EUROPEAN COMMISSION
Community Research

ESDRED

(Contract Number: FI6W-CT-2003-508851)

DELIVERABLE D5 OF MODULE 1 – WP5

Evaluation and Final Report

Testing Non-Intrusive Monitoring Systems

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Date of issue of this report: **12 December 2008**

Start date of project: **01 February 2004** Duration: **60 Months**

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)

Dissemination Level		
PU	Public	Yes
RE	Restricted to a group specified by the partners of the [ESDRED] project	No
CO	Confidential, only for partners of the [ESDRED] project	No

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EXECUTIVE SUMMARY OF ESDRED MODULE 1, WORK PACKAGE 5

ESDRED (Engineering Studies and Demonstration of Repository Design) is a technological integrated project within the context of the 6th Framework Programme of EURATOM. The project aims to demonstrate the technical feasibility, at an industrial scale, of a number of specific technologies related to the construction, operation and closure of a geological repository for vitrified high-level radioactive waste (HLW) and spent fuel.

A component of ESDRED Module 1 (Buffer Construction Technology) aims to investigate and further develop the use of non-intrusive monitoring techniques under repository conditions.

Module 1 partners considered the available technical options for applying non-intrusive monitoring within the timeframe of the ESDRED project and concluded that seismic tomography was the most promising technique to pursue in the project. It was decided that the most appropriate approach for applying and developing this non-intrusive technique would be to monitor the phases of the Nagra HG-A experiment at Mont Terri, which is investigating gas flow through the near-field host rock and along seals in the Excavation Damaged Zone (EDZ).

The study has achieved the following:

- A review of the requirements of monitoring in national waste disposal projects and an assessment of available monitoring techniques against these requirements was conducted. This led to identification of seismic tomography as the most promising technique for conducting non-intrusive monitoring for the designs and host geologies considered.

- The sparker source proved to be a suitable option for non-intrusive monitoring of the HG-A experiment with seismic tomography. It produced well-repeatable waveforms in a frequency band up to 3 kHz. This will allow waveform inversions to be conducted with sufficient spatial resolution.

- Anisotropic travel-time tomography using data sets from the Mont Terri test site allowed the elastic properties of the Opalinus clay host rock to be delineated. A high degree of anisotropy (up to 30%) could be identified.

- Additional geophones placed within the HGA micro-tunnel proved to be of significant value to the project. Data recorded by the geophones allowed the changes within the micro-tunnel and in the excavation damage zone around the micro-tunnel to be identified.

- Results from cross-hole travel-time inversions were unable to detect differences associated with saturation of the micro-tunnel. This indicates that full waveform analysis is required for non-intrusive repository monitoring. Development of an anisotropic frequency-domain 2.5D modelling algorithm, suitable for tomographic waveform inversions is being progressed (this exploits the symmetry of the system to reduce the 3D equation to several 2D equations, while the solution still contains the 3D features). This work, which forms part of the PhD thesis, will continue beyond the end of the ESDRED project. On completion of the measurement campaigns and full waveform analysis the report will be updated to include the findings.

The following recommendations for development of non-intrusive monitoring of geological repositories are made:

- On the basis of our investigations, seismic tomography has been identified as a potentially useful option for non-intrusive monitoring. It is recommended that more research should be undertaken for further improving the usefulness of this technique. In particular, linking the tomogram and waveform data to specific processes will be an important part of future research.

- Our study highlighted the importance of seismic sensors emplaced directly in the repository. It is recognized that wired sensors, as they are installed in the HGA micro-tunnel at Mont Terri would be unsuitable for a sealed repository. Therefore, a monitoring programme employing seismic tomography should consider collection of data and calibration of the tomographic data with data collected from the disposal cell.

- Monitoring temporal changes via seismic waveform tomography requires precise knowledge of the background medium in which the repository will be embedded. This requires calibration measurements. Accordingly, seismic tomography experiments should be performed prior, during and after excavation of the disposal cell. Identical experimental configurations should then be used for the subsequent monitoring phases.

- Further work should be undertaken to identify monitoring objectives, strategies and decision-making processes, in order to identify requirements on monitoring techniques and guide technology development.

A group of ESDRED partners (Nagra, NDA & ANDRA) recognised the opportunity to build upon the non-intrusive work within the ESDRED programme by installing and conducting ‘wireless’ monitoring and non-intrusive monitoring alongside conventional wired techniques. A low-pH shotcrete plug, constructed under Module 4 of the ESDRED programme, provided a robust opportunity to simultaneously test and evaluate the three monitoring methods in a situation which would have similarities with a repository vault-end seal. This work was outside the scope and budget of ESDRED, but was pursued independently by the partners as a valued development of non-intrusive monitoring techniques.

1 - INTRODUCTION

ESDRED (Engineering Studies and Demonstration of Repository Design) is a technological integrated project within the context of the 6th Framework Programme of EURATOM (ESDRED, 2008a). The integrated project is a joint research effort by major national radioactive waste management agencies and by research organisations representing nine European countries. The project aims to demonstrate the technical feasibility, at an industrial scale, of a number of specific technologies related to the construction, operation and closure of a geological repository for higher-activity wastes, including vitrified high-level radioactive waste (HLW) and spent fuel. Four technical Modules each address one or more specific research area.

ESDRED Module 1 (Buffer Construction Technology), Work Package 5 (Testing Non-Intrusive Monitoring Systems), aims to investigate and further develop the use of non-intrusive monitoring techniques under repository conditions (ESDRED, 2008b). The Nuclear Decommissioning Authority (NDA) is responsible for managing this work package (NDA, 2006).

ESDRED Deliverable D5 (this document) reports on the development and outcomes of Module 1, Work Package 5. It has the following structure:

- Section 1 provides an introduction to Module 1, Work Package 5, outlining the value of non-intrusive monitoring within a step-wise repository programme, describing the objectives of Work Package 5, and providing an overview of the work programme followed.

- Section 2 records how various non-intrusive monitoring techniques were evaluated, in the context of Module 1 partners' repository programmes and their requirements for monitoring, to identify the appropriate technique for investigation under Work Package 5. It also reports how an appropriate site for research into non-intrusive monitoring was identified.

- Section 3 describes the non-intrusive monitoring work programme followed under Module 1, Work Package 5.

- Section 4 presents the data collected during non-intrusive measurement campaigns and provides an analysis of the results obtained.

- Section 5 presents the conclusions of this study and provides some recommendations for future work regarding non-intrusive repository monitoring.

