CHAPTER 2

BACKFILL AND PLUG TEST PROJECT

2.1 INTRODUCTION

SKB (Svensk Kärnbränslehantering AB) was founded in 1972. It is the Swedish Agency in charge of the handling, transport and storage of the nuclear waste generated at the Swedish nuclear plants. SKB has carried out a large number of projects dealing with the storage of nuclear waste. Different projects, studying the location of a deep geological disposal site tectonically stable in order to isolate the waste in a safe way, involve a lot of work from very different technical fields. The general goals of SKB's research and development activities are:

- To increase the existing knowledge of rock as an isolating media in a deep disposal site with especial interest in a geomechanic, geochemical and hydrogeological characterisation of host rock.
- To study the behaviour of the deep repository, focusing on their performance in a long-term perspective.
- To develop theoretical models and their implementation in numerical codes as tools to assess and study the groundwater flow in fractured rock or coupled phenomena such as temperature, stresses and hydraulic conductivity in rock and sealing materials (buffer, backfill, concrete).
- To develop the necessary resources and technology to build and observe the behaviour of the disposal site.

Certain mechanical stability conditions, groundwater movement and chemistry have to be achieved to assure the security of canisters, deposition holes and the surrounding bedrock in a repository for nuclear waste. Depending on the conditions of the host bedrock at the selected site, the detailed design of the repository (direction of tunnels, selections of locations for the deposition holes, etc.) has to be adapted.

The Swedish concept of management of radioactive waste is based on proposals made in the latter half of the 1970s (Ericsson, 1999). At first, spent nuclear fuel will be placed at the CLAB (Central Interim Storage facility) for 30 years. In this facility, high-level waste radioactivity will fall by around 90% (SKB, 1997). Then, after 30 years, spent nuclear fuel will be moved to the deep disposal site. The Swedish deep repository concept considers an excavated vault below 500 meters in crystalline rocks (gneisses and granitoids because Sweden is geologically located in the Fennoscandian Shield).

The main components of the classical Swedish concept (KSB-3) are at this moment:

1. High-level waste is placed at copper canisters. Then, canisters are deposited in disposal holes (1.75 meters in diameter and spacing of 6 meters) drilled vertically.
2. Space between canisters and rock will be filled with blocks of highly compacted swelling bentonite clay.
3. Galleries will be backfilled with a bentonite-granular material mixture.

Figure 2.1 shows the scheme of the KSB-3 concept of a deep disposal vault. However, this concept is not definitely finished and important changes could occur until the moment of its construction. Among other waste management companies, the high-level waste storage concepts are similar to the Swedish concept, for example the Atomic Energy of Canada Limited (Lopez et al. 1984) or the Japanese Agency (Komine & Ogata, 1999). The Spanish concept for high-level waste is similar but depositional holes are horizontal, not vertical (FEBEX, 2000).

In 1990, SKB started the construction of the Äspö Hard Rock Laboratory (ÄHRL), a full-scale laboratory as a prototype of a future repository. This laboratory is spearheading SKB's work and enormous research interest arose after its construction. The main advantage of ÄHRL is that it is possible, in full scale and under realistic conditions, to test and demonstrate equipment, methodology and performance of important parts of the repository system in order to verify the quality and safety of the KSB-3 concept.

2.2 THE ÄSPÖ HARD ROCK LABORATORY (ÄHRL)

The Äspö Hard Rock Laboratory is the most important part of the work SKB has performed in the last 30 years on designing a deep repository, and it is located near Oskarshamn at the Southeast coast of Sweden (figure 2.2). The entry of this laboratory is in the island of Äspö. The site was chosen because of its geological environment, it is a non-populated area and the site is near of the Swedish interim storage facility for spent fuel (CLAB) and other facilities. Figure 2.3 shows a scheme of the ÄHRL. The *pre-investigation phase* and sitting of the ÄHRL took place from 1986 to 1990 (Clay Technology, 1997). During the *excavation phase* (1990-1995) the tunnel was excavated from the Simpevarp Peninsula continuing northward towards the southern part of Äspö where the tunnel continues in a spiral down to a depth of 450 meters. The total length of this tunnel is 3600 meters and the maximum depth is 450 meters. The tunnel was excavated by drill-and-blast and by tunnel boring machine. After 1995 the *operation phase* started. Since then, different projects have been developed and some of them are still being undertaken. These projects, briefly summarised, are (Ericsson, 1999):

- Prototype Repository.
- Zone of Excavation Disturbance Experiment.
- Degassing and two-phase flow.
- Redox Experiment in detailed scale.
- Backfill and Plug Test.
- Long Term Tests of buffer material.

Figure 2.4 shows a general overview of the galleries and where the different projects are currently being carried out at the ÄHRL. These projects study different problems as structural geology and mechanical stability (seismic hazard, discontinuities and its propagation, initial stresses at rock), hydro and geochemistry (geochemistry of the Baltic Sea, solubility and complexation of radio nuclides, stability and mobility of radio nuclides in colloidal form, retention of radio nuclides in rock and backfill materials, microbial processes), groundwater flow and radio nuclide transport (hydraulic tests and its interpretation, nuclide transport and retention in rock) to different spatial scales. The work at the ÄHRL is of great interest and several international agencies of waste management are participating in those projects collaborating with SKB (SKB, 1996): AECL (Canada), PNC (Japan), ENRESA (Spain), ANDRA (France), POSIVA Oy (Finland), UK Nirex (United Kingdom), USDOE (United States), NAGRA (Switzerland) or BMBF (Germany)

The framework of this thesis is the Backfill and Plug Test. This test is mainly a classical hydraulic experiment, but also chemical effects of salt water on the hydro-mechanical behaviour of an active clayey soil are experimentally and numerically investigated. Saturated and unsaturated flow laboratory tests in order to study the backfill hydraulic conductivity taking into account the salt water effects were performed and analysed. Numerical simulations of the saturation process at the ZEDEX gallery were also performed and a new mini-piezometer was designed and calibrated to study the local hydraulic conductivity of clayey soils.

2.3 BACKFILL AND PLUG TEST PROJECT (BPTP)

The Backfill and Plug Test is being carried out in the ZEDEX gallery at the ÄHRL and it is a full size version of a repository with a backfilled tunnel and a confining plug. It aims at testing different backfill materials and techniques for backfilling, plugging and studying the integrated function of rock, backfill and plugs. The main objectives of this project are:

- To test the coupled mechanical and hydraulic behaviour of backfill far away and near from bed or host rock in the ZEDEX tunnel excavated by careful blasting.
- To develop and test techniques and materials for backfilling of tunnels.
- To develop and test techniques for temporary plugging of deposition tunnels and to test the mechanical and hydraulic function of the concrete plug.

ENRESA collaborates with SKB in the Backfill and Plug Test project. The Department of Geotechnical Engineering and Geosciences of the Technical University of Catalonia (UPC) closely works with ENRESA in different projects of engineered nuclear barriers (FEBEX, 2000). In this context, UPC collaborates with SKB and Clay Technology AB studying, analysing and developing new technology within this project. The collaboration of UPC in this project follows three main branches. The first one, to develop a new minipiezometer called dynamic pore pressure system (DPPS) for carrying out constant and pulse tests in situ and their interpretation (Mata & Ledesma, 2001 and Mata & Ledesma, 2003). The second one, to characterise the backfill chemo-hydro-mechanical behaviour as sealant material. And finally, to perform numerical simulations of unsaturated and saturated flow tests in one and two dimensions.

Figure 2.5 shows an overview of the BPTP in the ZEDEX gallery. The test region can be divided in four different parts:

- The most inner part of the gallery was filled with drainage material, at the end of the ZEDEX gallery.
- The inner part filled with compacted backfill containing bentonite.
- The outer part filled with compacted backfill without bentonite (only crushed rock).
- The concrete plug.

2.3.1 *Close hydrogeology of the ZEDEX gallery*

The host rock consists of Äspö diorite with veins and inclusions of fine-grained granite and pegmatite. There is a main fracture set which trends NW with steep angles of dip. These fractures, due to the characteristics of the geologic formation, are the main water bearing structures in the area. The first 38 meters of the ZEDEX tunnel contains two water-bearing

NW fractures. Up to five of them were observed in the inner part of the tunnel. A mapping of the fractures after the blasting of the tunnel was performed by Stenberg & Gunnarsson (1998). Figure 2.6 shows the mapping of the fractures observed after the excavation of the ZEDEX gallery. The highest number of conductive fractures was found in the floor, probably, baecause the explosive load was higher close to the floor than other parts of the section. In order to study the water flow due to the fractures, the tunnel was divided into eleven different sections and flow rate of water coming from the fractures was measured in each section. Close to the inner part of the tunnel, where there are up to five water bearing fractures, a flow rate of 6 L/min was measured. However, where no water bearing fractures were present no significant amount of water flowing was observed (Stenberg & Gunnarsson, 1998). To minimise the effect of uncontrolled incoming water from the rock, the inner part of the ZEDEX gallery was backfilled with crushed granite rock as drainage material and finally a concrete wall was built with the aim to separate the most fractured area and the zone where all the tests would take place.

From this study, it was also observed the presence of an altered zone of granite rock due to the blasting of the tunnel. This area, surrounding the tunnel, is called Excavation Disturbed Zone (EDZ). Hydraulic tests were performed in selected boreholes drilled for monitoring the water pressure close to the tunnel. Results of these tests showed that hydraulic conductivity in the rock surface (0.3 – 0.7 meters perpendicular from the tunnel surface) was normally lower than $5{\cdot}10^{-8}$ m/s (the highest measured value), but values as low as $1{\cdot}10^{-12}$ m/s were also measured. This clearly shows the heterogeneity of the results and the importance of flow through fractures.

2.3.2 *Layout of the test*

The study of different sealing materials for accessing galleries was initiated in early 1996. Different mixtures of sodium bentonite MX-80 and crushed granite rock were mechanically and hydraulically tested (Börgesson et al. 1996; Johannesson et al. 1999). The main properties of this material had to be low permeability and cost. Finally, a mixture of 30% of sodium bentonite and 70% of crushed granite rock (with a maximum grain size of 20 mm) was chosen as a sealing material for BPTP (Gunnarsson et al. 2001). The reasons for this low bentonite content were mainly economical and environmental. Granite coming from the blasting of the same gallery was recycled and used as granular material in this mixture.

Water used to mix sodium bentonite and crushed granite rock came from different fractures. These fractures are connected to the Baltic Sea, as a consequence, water used in the Project was salt water. Depending on which fracture water was taken from, different salt concentrations were measured. An initial average concentration of salts present in the so-called *Äspö water* was measured (12 g/L). The chemical analysis of this water showed that the main salts are sodium chloride and calcium chloride (around 50/50 by mass). One of the most important aspects of this project has been precisely the mixing and hydration of this backfill with salt water and how salt water can affect backfill hydro-mechanical behaviour

Backfill was initially mixed up with Äspö water (supposedly 12 g/L of salt concentration), and then stored keeping constant its water content until compaction in the ZEDEX gallery. It will be shown later that the initial concentration of salt in mixing water was lower (6 g/L), which produced an important decrease of the measured backfill hydraulic conductivity if compared with the experimental results obtained in laboratory when water containing 12 g/L was used. The reason of the decrease of water salinity was that water used to mix up the bentonite and crushed granite rock came from a fracture where salt concentration was lower. Range of water salinity in different fractures is big because of age of stored water. The decrease (6 g/L) of salt content in the water used in the mixing process was discovered when backfill had been already compacted in situ. Therefore, backfill hydraulic conductivity decreased and the estimated time to saturate the backfill increased up to prohibitive values. To solve this problem, salt concentration in water used to saturate the backfill was increased up to 16 g/L (NaCl and $CaCl_2$ as predominant chemical species, 50/50 by mass). In such conditions, it is necessary to distinguish between *mixing water* (6 g/L of salt) and *hydrating water* (16 g/L of salt, NaCl and $CaCl_2$ 50/50 by mass) because of their different salt concentrations.

