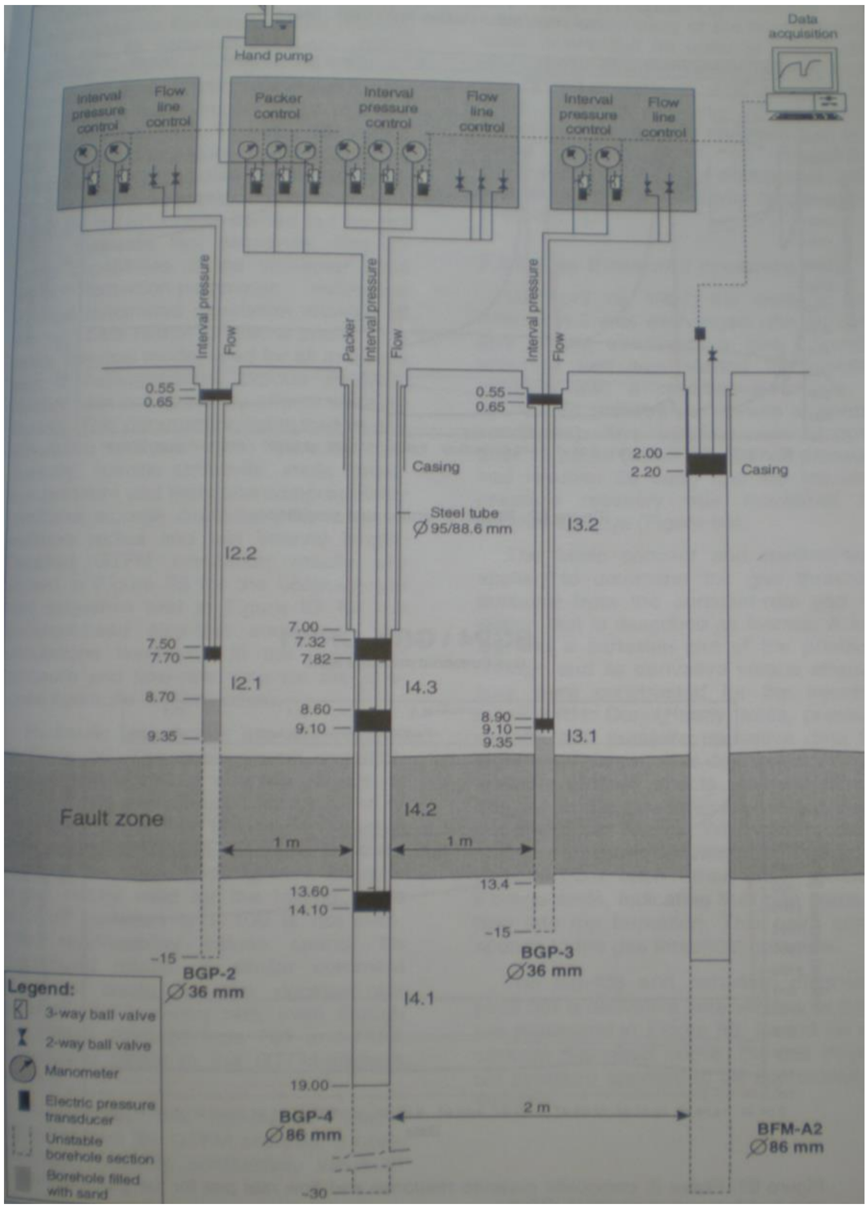


Figure 6.13 a sketch of borehole instrumentation using triple packer for GP testing.

The test was conducted using a triple packer system in borehole, two mechanical mini packer systems and a mechanical packer. Solexperts was responsible for providing the equipment and performing and analysis the tests. A sketch of the bore hole installation setup is shown in figure 6.6. After packer installation the hydraulic test sequence started with a 26-days pressure recovery period to allow the interval pressure to stabilise. During this period the packers were re-inflated twice. A 51 days period follows, during which a constant rate and a five-step constant head injection test with pressure recovery period in between were conducted. The flow rate during the constant rate injection test was 16ml/hr. The purpose of the five step constant head injection test was to investigate whether the Opalinus Clay exhibit a pressure-dependent permeability.