1.1 Non-Intrusive Monitoring

Non-intrusive monitoring, which can incorporate borehole-based, surface-based or airborne techniques allows monitoring of the repository to be carried out remotely from the waste emplacement location. The application of non-intrusive monitoring has been considered by several waste management organisations (e.g. European Commission, 2004; Thompson *et al.*, 2003; White *et al.*, 2004; GSL and Golder Associates, 2004; Torata *et al.*, 2005). Non-intrusive monitoring avoids any potential consequences to the passive safety provided by the Engineered Barrier System (EBS) associated with *in situ* monitoring. It also avoids problems associated with the failure of monitoring sensors located in the EBS, which can only be repaired or replaced by disturbing the engineered barriers.

Non-intrusive monitoring is of particular importance for any monitoring of the repository that may occur post-emplacement; monitoring activities must not affect the passive safety of the repository barrier system (IAEA, 2001). This requirement limits the feasibility of using conventional techniques and favours the use of alternatives, such as remote (wireless) transmission of monitoring data. However, wireless transmission will be challenging to implement over long timeframes, given the potential for failure of sensors, the limited lifetime of a power supply for remote data collection/transmission and the limited distances over which through-the-earth (TTE) wireless data can be relayed.

The development of non-intrusive monitoring techniques, in conjunction with conventional intrusive or wireless monitoring techniques, in underground research laboratories (URLs), provides an effective means of calibrating a non-intrusive technique and demonstrating its performance and applicability. Obtaining comparable information through a variety of approaches leads to confidence-building in the non-intrusive technique and in its ability to provide reliable, reproducible data if implemented to monitor a repository after waste emplacement and/or post-closure.

1.2 Project Objectives

The principal objectives of activities under ESDRED Module 1, Work Package 5 were as follows (NDA, 2006):

- To further evaluate and develop cross-hole seismic tomography techniques for non-intrusive monitoring of repository systems, by investigating the potential of the technique to monitor the performance of the EBS and the near-field host rock at Mont Terri.

- To provide recommendations for designing repository monitoring programmes incorporating non-intrusive techniques.

These objectives were addressed by:

- Evaluation of the requirements of monitoring in national waste disposal projects, and considering the pros and cons of different non-intrusive monitoring techniques.

- Analysing the effects of varying state (saturation and pressure) of the material filling a micro-tunnel using cross-hole seismic methods.

- Comparing these non-intrusive measurements with those obtained using more conventional, intrusive monitoring techniques, (in this case, geophones in the micro-tunnel itself).

- Development of techniques for analysing seismic tomography data, and identifying the key areas of development that need to be completed before the technique can be applied in repositories.

1.3 Overview of Work Programme

1.3.1 Non-Intrusive Monitoring within ESDRED Module 1, Work Package 5

The NDA, together with Module 1 partners (principally Nagra, ONDRAF/NIRAS and ANDRA) considered the available technical options for applying non-intrusive monitoring within the ESDRED Project, and considered what was feasible given the time constraints of the project. Following consideration of repository concepts, monitoring objectives and potential non-intrusive techniques, the partners concluded that cross-hole seismic tomography was the most promising technique to pursue.

It was also decided that the most appropriate approach for applying and developing seismic tomography would be to monitor the phases of the Nagra HG-A experiment at Mont Terri, which is related to gas flow through the near-field host rock (the Opalinus Clay Formation of northern Switzerland) and along seals in the Excavation Damaged Zone (EDZ) of a repository (Nagra, 2005). An outline description of the HG-A experiment is provided in Section 3.1 of this report. Section 2.3 summarises the process followed to identify the preferred technique and study location for non-intrusive monitoring within Module 1, Work Package 5.

Initial field trials were undertaken at the HG-A gallery prior to this ESDRED study, to establish the feasibility of using cross-hole seismic tomography. The results of these initial trials indicated a high degree of confidence that the technique could be further developed for the application of non-intrusive monitoring (Maurer, 2006 and 2007).

1.3.2 Seismic Tomography as a Non-Intrusive Monitoring Technique

Seismic tomography has been widely applied in geological studies. For example, it has been developed and applied by a number of radioactive waste management organisations for specific applications in repository programmes. Mining companies have also used the technology to address specific issues (Albert, 2005; GSL and Golder Associates (UK) Ltd., 2004; NDA, 2005b).

Cross-hole seismic tomography is a sonic method that allows for the production of an image of the space or plane between two boreholes. An energy source (such as a high frequency sparking unit) is installed in one borehole and a receiver string (a number of sensors linked in a chain) is deployed in a second borehole. The energy source is excited and the resulting seismic wave propagates through the intervening space and is recorded by the receiver string.

Two types of seismic wave are typically analysed in seismic tomography. P-waves (primary waves) are longitudinal or compressional waves, which means that motion (e.g. in the sensor detecting the wave) is parallel to the direction of propagation. S-waves (secondary waves) are transverse or shear waves, which means that the motion is perpendicularly to the direction of propagation.

Based on the known distance between the source and receiver, and the time lapse between signal generation and detection, the speed of wave propagation through the intervening space can be determined. The source is then moved up the borehole a pre determined distance and the whole process is repeated until the entire section has been surveyed.

Spatial variations in this travel-time can be correlated to variations in the characteristics of the medium (which can include the EBS and near field host rock around a repository tunnel, if boreholes for signal and receiver equipment are deployed on either side of such a feature). Images in terms of seismic velocity or attenuation can be obtained through travel-time inversion (frequency only) or full waveform inversion (taking account of the frequency, amplitude and phase of the seismic data) and interpreted in terms of engineered and geological structures. The technique is sensitive to changes in physical characteristics such as the density of the medium, the degree of saturation, gas storage and gas pressure build-up and potentially can therefore be used to monitor changes in the state of the ~~of the~~ EBS components; potentially confirming evolution of a disposal cell following waste emplacement .

1.3.3 Experiment Location and Set-Up

The seismic tomography experiments conducted under ESDRED Module 1, have been carried out at the Mont Terri Underground Rock Laboratory (URL) in the Opalinus Clay in north-west Switzerland (Swisstopo, 2008). The tests have focused on monitoring the different phases of the Nagra HG-A experiment at Mont Terri, which aims to investigate gas flow through the near-field host rock and along seals in the EDZ.

The HG-A experiment consists of a horizontal micro-tunnel with a diameter of ~1 m, together with several observation boreholes (Figure 1.1). The micro-tunnel is located 11 m from Gallery 04 of the Mont Terri URL. A niche has been excavated to allow for the positioning of drilling equipment. To facilitate non-intrusive monitoring by cross-hole seismic tomography, two additional boreholes, approximately 27 m long, were drilled, one above and one below the micro-tunnel, and stabilised with a concrete liner. A schematic drawing of the experiment layout is provided in Figure 1.2.