Inner part of the tunnel, filled with the bentonite-crushed granite rock mixture, was divided into six different sections (A1 to A6) separated by permeable mats. The aim of these mats is to inject and collect water to/from the backfill. Each backfill section was compacted in six different layers and these layers were named from 1 to 6. SKB and Clay Technology AB instrumented the gallery (backfill and host rock). Moreover, ENRESA installed 13 units of a new mini-piezometer (dynamic pore pressure system - DPPS) in section A4 (AITEMIN, 1999). This new mini-piezometer, designed to carry out constant and variable head tests in situ, will be explained in length at chapter 4. Crushed granite rock was compacted at the outer part of the tunnel. Sections were classified as B2 to B5 in this part of the tunnel.

The compaction process was carried out with a vibrating plate developed for this purpose. The final slope chosen to compact the backfill was 35° due to compaction technique requirements. A higher slope (45°) was initially considered but the compaction process was more difficult for the compacting facility. Despite the reduction of slope, problems appeared when backfill was compacted close to the roof as the compacting tool could not work properly near the host rock. Figure 2.7 shows the construction and compaction process of a layer and figures 2.8 and 2.9 show the designed tool to compact the backfill close to the roof and the slope compactor used to compact the backfill far away from the roof. The final geometry of a backfill section is shown in figure 2.10. The thickness of each compacted layer was intended to be approximately 37 cm in the axial direction of the tunnel, corresponding to a thickness of approximately 21 cm in the perpendicular direction to the surface of the layer. In practice, the thickness varied slightly (Gunnarsson et al. 2001).

The energy applied during the compaction process was experimentally estimated before the in situ backfill compaction. After compaction, backfill dry specific weight had to be 16.6 kN/m^3. However, big variations of this parameter were measured in situ. Near the roof dry specific weights around 13.5 kN/m^3 were measured and in the central part of the tunnel dry specific weights up to 17.5 kN/m^3 were found (Gunnarsson et al. 2001). Figure 2.11 shows the points where dry density was measured. Two different methods were used for this purpose: a penetrometer close to the roof and a nuclear gauge in the central part of the layer. Figure 2.12 shows the average dry densities measured by nuclear gauges in the central part of sections A3 and A4 at 20 cm of depth from the compacting surface. It can be observed that the dry specific weight in layers 1 and 2 of both sections are smaller. This is due to the dumping effect of mats, which reduced the compaction effectiveness. Figure 2.13 shows the variation of dry density measured in each layer of section A3 close to the rock. Figure 2.14 shows the average of initial water content of backfill after compacting sections A3 and A4.

Between each section three permeable mats were placed. Their purpose is to inject or collect water to or from the backfill. Figure 2.15 shows the mats layout among different backfill sections and figure 2.16 shows a picture of the three mats placed at a layer after finishing one section. Mats or drainage layers are named from D1 to D12. Figure 2.17 shows the vertical section of ZEDEX gallery in its final layout after the backfilling operation.

2.3.3 *Historical evolution of Backfill and Plug Test Project*

The ZEDEX tunnel, where Backfill and Plug Test is being performed, was excavated in two steps. It has a total length of 55 meters. The first 39 meters were excavated by blasting in January 1995. The next 16 meters were excavated in August 1996 by careful blasting. Characterisation of host rock and fractures present in the surrounding formation after the excavation of the tunnel was performed during 1997 (Stenberg & Gunnarsson, 1998). Also, throughout 1997 and early 1998, a lot of work dealing with design and planning of the BPTP was done as well as an experimental characterisation of different backfill materials. After all this work, main decisions about final geometry and sealant materials were made. From one-dimensional water uptake tests performed in laboratory, some families of parameters were estimated and used for preliminary calculations. These calculations were performed by Clay Technology AB (using ABAQUS) and by UPC (using CODE_BRIGHT, Olivella et al. 1996). The backfill hydration process was simulated and different material properties, different geometries and boundary conditions were considered (only the hydraulic problem was solved). After these first simulations some preliminary conclusions were drawn (Mata & Ledesma, 1999):

- Two initial backfill water contents (6% and 13%) were experimentally studied by means of water uptake tests. Chosen initial water content of backfill was 13% due to its lower hydraulic conductivity. This is due to different soil structures after compaction at different water contents, as verified by Mitchell et al. (1965).
- Flow of water is mainly one-dimensional at the central part of the backfill (far away from the rock) between mats when two-dimensional unsaturated flow in an isotropic and homogeneous medium was solved.
- When increasing the injected water pressure at mats, the time to reach full saturation of backfill is notably reduced. However, hydraulic fracture could appear if this increase is sudden and large.

MX-80 sodium bentonite and crushed granite rock were mixed up with salt water (6 g/L) up to initial water content from 12% to 13% in 1998. At the beginning of 1999, backfill was compacted and all devices, mats, tubes, and instruments for measuring water pressure, temperature, total pressure, relative humidity, etc., were installed. Backfill hydration process was initiated in June of 1999. Initially injection water pressure was less than 100 kPa to avoid backfill hydraulic fracture. Salt concentration of water used to saturate backfill was increased up to 16 g/L to speed up the saturation process. Since then, hydration continued at small injecting water pressure due to some leakages that appeared at the concrete plug. The plug was grouted on June 27 of 2001. In connection with the grouting, the inflow into the mats close to the plug was reduced and leakages were solved.

The injected water pressure was increased up to 500 kPa in all the mats in order to speed up the saturation process after the leakages at the plug were solved. It is expected that full saturation will be reach at the end of 2002 or beginning of 2003 after the increase of injecting water pressure (Goudarzi et al. 2002). After full saturation, flow tests will be performed in order to investigate the backfill hydraulic conductivity in situ.

2.3.4 *Instrumentation installed at BPTP*

Backfill and Plug Test Project is a full-scale flow problem. The instrumentation, installed in different sections and host rock, mainly consisted of psychrometers and pressure transducers to measure total suction and pore water pressure respectively. However, some load cells and total pressure cells were installed to check backfill swelling pressure. Instrumentation at ZEDEX gallery is briefly summarised below.

Water pressure in host rock is being measured at 73 points, pore water pressure in the backfill at 33 points, total pressure at 20 points and water pressure in the drainage layers of filter mats is being monitored at all 12 layers. Backfill saturation process is monitored at 57 measuring points (Goudarzi et al. 2002) by means of psychrometers. Position of the measuring points in the backfill is related to the backfill section, the number of the compacted layer, the tunnel axis, and the rock surface. Location of measuring points in the rock is related to the backfill section where the hole enters and the measuring section in the borehole. Connexions and cables of all devices are directed to “cable corridors” especially conceived in the layers for this purpose. Figure 2.18 shows a cable corridor and the process of placing the different devices in one layer during the construction of the barrier. Finally, all these connections were directed to a parallel tunnel by means of “lead-throughs” sealed for maintaining a high water pressure in the test tunnel. Twelve of these lead-throughs were drilled at different positions of the ZEDEX gallery (Gunnarsson et al. 2001).

Instruments and devices were placed at the layers after compaction and their names were related to those layers. Each measuring point is also defined by coordinates in the layer, in a co-ordinate system as the one shown in figure 2.19. The *x*-coordinate is the horizontal distance from the centre of the tunnel and the *y*-coordinate is the distance perpendicular to the *x*-axis. Some instruments are best referred at a specified distance from the rock surface. In those cases, the coordinate begins with the letter R and the coordinate is given related to the intersection with the rock surface as centre. Thus, an instrument in the backfill will be named in the following way:

1. Type of measurement (1 letter): U for water pressure, W for total suction, P for total pressure, and D for DPPS.
2. Serial number (1-2 figures).
3. Section (1 letter, 1 figure).
4. Layer (1 figure).
5. *x*-coordinate.
6. *y*-coordinate.

Items 1 and 2 identify the device and items 3 to 6 describe the location. A pore water pressure transducer (number 8) located in section A3, layer 1, 0.5 m left of the centre line and 0.3 m below the roof in the y-direction will be named U8 (A3/1/-0.5/R-0.3). The instrumentation placed at section A4 is fully detailed in table 2.1.

Thirteen DPPS were placed at section A4 and they are used to study the backfill local hydraulic conductivity. Part of this thesis is focused on the calibration of this new mini-piezometer in laboratory and in situ. DPPS were installed in three different positions in order to investigate backfill permeabilit anisotropy. Different orientations of DPPS are depicted in figure 2.20. A picture of the designed DPPS is shown in figure 2.21. Installed devices at host rock have not been summarised in this thesis, and only water pressure far way from the tunnel has been assessed from data measured in the host rock. A brief summary of all devices installed (except DPPS which will be explained at chapter 4) is shown below (Goudarzi et al. 2002).

- Glötzl total pressure cells of hydraulic type. Two models are used: E 10/20 KF 50 VA24 model A (Glötzl A) and model F (Glötzl B). The measuring range is 0-5 MPa. Type A is used for measurement in the soil while type B will be fixed to the rock surface with concrete. Nine cells of type A and four cells of type B were installed.
- Roctest total pressure cell with vibrating wire transducer model TPC-0 (0-4 MPa). 8 cells of this type are installed in the backfill.
- Glötzl pore pressure cells of the hydraulic type. 18 pore pressure cells of model P4 S 50L VA with the measuring range 0-5 MPa are installed.
- Filter tips connected to Druck pore water pressure cells model PTX 1400 with tecalan tubes. The pore water pressure cells are located outside the test area. 16 devices with the measuring range 0-4 MPa are installed.
- Wescor psychrometers model PST-55. These devices measure the relative humidity in the pore system, which can be converted into water ratio or total suction (negative water pressure). The measuring range is 95.5-99.6 of relative humidity. Twenty-seven psychrometers were installed.
- Resistivity probes developed and built by Clay Technology and the University of Lund are used in the free bentonite backfill. The measuring principle is to apply an electrical current between two outer electrodes with relative distance 30 cm and measure the drop in potential between two inner electrodes with relative distance 10 cm. The devices were calibrated at different backfill densities and water ratios in the range of those expected throughout the project. The measuring range of water ratio is from 5% to 12%. Ten of these devices were installed.
- Filter tips connected to thin tecalan tubes. These filters, which were mainly installed in the bentonite free backfill, are simple devices for indicating when water saturation has occurred in the measuring point.

Figure 2.22 shows, for instance, the psychrometer Wescor PST-55 installed after the compaction process very close to the surface of the layer. Time evolution of total suction in six psychrometers in sections A3 and A4, water pressure at mats D3, D4 and D5, injected flow of rate at mats D2 to D6 and total pressure between the contact of the host rock and the backfill in sections A3 and A4 are shown in figures 2.23, 2.24, 2.25, 2.26 and 2.27 respectively (Goudarzi et al. 2002). These figures reveal that the saturation process was slow at the beginning but the increase of the injecting water pressure quickly speeded up this process. There is some scatter in the evolution of backfill total pressure or injected flow at mats. Current total pressure is close to 600 kPa at two total pressure load cells placed at the ground of sections A4 and A3. The measured total pressure should be the addition of the backfill swelling pressure and water pressure applied at the mats. However, total pressure at host rock in the roof of section A4 is only 500 kPa corresponding to the injected water pressure at mats. As a result, no backfill swelling pressure is developed close to the roof due to the low dry specific weight after the compaction.

2.4 FUTURE WORK AT BPTP

Once the backfill is fully saturated, an important part of the project, from a scientific point of view, will start: the full-scale saturated flow tests. Flow tests will be performed in order to characterise the backfill saturated hydraulic conductivity, anisotropy and heterogeneous behaviour. Moreover, backfill and host rock interaction (and the effect of the EDZ) will be studied. Different tests, constant and pulse tests will be also performed in section A4 using the DPPS sensor in order to compare local and global hydraulic conductivities obtained from global flow tests. With this amount of information, numerical simulations will be performed to reproduce the measured behaviour in different flow tests. The final aim of this study is to decide if the material will be used as a sealant material for the galleries in the future repository. Additionally, salt water effects on backfill hydraulic conductivity and its consequences on saturation and saturated flow tests will be taken into account by means of a fully coupled hydro-chemical formulation, within a more general one (Guimarães, 2002).