Gas threshold pressure test

The water test in interval l4.2 (fault zone) was exchanged with nitrogen and shortly afterwards a gas threshold pressure test was started by injecting nitrogen with a constant flow rate of $40ml_n/m$ (millilitre per minute at normal conditions). The injection was stopped after 19 hours (when the interval pressure had reached 30 bars) and the following pressure recovery was monitored for another 53 days.

6.5 Monitoring of the slope movement by TRIVEC

The road side slope at Fallanden is gradually moving down even the slope is not so steep and high. The clear deformation (crack) can be observed at the surface along the road side. The area is densely populated and there are a number of houses above and below the slope. If it is triggered might have damage the properties and life. Therefore it is extremely important to monitor the behaviour of the movement to carry out the remedial measure in case of any indication of trigger.

Figure 6.14 clearly shows the deformation (crack) line at the surface along the road site. Solexperts has established two measurement stations at the drilled bore hole at the axis of deformation and regularly measure the movement along the X, Y and Z direction by using Trivec instrument.

6.5.1 Measurement Procedure

The probe is introduced into the measuring tube using a guide rod and is positioned in steps of 1.0 m between two neighboring measuring marks. The two spherical-shaped heads of the probe and the circular cone-shaped measuring marks guarantee a very accurate placement of the probe. Openings in the measuring marks and in the measuring heads of the probe permit a stepwise movement of the probe in the sliding position. By rotating the probe by 45° about its axis into the measuring position and pulling the cable or the guide rod the two heads of the probe are tightened between the measuring marks.

Figure 6.14 shows the measurement of slope movement X, Y and Z vector by Trivec probe on road side slope at Maur.

A high precision displacement transducer for the z-component and the inclinometer sensors for the x- and y-components are activated and the three measured values are transmitted to the digital data acquisition equipment SDC (Solexperts Data Controller) via the cable. For each measuring position the probe is rotated by 180° using of the guide rod. Measurement in two positions (0° and 180°) compensates the temperature influence and any systematic instrument errors.

Charter - 7
Conclusion

7.1 General Conclusions

- Cost of Investigation and monitoring is not waste of money, it is worth for the project to make it safe and economic.

- In the past most of the investigation, design and construction tunnelling has been done on the basis of experience and empirical approach but now detailed investigations are the basic requirements for any tunnelling and foundation related to underground excavation projects.

- Good exploration reduce the BID cost of any tunnelling and underground excavation project by 10 to 15 times of the exploration cost and reduces the possibility of claim and uncertainties where as poor investigation increase the bid cost as well as support for the claim.

- There are high precision various portable borehole probes available for the measurement of different geotechnical parameters and geomonitoring but selection of the proper investigation methods, monitoring system and appropriate equipment according to the site condition is very important.

- Knowledge of regional hydrogeology is required for the alignment of the tunnel path, environmental impact assessment preparation of tender documents, Knowledge of local hydraulic conditions to optimize design and construction parameters

- Particularly the hydrological test used to conduct to obtain the following hydraulic parameters of soil and rock which are the design parameters.
  - – Transmissivity **T** [m2/s]

– Hydraulic conductivity **K** [m/s]
– Hydraulic head **h** [m]
– Aquifer storability **S** [-]
– Evaluation of flow regimes and boundaries

- For systematic measurements and monitoring in geotechnical field, computational methods has become a powerful tool in order to construct safe and economical new underground infrastructure.

- During the construction of urban tunnelling and underground facility the visibility of any small damage at the surface is very high. If there is not proper monitoring system, duly take care of any indication is not possible, resulting the probability of damages and consequences is very high.

- hiDCon is a new invention in concrete technology and well proven of it's function used at several tunnelling project in Switzerland, a best solution for tunneling in swelling clay and squeezing rocks (in critical condition).

- Involvement to perform the various insitu tests on job site gives practical experience for data analysis and interpretation as well as knowledge of operation technique of various instruments and required accessories details.

- Observation and brief study of Mont Terri Rock Laboratory is an important opportunities for a student of tunneling and rock mechanics to know about the various required geological/ geotechnical, hydrogeological, biochemical, geochemical and geothermal insitu testing and investigation to assure the safe geological repository of such a sensitive nuclear west.

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