The micro-tunnel was back-filled with a coarse grained sand mixture (∅ 2 - 6 mm grain size) and closed by a hydraulic mega-packer. This “backfill” was then saturated with water before being subject to overpressure. Further phases of the HG-A experiment include gas injection (nitrogen) to cause desaturation. To date one pilot study and six seismic tomography measurement campaigns have been carried out to determine the influence of the degree of saturation and pressure build-up on the geophysical data obtained (see Section 3). A further four campaigns are planned be undertaken and analysed after the ESDRED Project has finished, these correspond to the gas injection phases. The seismic measurements provide the basis for a comparison with direct observations from sensors in the backfill and in the near-field host rock, although the majority of these direct observations are carried out by other Mont Terri partners and are outside the scope of the ESDRED Module 1, Work Package 5 project.

In addition to the boreholes drilled for the experiment, the main components of the set-up are a seismic source (high-frequency sparker), which is inserted into the lower inclined borehole and a 24-channel hydrophone chain (receiver), which is inserted into the upper inclined borehole. To operate these require the boreholes to be filled with liquid (fluid coupled). Therefore, a special purpose sealing cap was required for the upper inclined borehole.

Further details of the experimental set-up for non-intrusive monitoring of the HG-A experiment at Mont Terri is provided in the work programme description (Section 3).

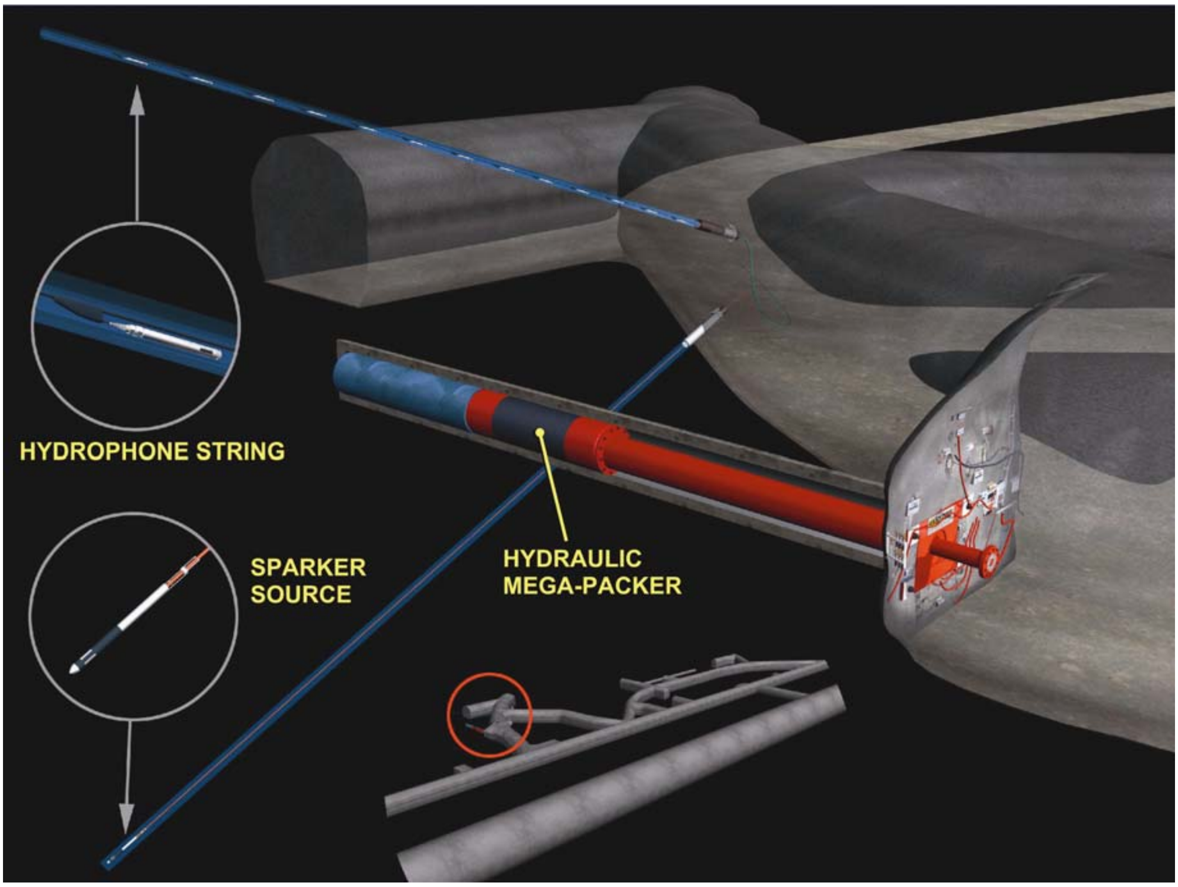

Figure 1.1: Layout of the HG-A experiment in the Mont Terri URL.