Type and number	Section	Layer	X (m)	Y (m)	Fabricate	Remarks
P7	A4	3	0.0	R-0.0	Glötzl B	At rock
P8	A4	3	0.0	R+0.0	Glötzl B	At rock
U8	A3	1	0.25	-2.8	Glötzl	
U16	A4	3	0.0	0.3	Glötzl	
U17	A4	3	0.0	R-0.0	Glötzl	
U18	A4	3	0.0	R+0.0	Glötzl	
U19	A4	3	R-0.0	0.0	Glötzl	At rock
U20	A4	3	R+0.0	0.0	Glötzl	At rock
W18	A4	1	0.0	0.0	Wescor Psychr.	
W19	A4	3	0.0	0.0	Wescor Psychr.	
W20	A4	4	0.0	0.0	Wescor Psychr.	
D1	A4	2	0.24	R-0.35	AITEMIN	Orientation 1
D2	A4	2	0	-1.10	AITEMIN	Orientation 1
D3	A4	2	0.20	R+0.50	AITEMIN	Orientation 1
D4	A4	3	0	2	AITEMIN	Orientation 3
D5	A4	3	-0.20	R-0.35	AITEMIN	Orientation 2
D6	A4	3	-0.20	R+0.60	AITEMIN	Orientation 2
D7	A4	3	-1	-1	AITEMIN	Orientation 3
D8	A4	3	R+0.30	0.90	AITEMIN	Orientation 3
D9	A4	3	1	-1	AITEMIN	Orientation 3
D10	A4	3	R-0.30	0	AITEMIN	Orientation 3
D11	A4	4	0.20	R-1.40	AITEMIN	Orientation 3
D12	A4	4	0.20	-1	AITEMIN	Orientation 3
D13	A4	4	0.30	R+0.75	AITEMIN	Orientation 3

Table 2.1: Final location of all devices installed in section A4 at ZEDEX gallery (Gunnarsson et al. 2001 and AITEMIN, 1999).

2.5 CONCLUSIONS

Since the project is not finished yet, conclusions cannot be drawn of the results. Only some conclusions regarding the installation process and evolution of the saturation phase can be made. The mixing and compaction processes were successfully performed. As it was expected, difficulties while compacting backfill close to the roof and to the ground of the ZEDEX gallery appeared. The average dry specific weight after the compaction process in the central part of the gallery was around 16.5 kN/m^3 and the average initial water content was 12%. Salt water coming from the surrounding aquifer was used. However, salt water used to mix up bentonite and crushed granite rock was lower (6 g/L) than measured at the beginning of the testing campaign (12 g/L). Backfill hydraulic conductivity was then lower than the measured at the beginning of the project. To speed up the saturation process, water containing a higher salt content (16 g/L) was used. Injected water pressure at mats was lower than 100 kPa during the first two years of the saturation process to avoid backfill hydraulic fracture and leakages in the concrete plug. After solving the leakages at the plug, water pressure was increased up to 500 kPa. The increase of injected water pressure notably speeded up the saturation process. Backfill saturation is expected by the beginning of 2003. Effects of salt water on the hydro-mechanical behaviour have been of great importance in this project. Therefore a large number of tests and studies have been performed dealing with this matter.

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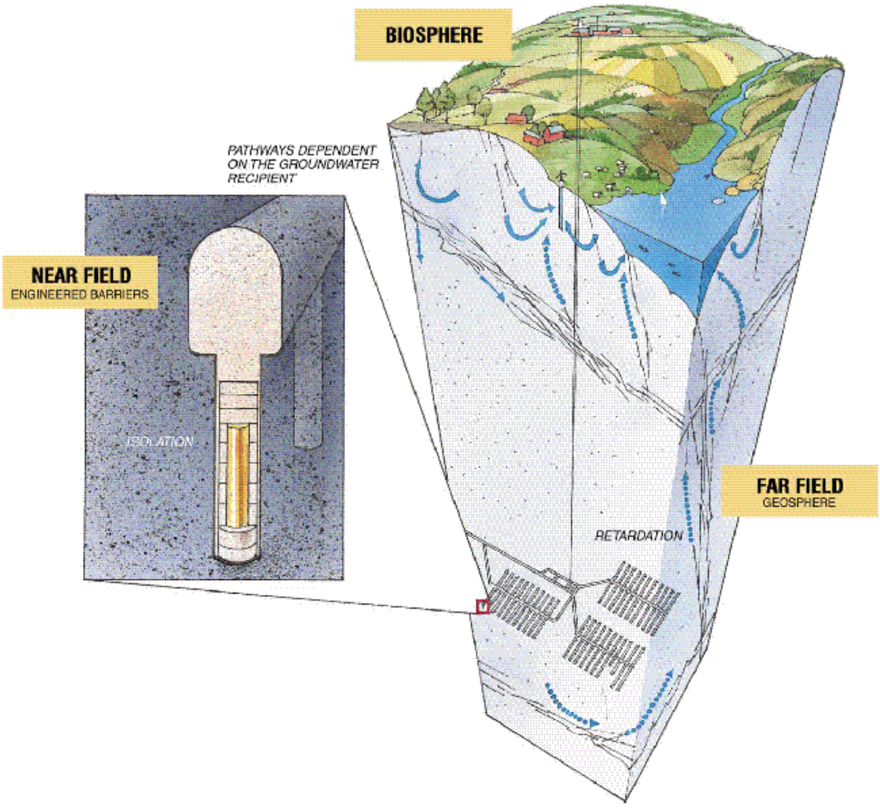


Figure 2.1: KSB-3 proposal for a deep repository (Ericsson, 1999).

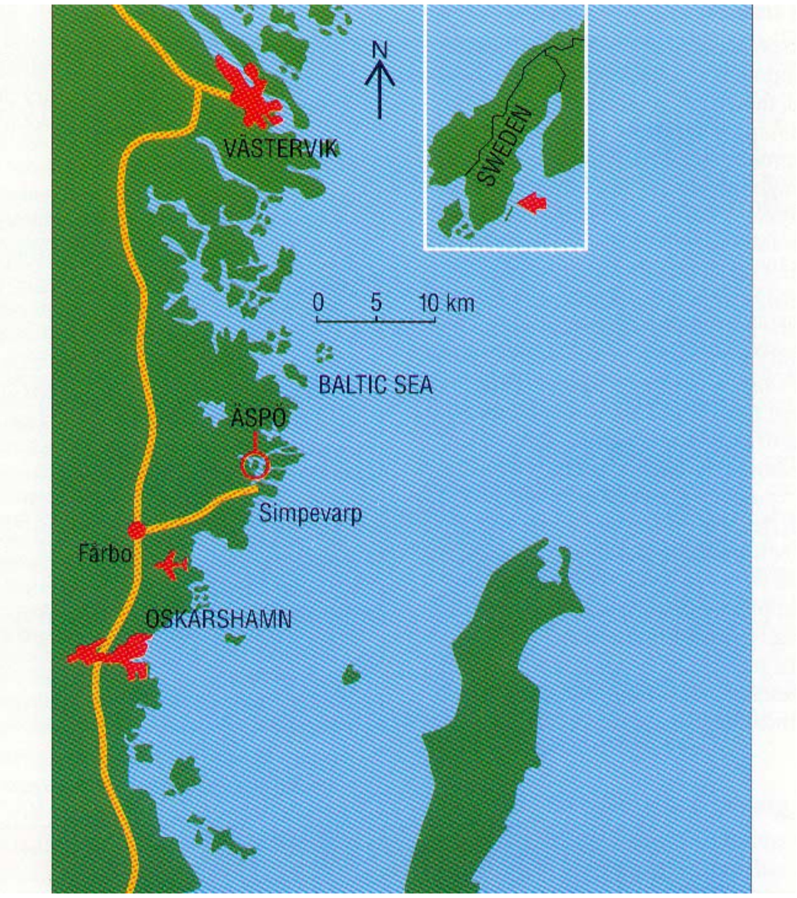


Figure 2.2: Location of the Swedish Island of Äspö, where the Äspö Hard Rock Laboratory is located (SKB, 1996).

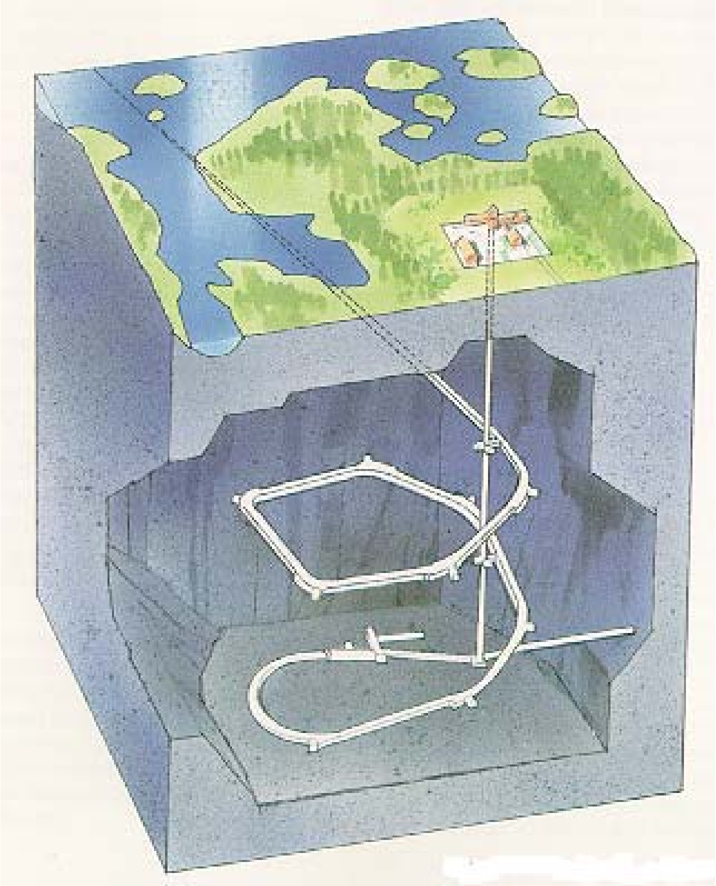


Figure 2.3: Schematic final layout of the Äspö Hard Rock Laboratory. Different experiments are being carried out in different tunnels (SKB, 1997).

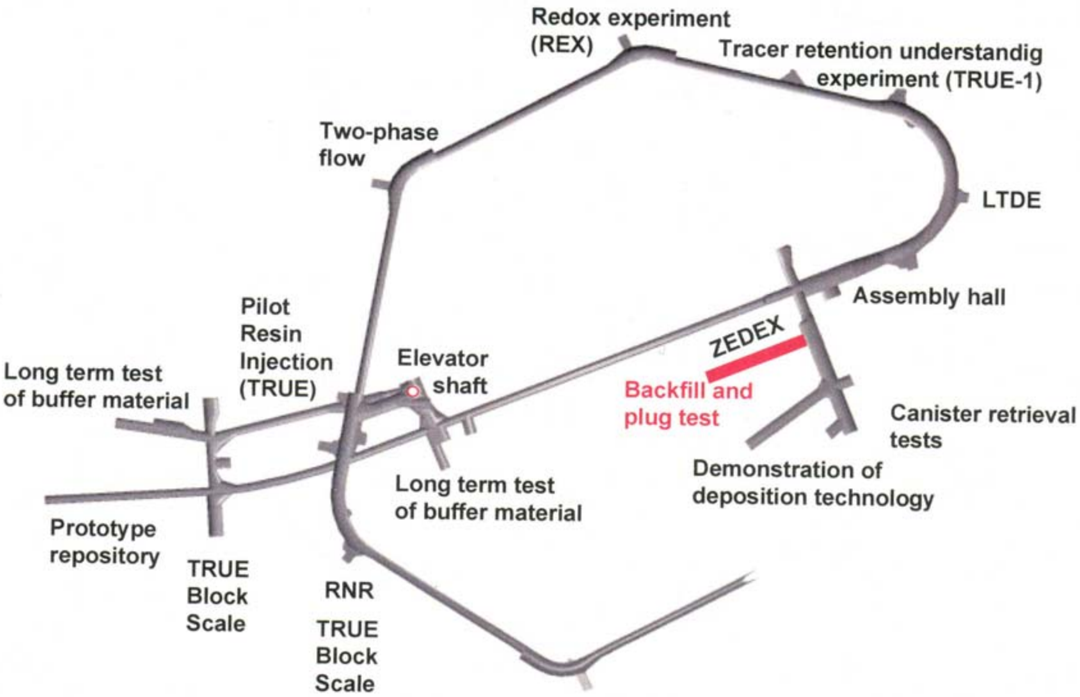


Figure 2.4: Location of the ZEDEX gallery where Backfill and Plug Test and other different tests in the ÄHRL are being carried out (Gunnarsson et al. 2001).