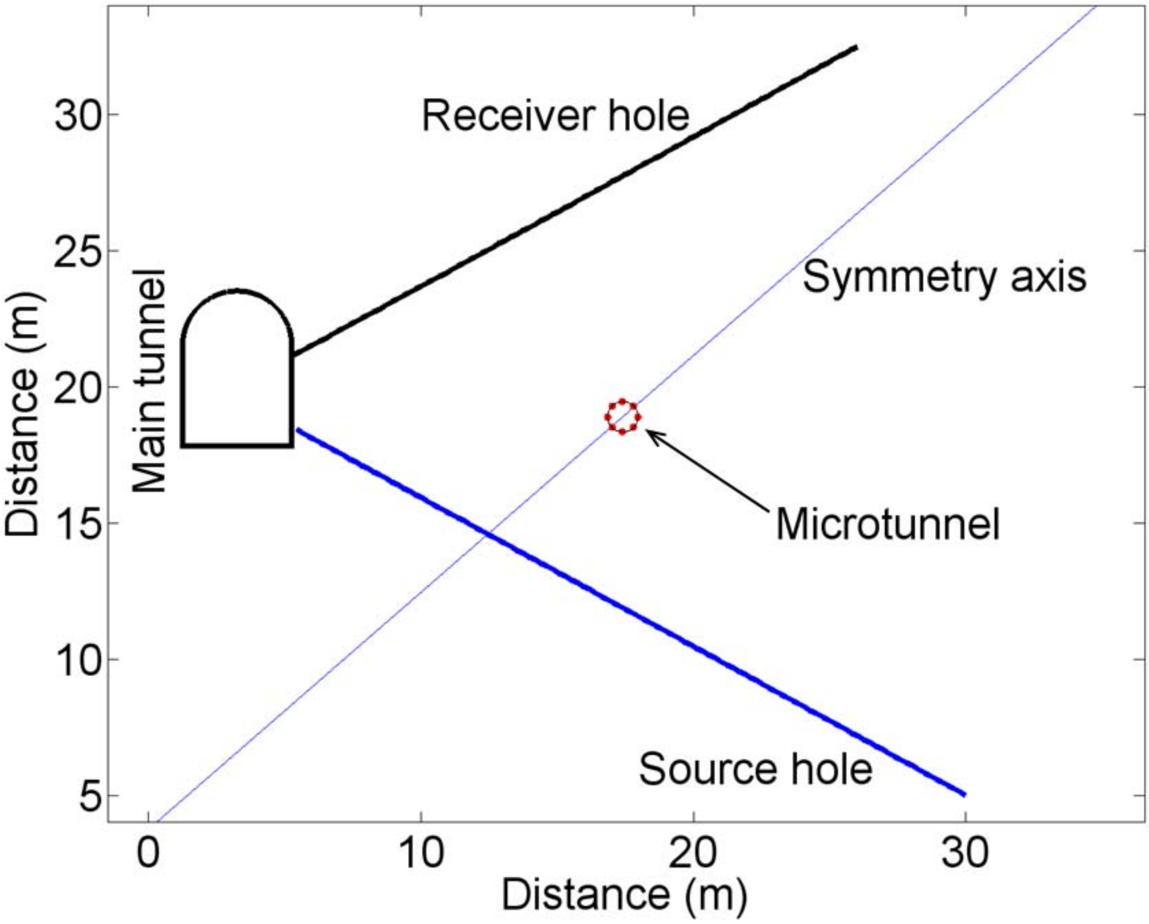

Figure 1.2: Schematic drawing of the layout of the non-intrusive seismic tomography experiment in the HG-A micro-tunnel, Mont Terri (taken from Breen et al., 2008). The symmetry axis about which the Opalinus Clay is approximately isotropic is shown (see Section 3 for discussion).

1.3.4 Initial Pilot Study

Prior to commencement of work under ESDRED Module 1, Work Package 5, an initial pilot study was performed outside of ESDRED to:

- Check the technical feasibility of acquiring appropriately high-quality P-wave and S-wave data.
- Investigate the influence of seismic anisotropy in the Opalinus Clay at the Mont Terri site.
- Explore the possibilities and limitations of P-wave travel-time tomography for inverting data acquired at the site.
- Determine if the waveforms are influenced by the presence of the micro-tunnel.
- Estimate the utility of the S-wave data.

The conclusions from this study are discussed in Maurer (2006) and Maurer (2007) and can be summarised as follows:

- The experiment was shown to be technically feasible and the experimental set-up tested produces high quality P-wave data.
- Seismic anisotropy (the directional dependence of seismic wave velocity through a medium) of the Opalinus Clay is pronounced (of the order of 30%).
- Velocity tomograms accurately reproduce geological features of the Opalinus Clay, e.g. the layering of strata. However, the velocity delays caused by the micro-tunnel are too small to have a significant effect on the tomogram. Travel-time cross-hole tomography is therefore not capable of resolving changes occurring within the micro-tunnel.
- The micro-tunnel does have an effect on the shape of the waveform in the seismograms. This can be exploited through full-waveform inversion of the data.
- It was not possible to record S-wave data of sufficiently high quality (due to its attenuation in soft rock). Further work will therefore focus on P-wave analysis.

1.3.5 Outline of Work Programme

Following the initial pilot study and test measurements, seismic tomography measurements on the HG-A experiment at Mont Terri were planned to coincide with the key phases of the HG-A experiment:

- Measurement of the empty micro-tunnel.
- Measurement after sand emplacement in micro-tunnel.
- Measurement after saturation of backfill material with water.
- Measurement prior to and after gas injection

Six measurement campaigns have been performed so far during the period March 2006 to June 2009 (see Section 3.3). Measurement campaigns prior to and after gas injection are planned for the period October 2008 to May 2009.

The technical components of activities under ESDRED Module 1, Work Package 5, including field measurement, research and full waveform inversion of tomographic data have been undertaken by the Swiss Federal Institute of Technology, Zurich (ETH), in the framework of a four year PhD thesis sponsored by the NDA and undertaken by Edgar Manukyan under the supervision of Dr. Hansruedi Maurer and Professor Alan Green at ETH.

1.4 Non-intrusive monitoring of the ESDRED Module 4 low pH shotcrete plug

Under ESDRED Module 4, a programme of work was undertaken to construct a 4m long low pH shotcrete plug in a 3.5m diameter tunnel end; located at the Grimsel URL in Switzerland. The shotcrete plug will provide a confining force for a 1m bentonite plug made up of 5 rings of bentonite blocks. These rings will be artificially saturated by injecting water between each ring with the aim of developing a swelling pressure of circa 4MPa when saturated. The Module 4 objective was to demonstrate that it is possible to construct a low pH shotcrete plug which would be capable of withstanding the typical swelling pressure from saturated bentonite (i.e. up to 5MPa).

A group of ESDRED partners (Nagra, NDA & ANDRA) recognised the opportunity to build upon the work within the ESDRED programme by installing and conducting 'wireless' monitoring and non-intrusive monitoring alongside conventional wired techniques; thus providing a robust opportunity to simultaneously test and evaluate the three monitoring methods in a situation which would have similarities with a repository vault-end seal. NDA (through ETH, Zurich) conducted some preliminary simulation modelling of the design to assess the capability for effective non-intrusive monitoring using cross-hole seismic tomography. This indicated that this technique could prove effective in monitoring the changes in swelling pressure resulting from saturation of the bentonite.

Based on this the partners, supported by specialist sub-contractors (Solexperts for the wireless monitoring technology) and ETH Zurich (for the non-intrusive seismic tomography), initiated a programme to use non-intrusive monitoring to monitor the progressive changes in buffer saturation. Taking advantage of the ESDRED work allowed the partners to apply these monitoring techniques in a full scale experiment, in representative site conditions, but without costs associated with fabricating that condition. It also provided the potential for extending the monitoring application of non-intrusive monitoring (NI) techniques into granite rock at Grimsel. Pursuing the work supported the objective of developing enhanced understanding of monitoring capabilities and techniques as well as comparing NI monitoring with the latest technical developments in "wireless" or "through-the-earth (TTE)" monitoring and a unique opportunity to compare three techniques simultaneously.

The project, although a spin-off from the ESDRED work, could not be funded within the existing ESDRED programme and was initiated by the partners as a new project: Project TEM (**T**esting and **E**valuation of **M**onitoring Systems. This programme is continuing and will be carried forward into the European Commission 7th Framework programme as part of project MoDeRn (**Mo**nitoring **De**velopments for safe **R**epository operation a**n**d staged closure).

For the non-intrusive seismic tomography experiments six angled boreholes, each 25m long were drilled radially from the access tunnel prior to the construction of the low-pH shotcrete plug. A series of measurements were conducted to monitor baseline conditions and the various stages of saturation. This information could then be compared with the other monitoring systems. The configuration for the non-intrusive seismic tomography experiment is shown in Figure 1.3.