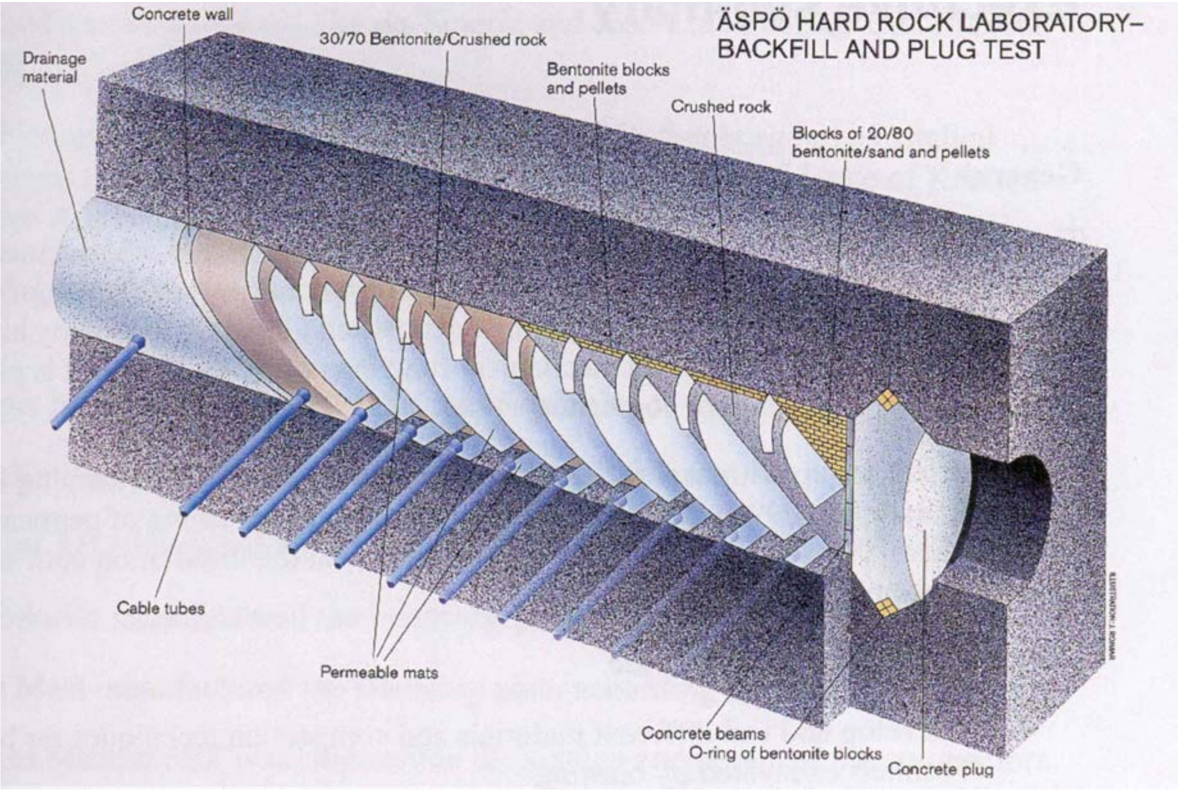
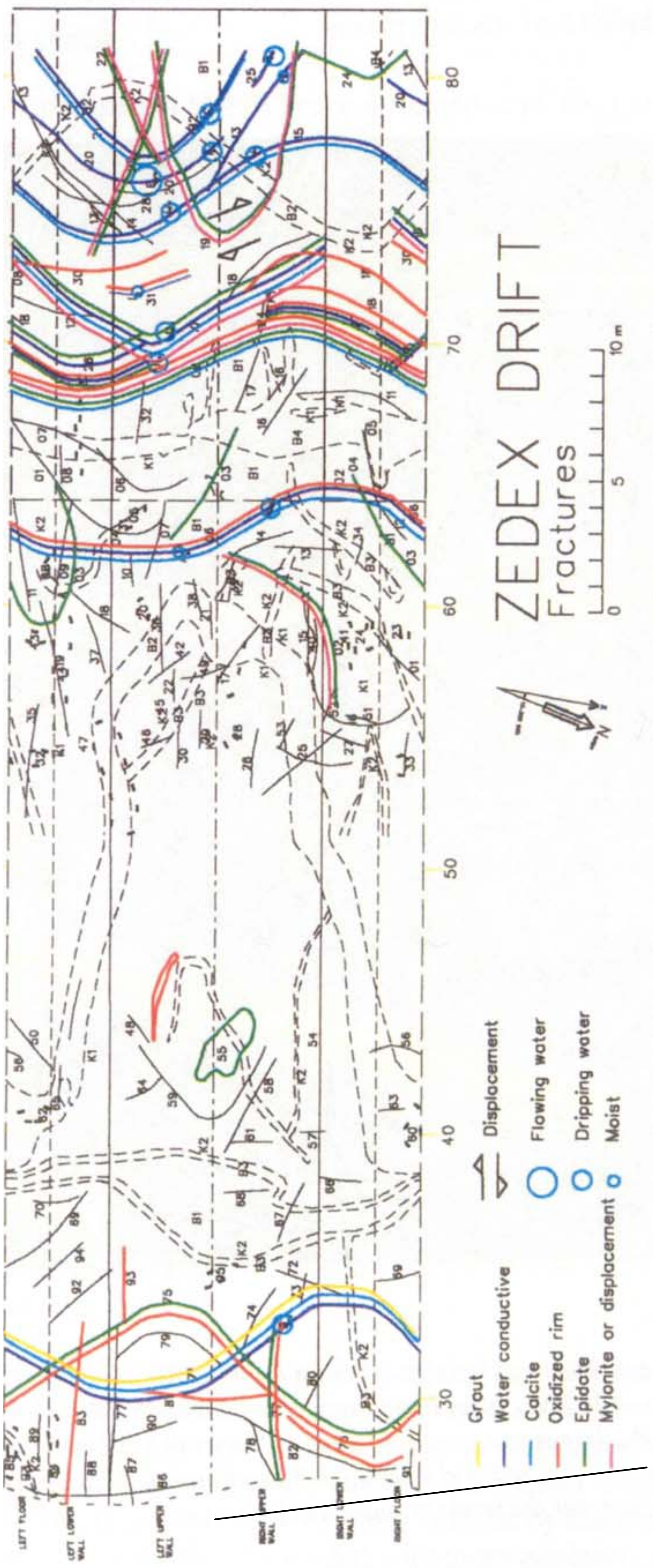


Figure 2.5: Three-dimensional visualisation of the ZEDEX gallery showing the main components of the project (Gunnarsson et al. 2001).



Entrance of the gallery

Figure 2.6: Mapping of observed fractures at the ZEDEX gallery after its excavation. The area, where main fractures are, was backfilled with crushed granite and isolated from the other part of the tunnel by means of a concrete wall. The Backfill and Plug Test was developed behind this wall (Stenberg & Gunnarsson, 1998).

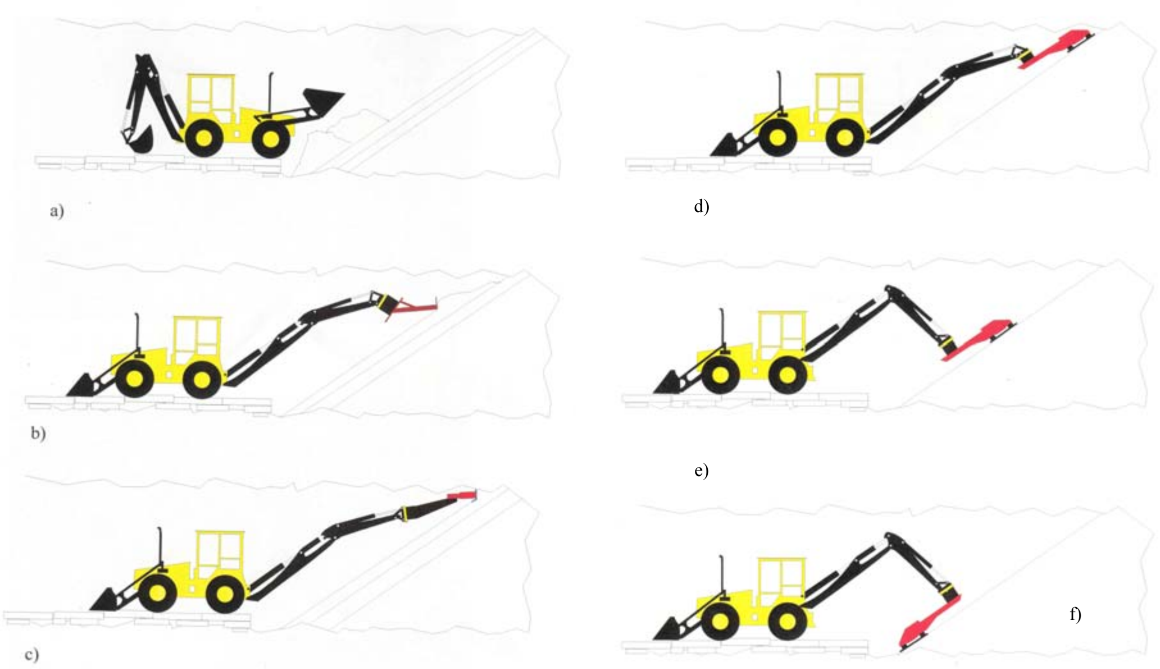


Figure 2.7: Different steps during the cycle of a layer construction. a) Placement of the backfill. b) Pushing the backfill in its position. c) Compaction close to the roof. d) to f) Backfill compaction by means of the slope compactor especially designed for this purpose (Gunnarsson et al. 2001).