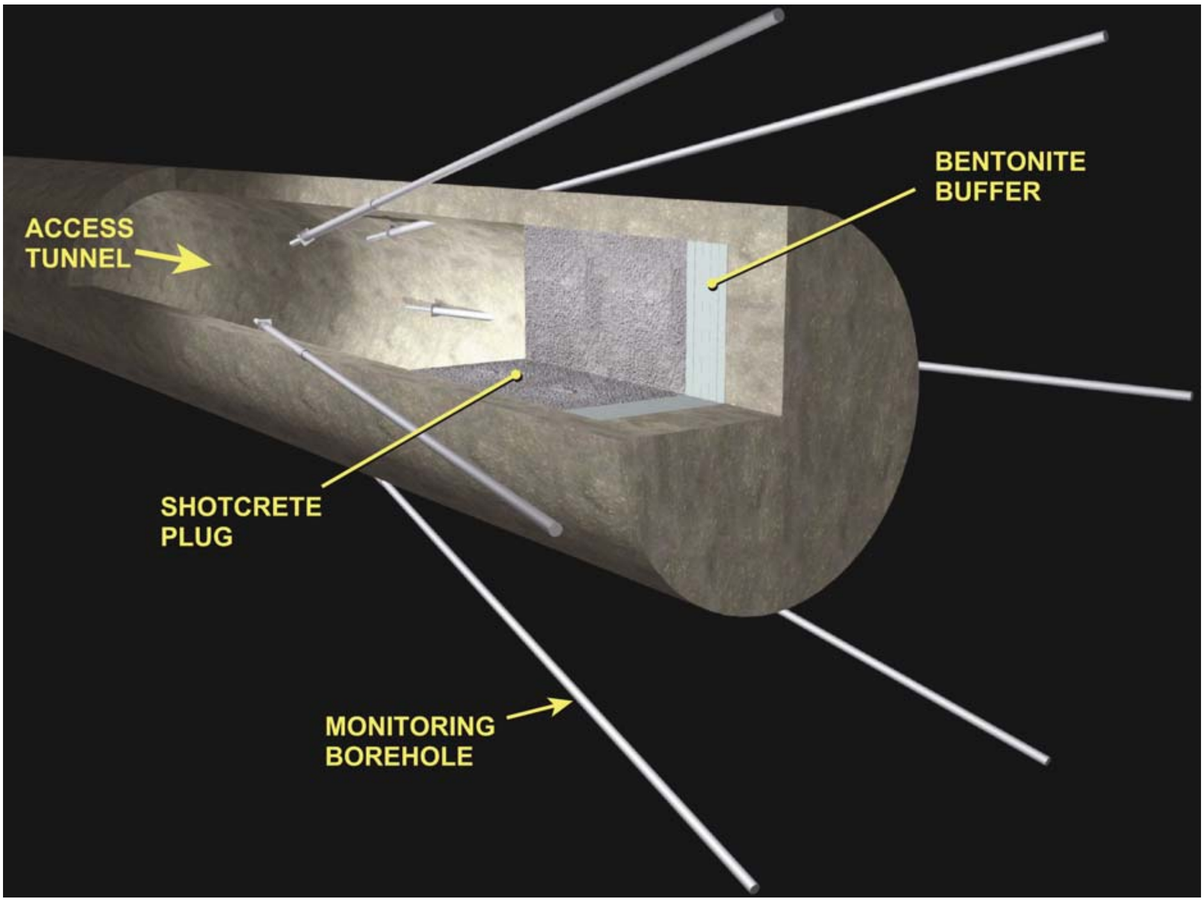

Figure 1.3: Configuration of the Grimsel non-intrusive seismic tomography experiment

2 - SELECTION OF MONITORING TECHNIQUE

This section describes how seismic tomography was selected as the monitoring technique for investigation and development under Work Package 5 of Module 1 of the ESDRED Project. First, there is a discussion of the key elements of disposal concepts in partners' programmes. Second, there is a discussion of the techniques considered for evaluation within ESDRED. Finally, the basis for selecting seismic tomography is provided, given the context of different disposal concepts and potential techniques.

2.1 Review of Partners' Programmes & Application of Monitoring

Within the partners in ESDRED Module 1, three waste management organisations, Andra, Nagra and ONDRAF/NIRAS, have developed disposal concepts for repositories to be constructed in argillaceous rocks. These concepts use different materials and components within the EBS, and have been classified within ESDRED as illustrated in Figure 2.1. The demonstration of design, construction and performance of the EBS materials and their interaction with the near-field, is the focus of ESDRED Module 1 (ESDRED, 2008b).

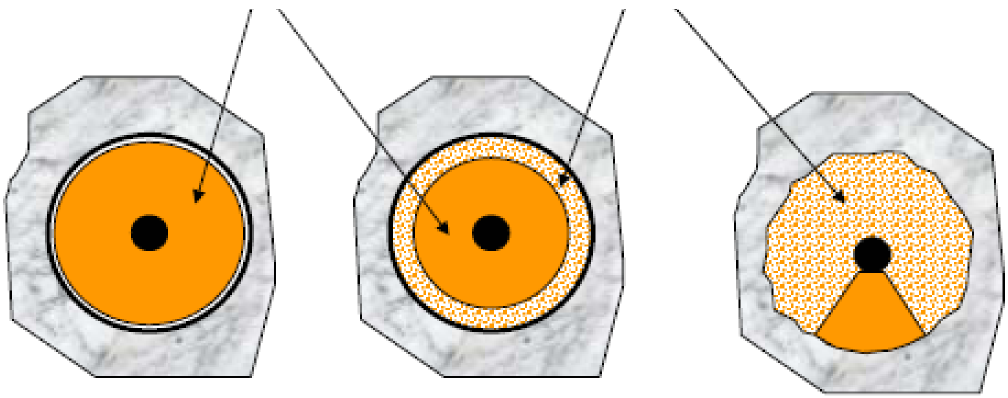

Figure 2.1: Cross-section of a conceptual waste emplacement drift showing alternative designs for buffer construction (taken from ESDRED, 2008b). The filled black circle represents a waste package; solid and hashed orange components are consolidated and granular buffer respectively; the outer black circle represents tunnel support structures for weaker rocks and the grey region represents the near field rock.

The Module 1 partners participated in the selection of seismic tomography as a non-intrusive monitoring technique for investigation under Work Package 5. This decision, reported in Section 2.3, took account of the objectives and scope of monitoring programmes developed by the Module 1 partners, based on their disposal concepts for HLW and spent fuel (NDA, 2005b).

This section summarises the main components of the repository design concepts for ANDRA, Nagra and ONDRAF/NIRAS, and comments on each organisations activities within ESDRED Module 1. Aspects of their approaches to monitoring a repository are outlined, together with the monitoring parameters that are currently of key interest to each partner (NDA, 2005b). The approach of Module 1 partners to non-intrusive and wireless monitoring techniques is discussed.

2.1.1 ANDRA

ANDRA (the French National Radioactive Waste Management Agency) is the public body responsible for the long-term management of all radioactive waste produced in France. ANDRA plans to dispose of HLW and long-lived intermediate-level waste (ILW) in a geological repository in an argillaceous formation. Retrievability of waste is an essential component of the French long-lived radioactive waste disposal concept (ANDRA, 2005a).

2.1.1.1 Disposal Concept for HLW and Spent Fuel

In the French disposal concept for vitrified HLW and spent fuel in an argillaceous host rock, a disposal cell is a horizontal cylindrical borehole accessible from one end only. Per ANDRA's Dossier 2005 the vitrified HLW disposal cell has a diameter of ~0.7 m and a length of ~40 m, and the spent fuel disposal cell a diameter of 2.6 m to 3.3 m and a length of ~46 m. For the spent fuel the EBS comprises the following components (ESDRED, 2008b) and is illustrated in Figure 2.2:

- A metal liner, perforated to allow groundwater from the surrounding host rock to enter the EBS and saturate the buffer.

- A 0.8 m thick buffer composed of 70% bentonite clay, 30% sand. 0.5 m high rings of the buffer material would be pre-fabricated on the surface and assembled together in sets of four using metal straps and corner bracings. This is an example of Case 1 as illustrated in Figure 2.1.

- A permanent steel inner-sleeve which fits inside the buffer, to receive the waste packages (spent fuel assemblies encased in unalloyed steel overpacks). The purpose of the inner-sleeve is to facilitate waste package emplacement and retrieval, should this be desired.

When closed, each disposal tunnel will be sealed with a steel plug (which ensures radiological protection during the operational period and allows manned access to the emplacement galleries), a low permeability bentonite seal and a retaining concrete plug.

2.1.1.2 Activities under ESDRED Module 1

ANDRA's main activities under Module 1 focus on improving pre-fabrication techniques for full-scale bentonite buffer rings and assembly of the buffer rings into sets of four, in preparation for emplacement.

2.1.1.3 Key Monitoring Parameters

ANDRA has identified key parameters that will require monitoring in its repository, in order to confirm performance of the EBS (NDA, 2005b). These concern the condition of the steel inner-sleeve and the environment inside this component, and include:

- The temperature inside the steel sleeve (the temperature of the sleeve should not exceed 100°C).

- The humidity inside the steel sleeve.

- Strain or other deformation of the steel sleeve.

- Pressure (after saturation) inside the metal sleeve (the water pressure inside the sleeve should not exceed 5 MPa).

- Gas inside the steel sleeve.

In addition, ANDRA requires the swelling pressure of the bentonite plug to be monitored. This pressure should not exceed 12 MPa.

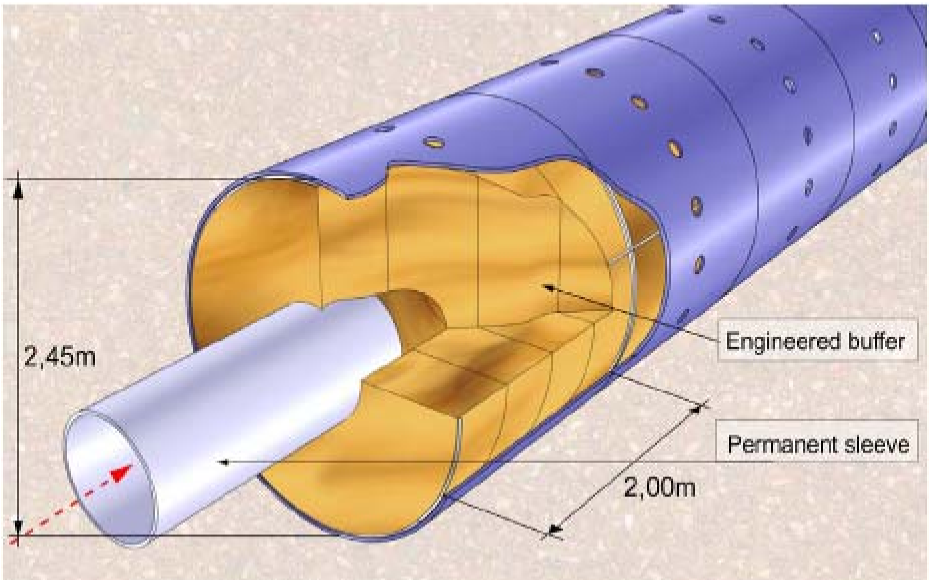

Figure 2.2: ANDRA's Engineered Barrier Assembly Design (taken from ESDRED, 2008b).

2.1.1.4 Monitoring the Geological Disposal of HLW and Spent Fuel

ANDRA provides some details on the implementation of monitoring the geological disposal of vitrified HLW (Type C) and spent fuel (Type CU) and long-lived ILW (Type B) in the Dossier 2005 (ANDRA, 2005b). Their planned approach to monitoring focuses on a number of "control" disposal cells and modules, in which conditions will be extensively monitored as an indicative guide of performance throughout the repository. Additional monitoring of ventilation air and strain/displacement will take place in access and connection drifts throughout the repository. Current monitoring programmes envisage the use of techniques that currently exist or can be developed within the foreseeable future, and can be used under repository conditions. Monitoring should be implemented during construction in such a way that there is no impact on operational or long-term safety (ANDRA, 2007).

Monitoring of emplaced Type CU waste will be undertaken in a control module (a part of the repository), in which sensors are employed in various repository drifts and a small number of disposal cells. Instrumentation within these disposal cells is likely to include fibre optic thermometers and various sensors placed on the steel sleeve. Instrumentation including extensiometers, interstitial pressure cells and vibrating wire thermometers will also be installed in boreholes surrounding the disposal cells (ANDRA, 2005b).

2.1.1.5 Development of Non-intrusive and Wireless Monitoring

ANDRA plans to employ wireless monitoring systems within a geological repository. Sensors will be deployed inside the disposal cells (outside the metal liner) and data will be channelled to a transmitter beyond the steel plug and behind additional radiological shielding. Several cables will need to be wired through the metal plug to connect the sensors and transmitters, but this is unlikely to compromise its function of radiological protection. The wireless transmitters will transmit the data to receivers in the access drifts beyond the low permeability bentonite seal and concrete plug, avoiding a requirement for cables running through these components. ANDRA has developed wireless monitoring technologies in collaboration with RWMC (ANDRA, 2007).

ANDRA is also considering installing transmitters inside the metal sleeve within the buffer material to monitor conditions closer to the waste packages themselves. Again, the wireless signal receiver would be placed in the access drift, which will remain open for some time.

Investigations concerning wireless transmissions over greater distances are in progress, which may lead to wireless technologies being implemented to transmit data further afield, either to a more distant receiver in the repository, or to the surface.