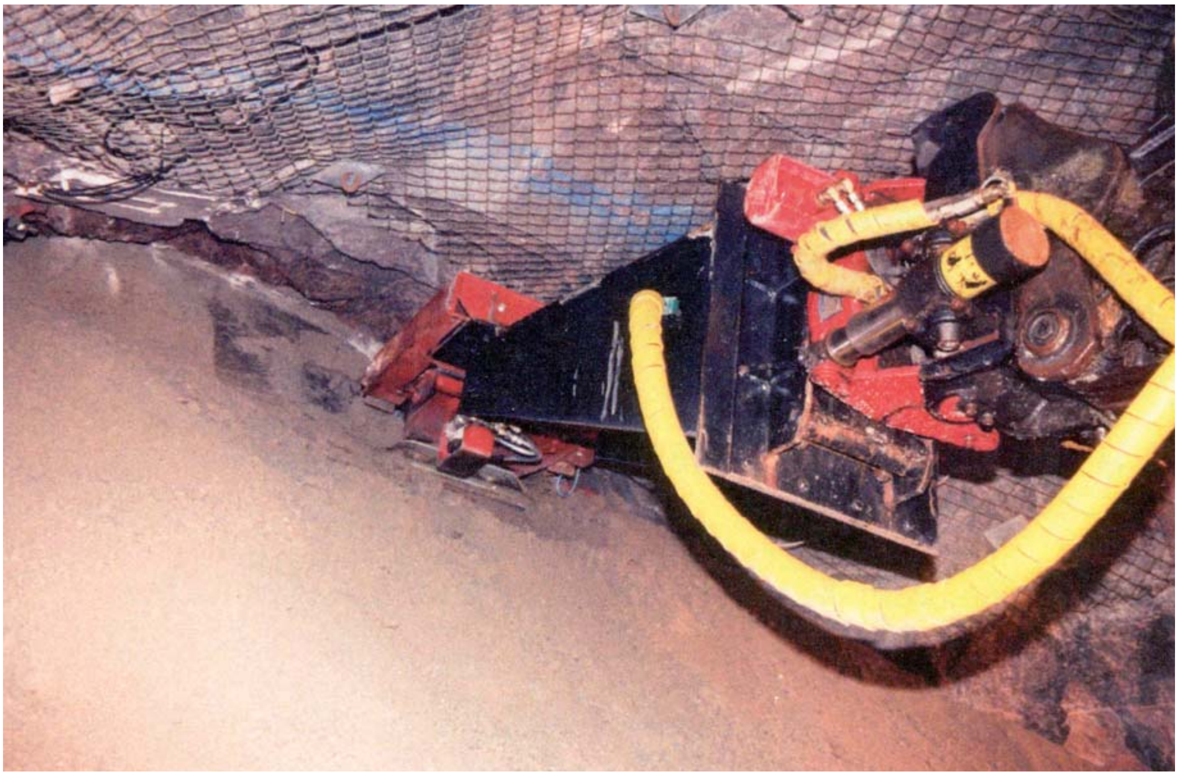


Figure 2.8: Designed facility to compact the backfill close to the roof (Gunnarsson et al. 2001).

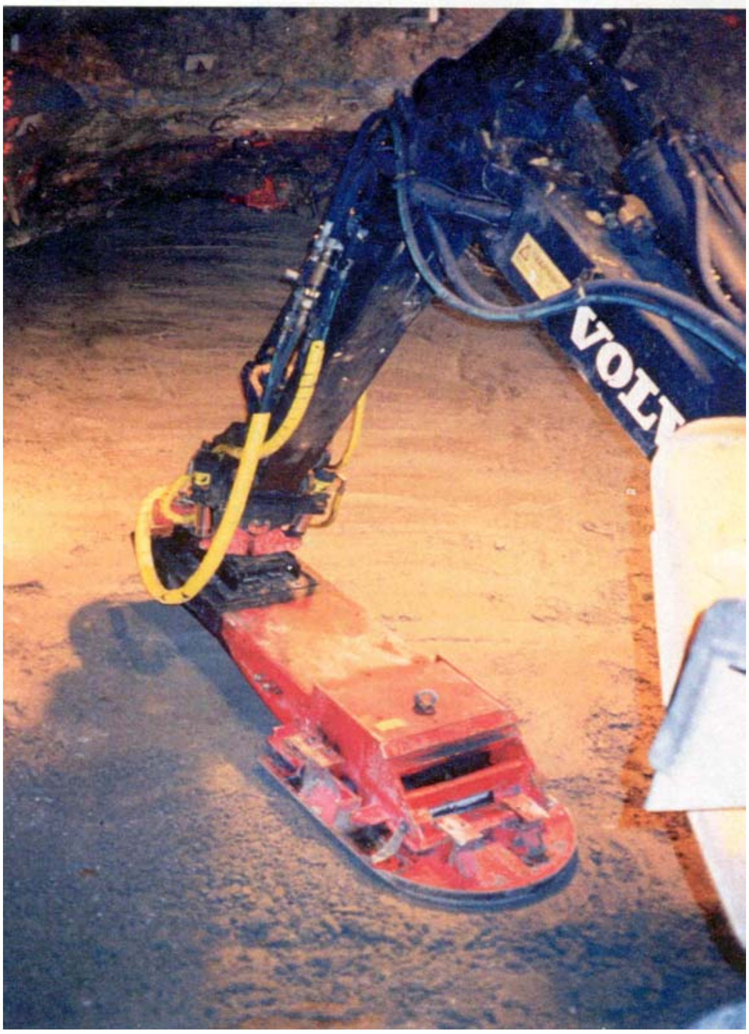


Figure 2.9: Designed facility to compact the backfill far away from the roof (Gunnarsson et al. 2001).

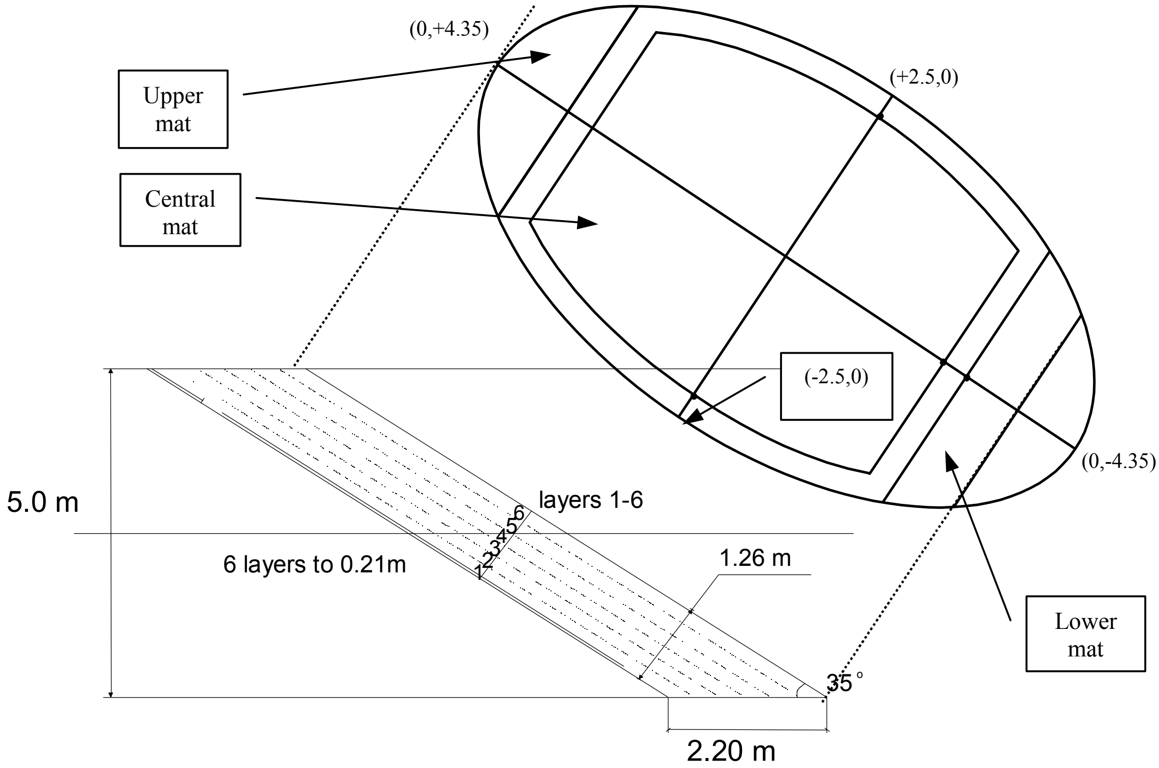


Figure 2.10: Geometry of a section of compacted backfill at the ZEDEX gallery (Clay Technology, 1998).

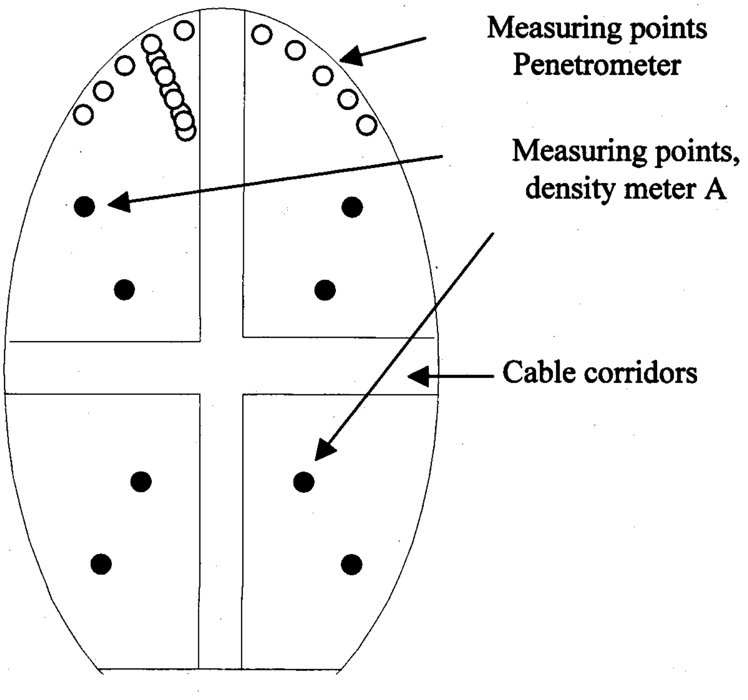


Figure 2.11: Standardised pattern of density measurements in the backfill layers and the arrangement of the cable corridors for tubes and connexions of the devices placed at the backfill (Gunnarsson et al. 2001).

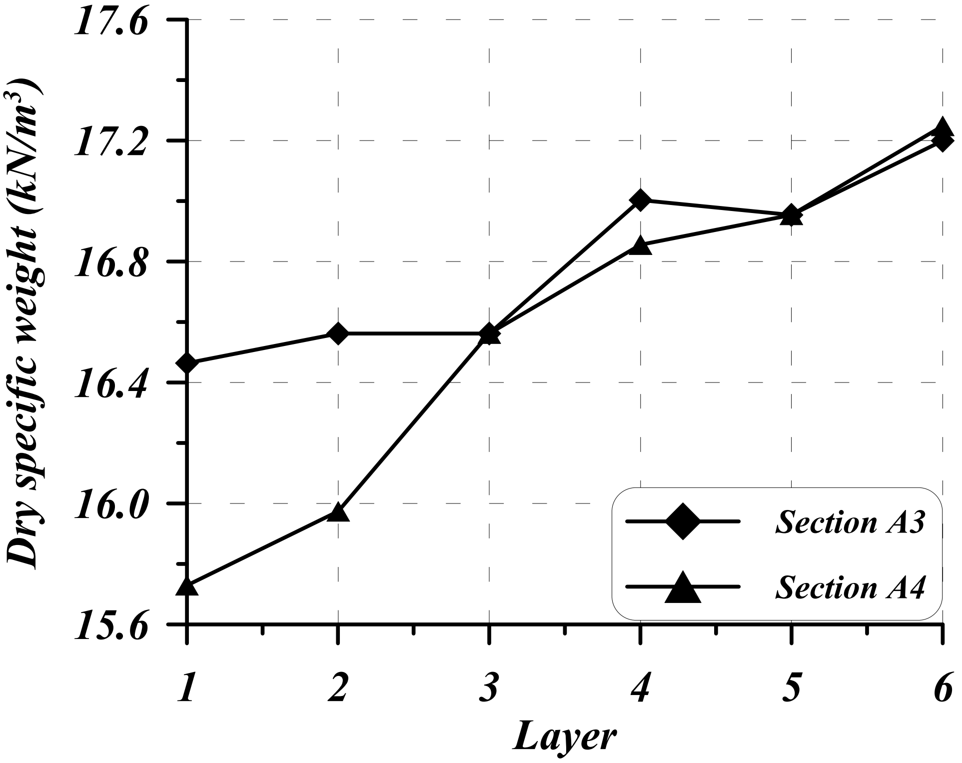


Figure 2.12: Average dry specific weight measured in the central part of different layers at sections A3 and A4 measured by means of nuclear gauges (Gunnarsson et al. 2001).