2.1.2 Nagra

Nagra, (the National Cooperative for the Disposal of Radioactive Waste) was set up by the primary Swiss radioactive waste producers in 1972, to carry out the research and development work leading to the safe long-term disposal of Swiss radioactive waste. Nagra considers that the Opalinus Clay Formation, which is found in the north of the country, has geological advantages over other feasible host rocks available in Switzerland. In 2006, the Swiss Federal Council approved the demonstration of disposal feasibility for HLW, spent fuel and long-lived ILW in such an environment (Nagra, 2002 and 2008).

2.1.2.1 Disposal Concept for HLW and Spent Fuel

In Nagra's disposal concept for vitrified HLW and spent fuel, the disposal canisters are encapsulated in steel overpacks and emplaced horizontally on a prefabricated, compacted bentonite cradle (as per Case 3, shown in Figure 2.1). The repository drift is then filled with bentonite pellets (ESDRED, 2008b). An image of this conceptual design is shown in Figure 2.3.

2.1.2.2 Activities under ESDRED Module 1

Under ESDRED Module 1, Nagra is investigating the full-scale emplacement of granular backfill material using a double-auger machine.

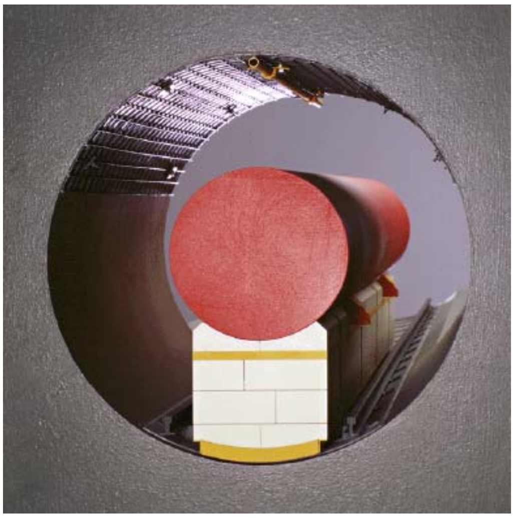

Figure 2.3: Nagra's Engineered Barrier Assembly Design (taken from ESDRED, 2008b).

2.1.2.3 Key Monitoring Parameters

Nagra have identified the requirement to monitor the following parameters relating to performance of the buffer (NDA, 2005b):

- Evolution of the buffer temperature (the buffer temperature should not exceed 130°C).
- Water content/water saturation in the buffer.
- Pore pressure (the maximum pore pressure in the buffer should not exceed 7 MPa).
- Total stress change.
- Displacement in the buffer and surrounding rock.

In addition, the swelling pressure of the bentonite buffer should not exceed 5 MPa. The anticipated timescale for monitoring has been identified as approximately 50 years (but may range from 20 to 80 years) (NDA, 2005b).

2.1.2.4 Monitoring the Geological Disposal of HLW and Spent Fuel

Nagra has developed an outline concept for monitored long-term geological disposal within its feasibility study for a repository for vitrified HLW and long-lived ILW in the Opalinus Clay (Nagra, 2002). A detailed monitoring concept is planned for development within six to eight years. This is likely to include both non-intrusive and wireless monitoring technologies.

Monitoring during site investigation, repository construction, operation and after waste emplacement will be undertaken through surface-based studies and through studies in

URLs developed at the repository site, and at small-scale waste emplacement locations in underground pilot facilities. Monitoring will be focused on studies that can be carried out without influencing the integrity of engineered and/or natural barriers to radionuclide release (i.e., at the surface and in a URL). Any direct monitoring of the repository, which may be required to confirm its performance, will be achieved through the use of non-intrusive or wireless techniques (Nagra, 2007).

A pilot facility will be located so that conditions are representative of those expected in the main facility, possibly close to the site of the main facility itself, and will contain a small, but representative waste component. The pilot facility will be constructed and tests performed there prior to full-scale waste emplacement, and will incorporate waste retrievability as a contingency approach. A limited number of non-intrusive or wireless monitoring techniques will be implemented at this facility. These will provide data by which to calibrate non-intrusive monitoring of repository performance. The reference case for monitoring of the pilot facility indicates a 50-year monitoring period.

Monitoring in the pilot facility will be complemented by more extensive studies in URLs. The environmental conditions will be representative of those in the main repository and pilot facility, but no waste will be emplaced in the URL. Consequently, a wider range of both intrusive and non-intrusive techniques can be implemented at such locations to determine environmental characteristics and to monitor processes occurring in the EBS and near-field, without compromising passive safety.

Underground monitoring investigations will be complemented by thorough investigations at the surface. For some studies, conditions underground can be replicated in the laboratory. Surface studies facilitate more rapid experiments, which may be repeated more readily. Sensors are easily accessible for replacement if they fail. Surface-based non-intrusive techniques may find application for the determination of baseline conditions and for post-closure repository monitoring.

2.1.2.5 Development of Non-intrusive and Wireless Monitoring

Nagra has carried out substantial research and development of a variety of non-intrusive geophysical monitoring techniques. A number of geoelectic, radar and seismic studies have been performed at Mont Terri and the Grimsel Test Site (GTS). This experience (summarised in Albert, 2005) was of key importance in defining the monitoring programme to implement under ESDRED Module 1. Several non-intrusive/wireless monitoring techniques are being considered for incorporation in Nagra's repository monitoring strategy.

Surface-based techniques under consideration include 4D seismic monitoring to determine fluid saturation, pore pressure and gas build-up in the geosphere, and Interferometry Synthetic Aperture Radar (INSAR), which allows ground surface elevation to be monitored. INSAR is discussed in more detail elsewhere (e.g. GSL and Golder Associates (UK) Ltd., 2004).

Seismic tomography is regarded as a promising sub-surface technique by Nagra. It is likely to be investigated and applied to a URL or pilot facility, rather than for monitoring the main repository facility, since the use of boreholes in proximity to waste emplacement drifts is regarded as an invasive process which may affect passive safety.

In addition to Nagra's involvement in non-intrusive monitoring studies under ESDRED Module 1, Work Package 5, Nagra is also involved in a work package under ESDRED Module 4 (Low pH Cement for Shotcrete and Sealing Plug Construction Technology), coordinated by Enresa. This work package is investigating the development of low pH cements for application in a geological repository, by full-scale construction of a sealing plug and rock wall lining using shotcrete techniques at the Grimsel Test Site in Switzerland. The shotcrete plug is emplaced next to a bentonite layer so that the effects of bentonite swelling can be investigated. Nagra and the NDA are collaboratively carrying out monitoring of the ESDRED Module 4 experiment, under "Project TEM". The objective of this study is to compare the results of monitoring the Module 4 experiment by conventional and wireless techniques and by non-intrusive seismic tomography.