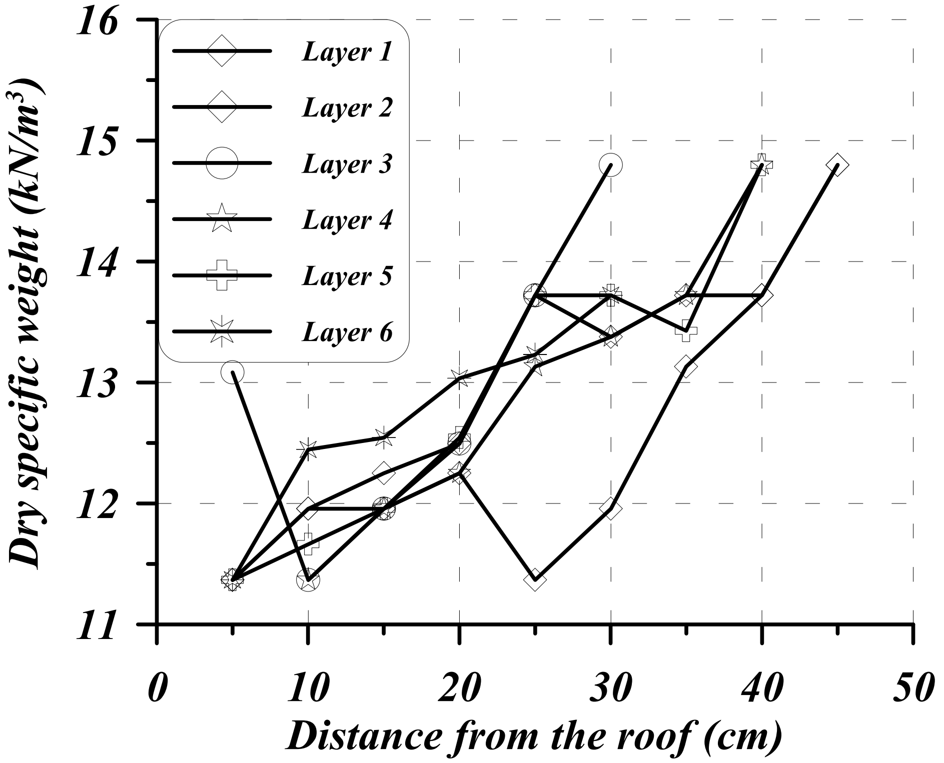


Figure 2.13: Dry specific weight measured close to the roof of section A3. It can be observed the important differences after the compaction process near the rock. Dry specific weight close to the rock was measured by means of a penetrometer instead of a nuclear gauge (Gunnarsson et al. 2001).

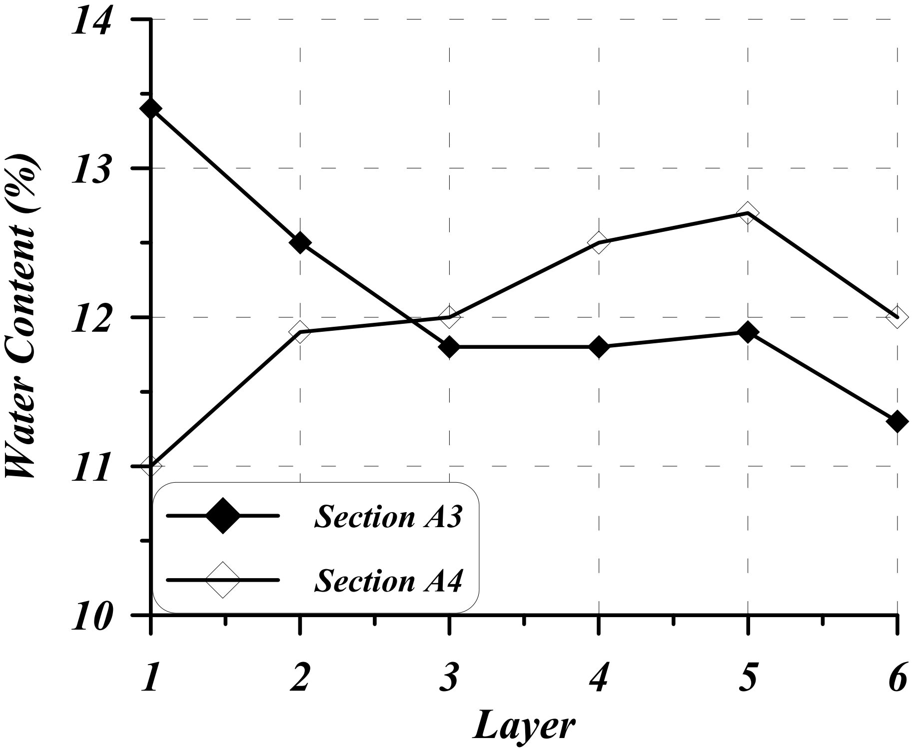


Figure 2.14: Measured average water content in sections A3 and A4 during the construction of the barrier (Gunnarsson et al. 2001).

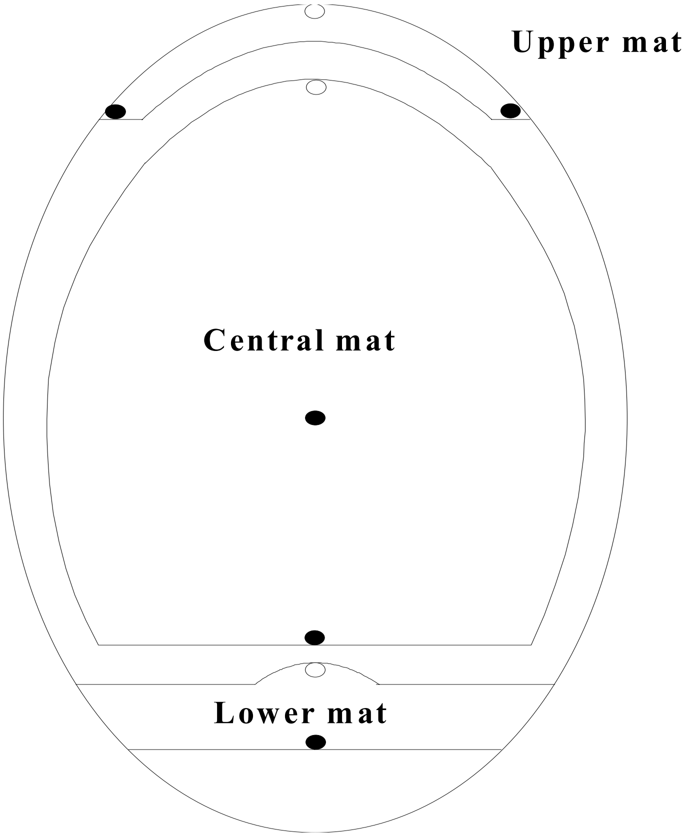


Figure 2.15: Three permeable mats were placed between two sections in order to inject and collect water (Clay Technology, 1997).

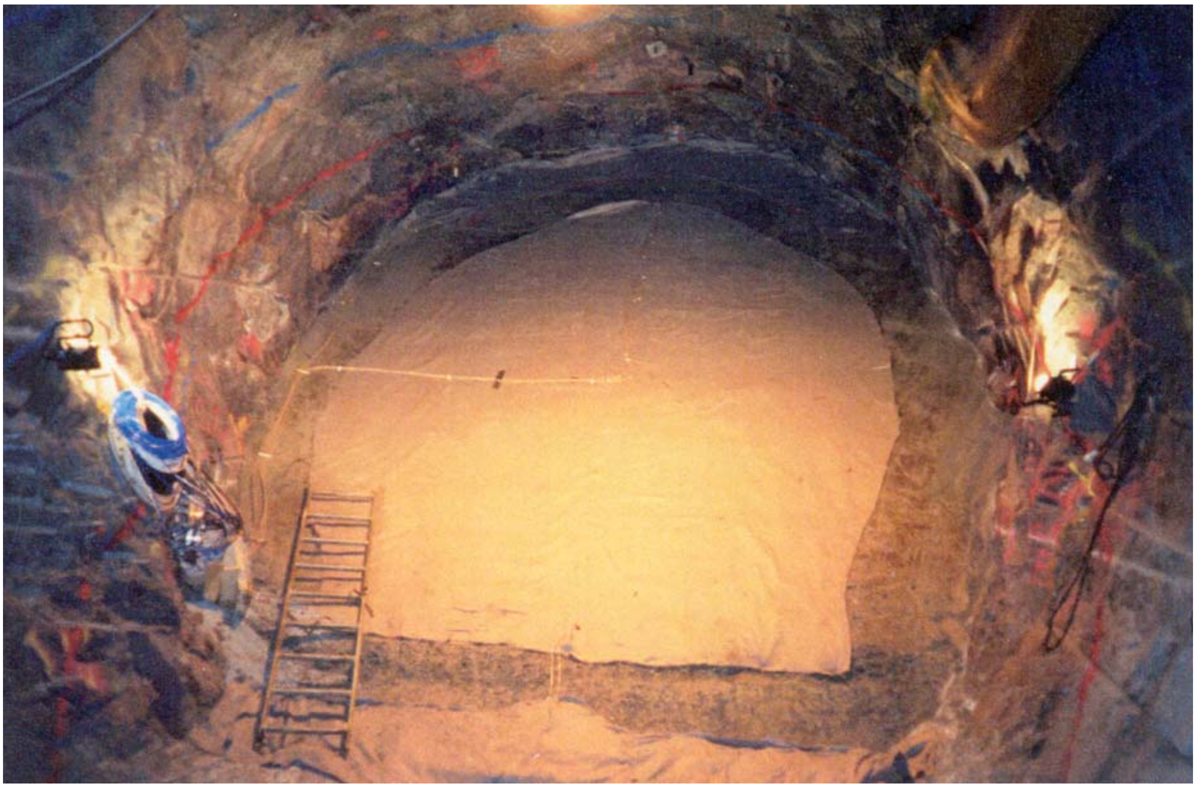


Figure 2.16: Detail of three permeable mats placed after the compaction of one of the layers (Gunnarsson et al. 2001).

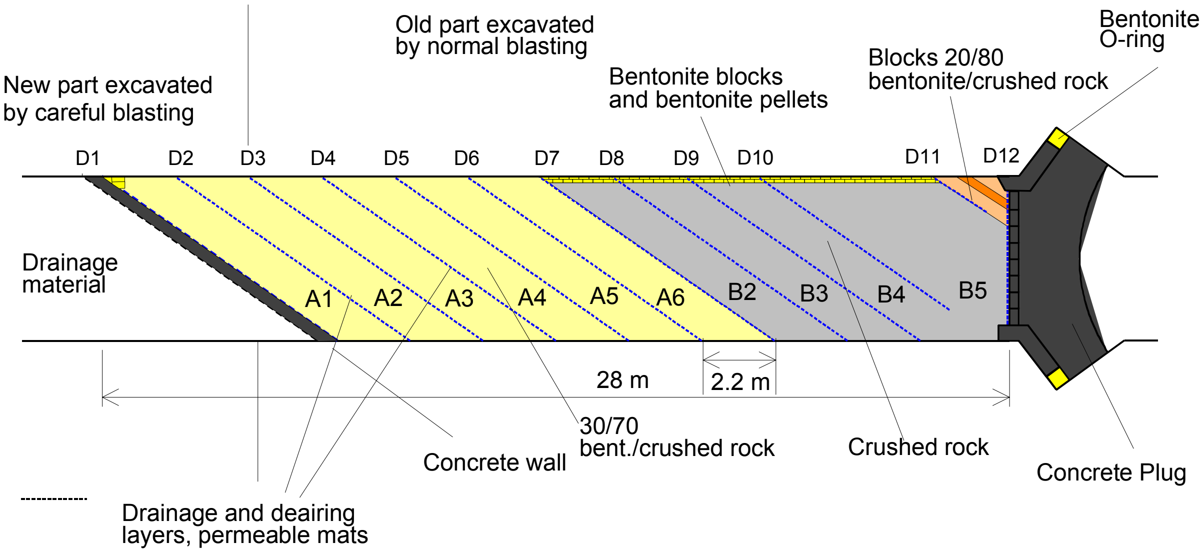


Figure 2.17: Vertical section of ZEDEX gallery showing the final layout and numbering of sections and mats (Goudarzi et al. 2002).

Figure 2.18: Cable arrangement in a 30/70 layer after compaction (Gunnarsson et al. 2001).

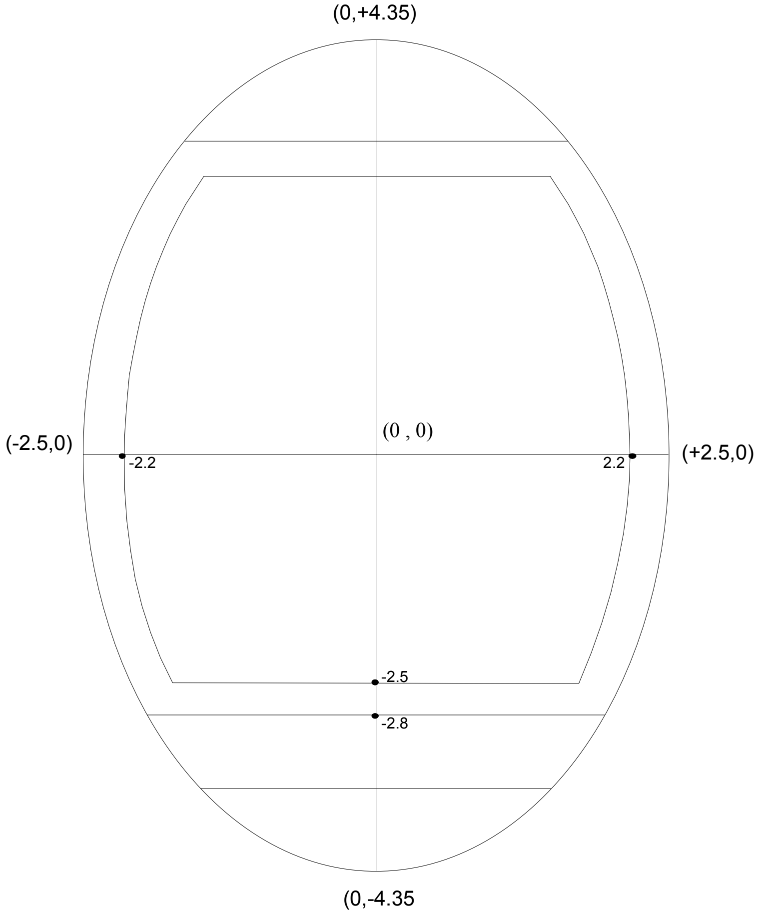


Figure 2.19: Coordinate system used to locate all the devices installed in backfill (Clay Technology, 1997).

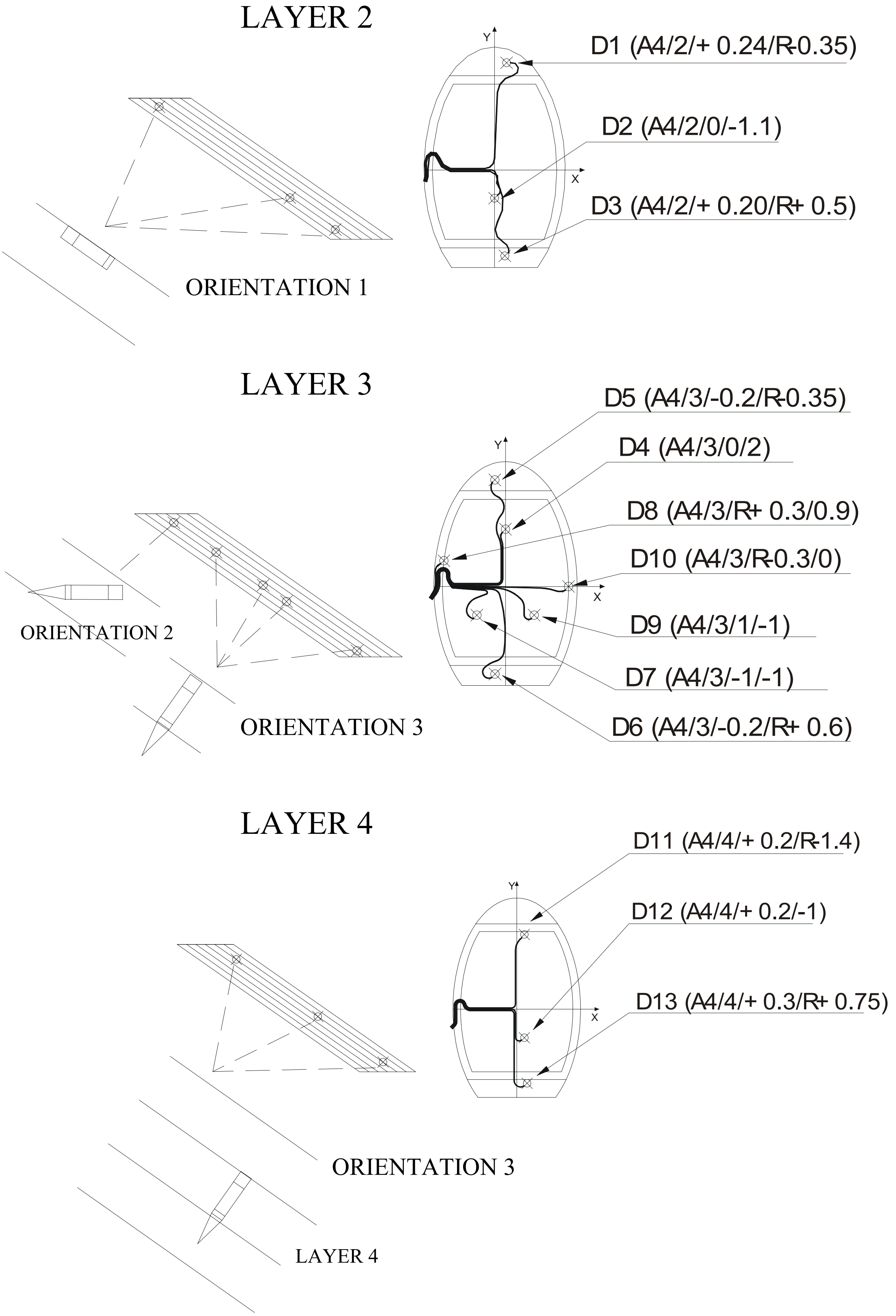


Figure 2.20: Final arrangement of the thirteen mini-piezometers (DPPS) installed by AITEMIN in section A4 (after AITEMIN, 1999).

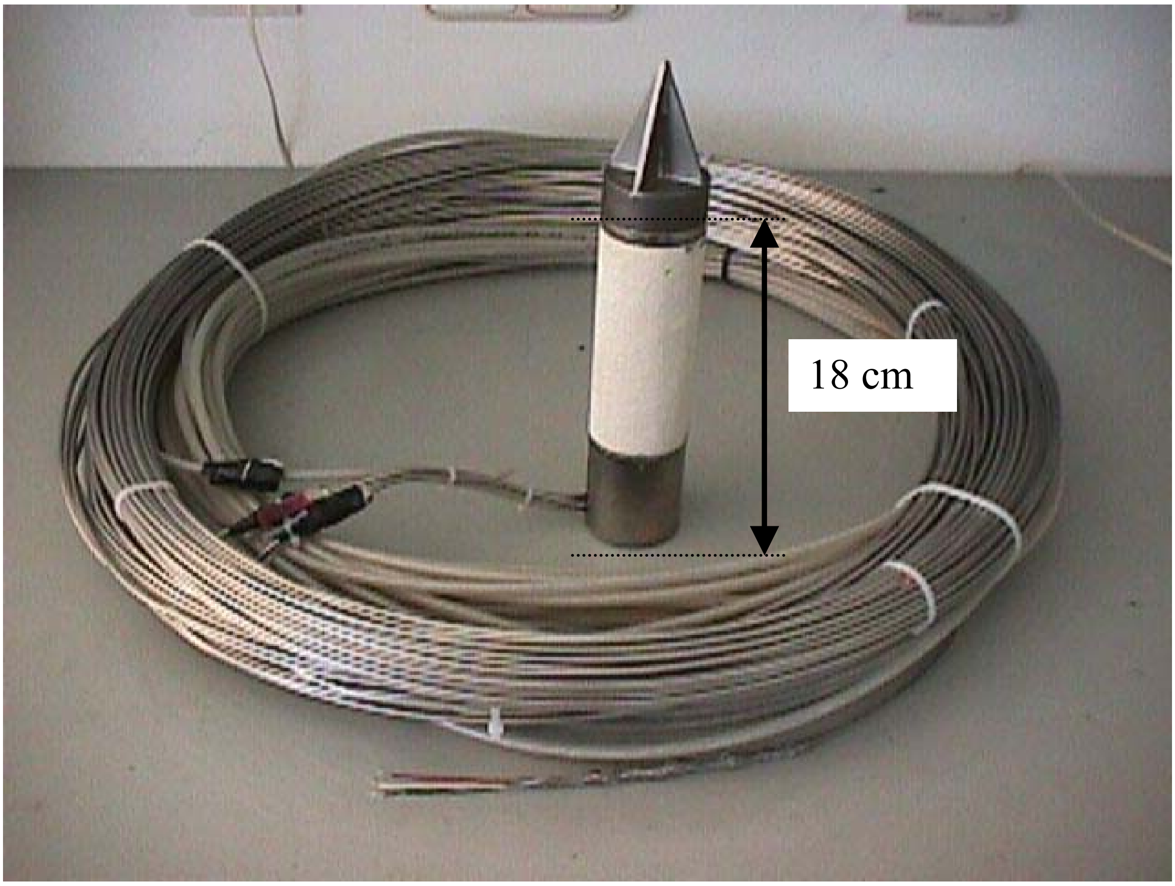


Figure 2.21: Designed mini-piezometer or DPPS (AITEMIN, 1999).

Figure 2.22: Wescor PST-55 placed in situ at one of the layers at the ZEDEX gallery (Gunnarsson et al. 2001). It can be observed that is very close to the surface of the layer.

Figure 2.23: Glötzl total pressure cell placed in situ at one of the layers of backfill in the ZEDEX gallery (Gunnarsson et al. 2001).

Figure 2.24: Glötzl pore water pressure cell placed in situ at one of the layers of backfill in the ZEDEX gallery (Gunnarsson et al. 2001).

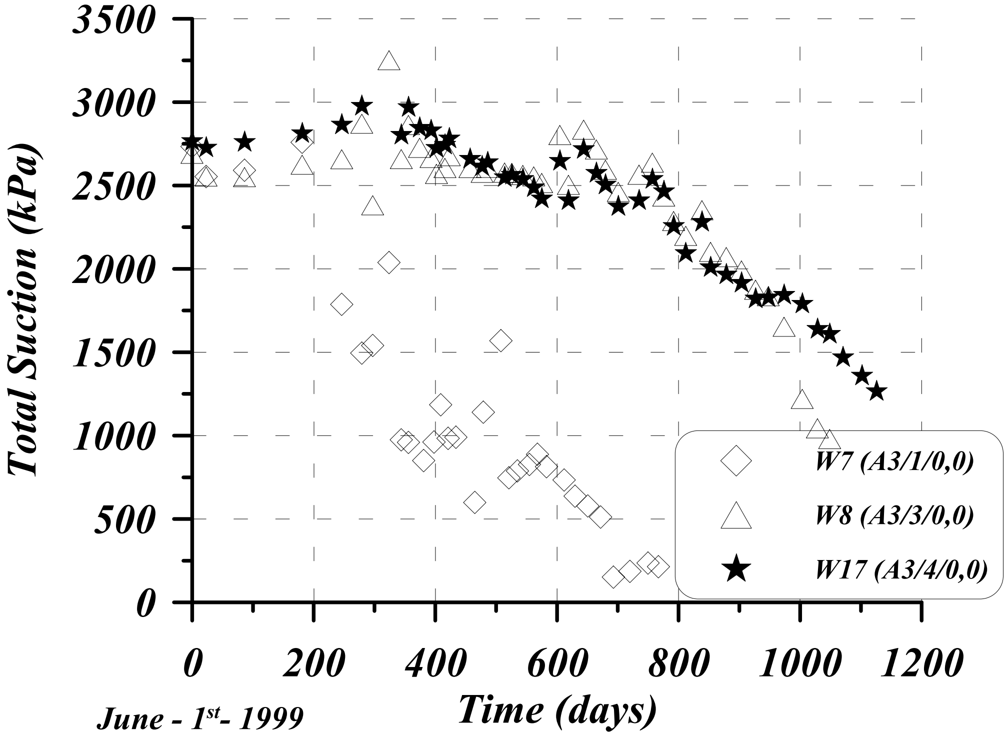


Figure 2.25: Evolution of measured total suction by three psychrometers located at section A3 (Goudarzi et al. 2002).

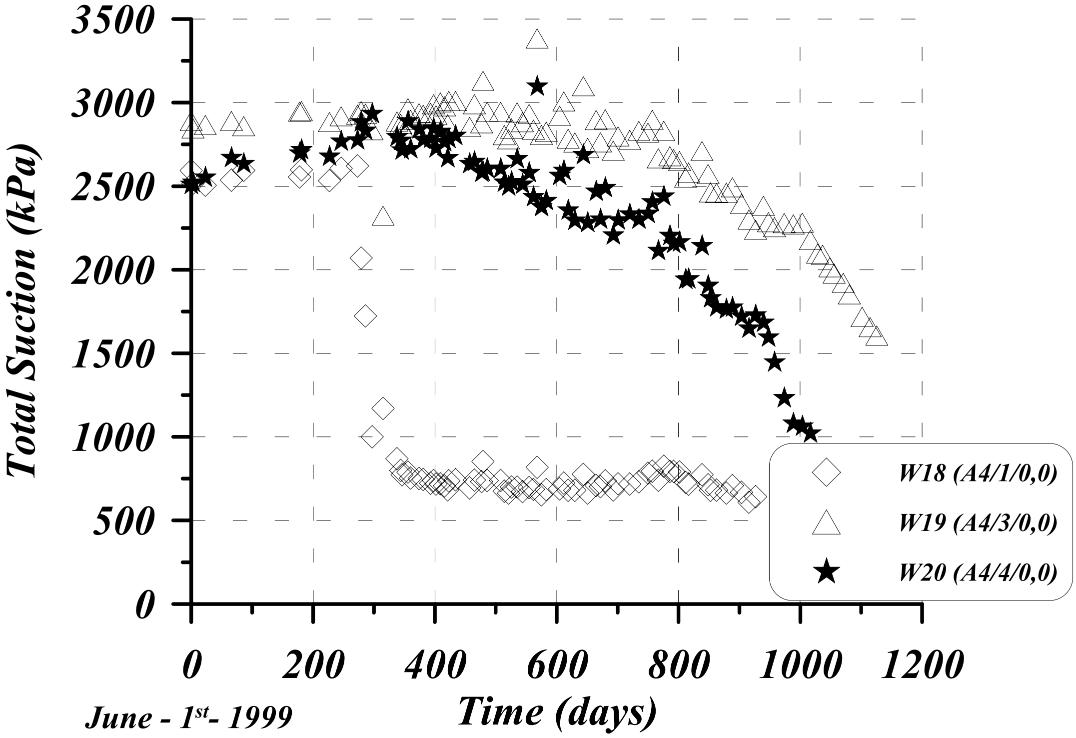


Figure 2.26: Evolution of measured total suction by three psychrometers located at section A4 (Goudarzi et al. 2002).

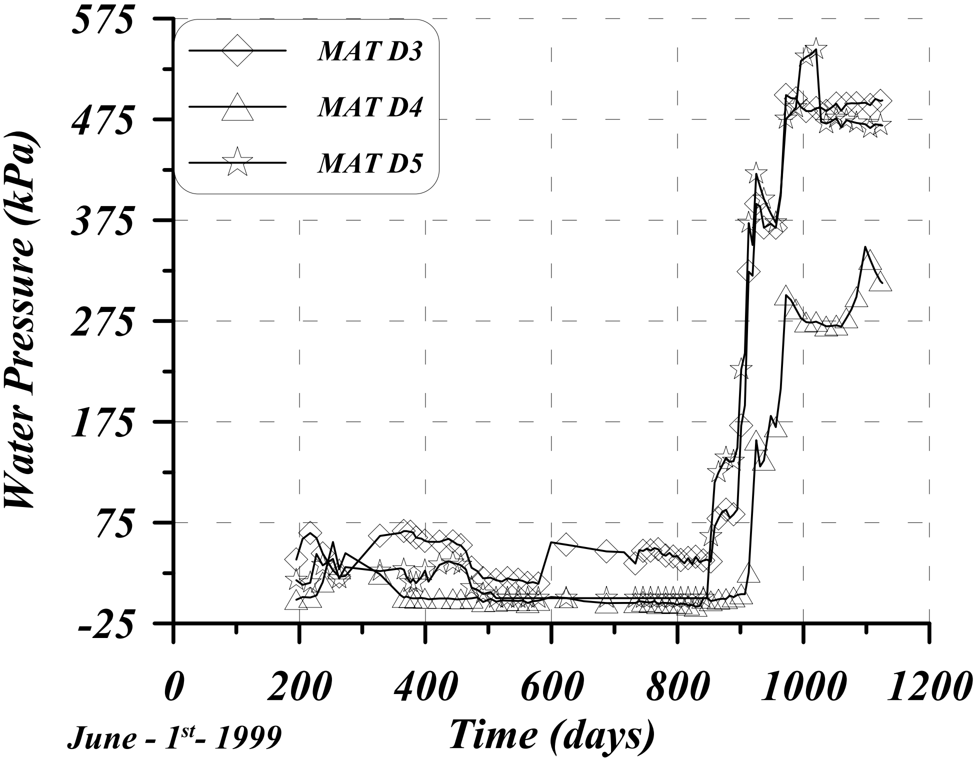


Figure 2.27: Measured evolution of injected water pressure at mats D3, D4 and D5 (Goudarzi et al. 2002).

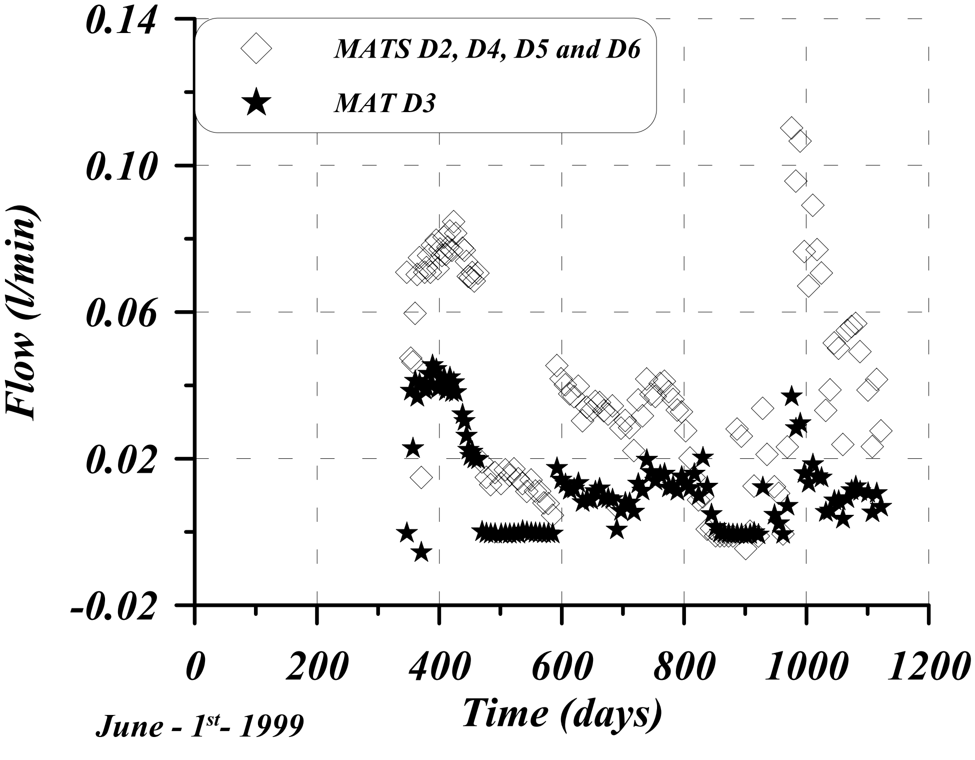


Figure 2.28: Injected flow rate of water at mats D2 to D6 during the first 3 years of the saturation process (Goudarzi et al. 2002).

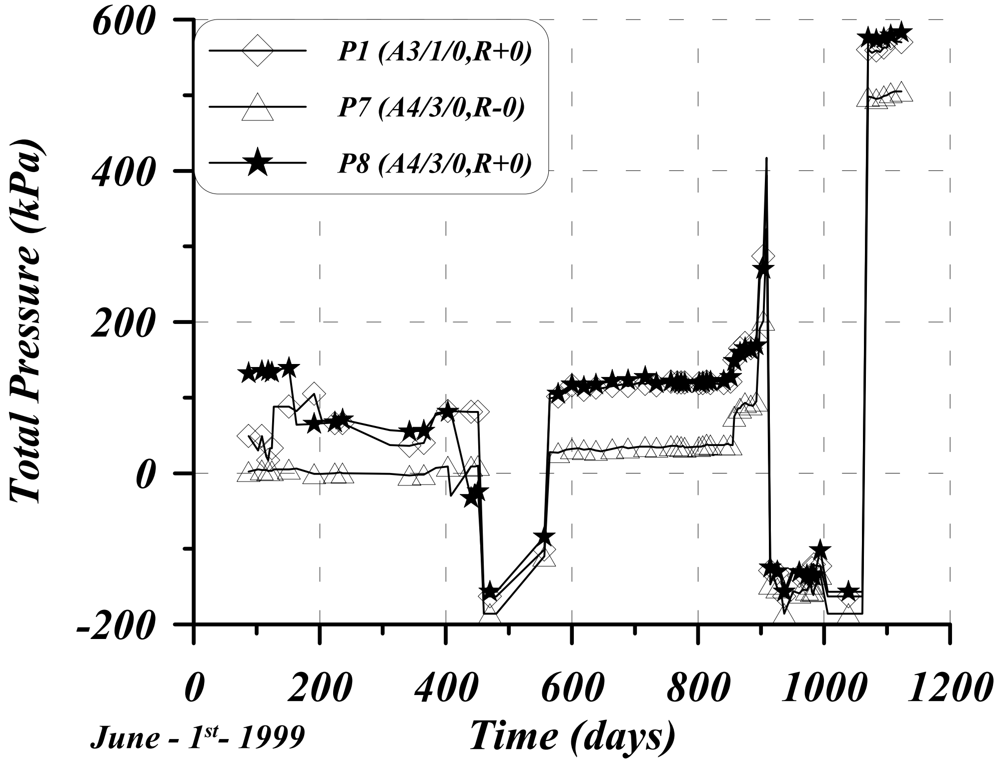


Figure 2.29: Monitored backfill total pressure in sections A3 and A4 at the host rock (Goudarzi et al. 2002).