Wireless data transmission is also being investigated at Mont Terri, the Grimsel Test Site (GTS). Conceptual designs for monitoring of the pilot facility, and perhaps the repository itself, indicate that reliable, wireless transmission over a distance of 100 m would be required to minimise any impact on the passive safety of the waste.

2.1.3 ONDRAF/NIRAS

ONDRAF/NIRAS (the Belgian Agency for Management of Radioactive Waste and Enriched Fissile Materials) is a government agency created in 1980 and entrusted with the long-term management of Belgian radioactive waste. ONDRAF/NIRAS is researching the feasibility of disposing of radioactive waste, including high-level short or long-lived waste (Category C waste) in poorly indurated argillaceous rocks, such as the Boom Clay in the north-east of the country.

2.1.3.1 Disposal Concept for HLW and Spent Fuel

The most promising design concept for Category C waste within the Belgian disposal programme is the Supercontainer (illustrated in Figure 2.4). This is an example of a Case 2 EBS concept, as illustrated in Figure 2.1. The Supercontainer would be constructed above ground, facilitating the implementation of a comprehensive quality control programme. The Supercontainer incorporates a thick buffer layer that provides radiological shielding (ESDRED, 2008b).

2.1.3.2 Activities under ESDRED Module 1

ONDRAF/NIRAS is leading Module 1 investigations into backfilling the annular space around the Supercontainer with granular buffer material.

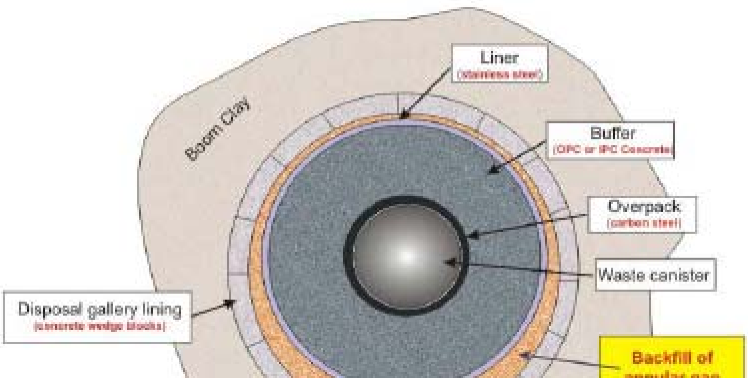

Figure 2.4: The Supercontainer concept developed by ONDRAF/NIRAS (taken from ESDRED, 2008b).

2.1.3.3 Monitoring the Geological Disposal of HLW and Spent Fuel

The current Belgian strategy for monitoring of a geological repository focuses on the performance of the Boom Clay and the evolution of this natural barrier in response to thermal, chemical, mechanical, hydrogeological and radiological effects arising due to repository excavation, waste emplacement and EBS evolution (ONDRAF/NIRAS, 2007a). The Boom Clay is the most important contributor to the long-term safety of the Belgian repository concept, since it provides the dual functions of isolation of the waste from the biosphere and retardation of radionuclide migration following failure of the EBS. The Belgian monitoring strategy therefore aims to minimise disturbance to this barrier, whilst providing an enhanced understanding of the underlying processes which may affect its performance. With this in mind, ONDRAF/NIRAS has identified that monitoring of the following parameters will be required (NDA, 2005b):

- Supercontainer surface temperature (temperature measurements should be accurate to within 1% over a range of 16-100°C).
- Stresses in the wedge blocks lining the disposal galleries (accurate to within 20%).
- Pore pressure in the Boom clay (accurate to within 20%).
- Temperature of the Boom Clay.

The planned timescale for monitoring is approximately 100 years for dose rates. Pore pressures and temperatures will also be monitored over the long-term (NDA, 2005b).

ONDRAF/NIRAS shares a common vision held by a number of waste management organisations that the location and type of monitoring activities will evolve over the phases of a geological repository, with non-intrusive and remote techniques having particular importance during the determination of baseline conditions and during post closure monitoring (ONDRAF/NIRAS, 2007b).

Following repository closure, it is expected that remote techniques will be used to measure the thermal impact of heat output from emplaced HLW and spent fuel on local aquifers. The thermal output from the waste is considered by ONDRAF/NIRAS to be most pronounced in the first fifty years after disposal (ONDRAF/NIRAS, 2007a), and this is also considered a feasible timescale for post-closure monitoring activities. It is recognised that non-intrusive monitoring of other factors, such as radionuclide migration, whilst desirable, may not be practicable, given the limits in detection of the low radionuclide concentrations expected, even after 10^4 years, against natural background radiation. The societal role of monitoring to confirm zero or negligible effects on the environment is acknowledged (ONDRAF/NIRAS, 2007b). In 2009 ONDRAF/NIRAS plan to further develop their monitoring strategy for geological disposal.

Monitoring techniques are tested *in situ* at the HADES URL in the Mol-Dessel area of north-east Belgium. Long-term monitoring investigations (over several years or decades) will aim to establish:

- The extent of displacements due to excavation, including the size of the EDZ and Engineered Disturbed Zone (EdZ). In this context, monitoring can be used as a tool to help limit the size of the EDZ/EdZ, through careful selection of excavation techniques, based on their impact on undisturbed conditions.
- Chemical effects in the Boom Clay, including pore water pressure and composition and redox/dissolution processes affecting Boom Clay minerals.
- Stress in the host-rock/gallery lining.
- Hydraulic conductivity.
- Temperature.

The effect of heating on processes in the EBS and near-field rock is receiving particular attention at present through the PRACLAY (PReliminAry concept in CLAY) large scale heater test. This project involves a ten-year heating experiment in the PRACLAY gallery of the HADES URL, simulating the heat output from emplaced waste. The objectives of the study are:

- To contribute to the assessment of the performance of the disposal system by confirming and refining understanding of the thermal and thermo-chemical coupled processes in the Boom Clay.
- To demonstrate the technical feasibility of repository development, taking into account the real and practical nature of the operations.
- To provide data to build confidence in mathematical models of system performance.
- To investigate techniques for monitoring thermal effects in a geological repository. A proposal to carry out non-intrusive measurements around the PRACLAY gallery under ESDRED Module 1 was submitted (Verstricht, 2005), but, as discussed in Section 2.3, this proposal was not selected for implementation owing to timing considerations.

This work is being undertaken by EIG EURIDICE (the European Underground Research Infrastructure for Disposal of Nuclear Waste in the Clay Environment), an economic interest group drawing expertise from SCK.CEN and ONDRAF/NIRAS, which actively contributes to feasibility studies on the disposal of radioactive waste in argillaceous rocks and which is responsible for the management and operation of the HADES URL facility.

Through this work, ONDRAF/NIRAS is developing a database of sensor types and their applications and optimised emplacement procedures for sensor performance together with an enhanced understanding of common pitfalls when implementing monitoring techniques and consideration of building redundancy into monitoring strategies (ONDRAF/NIRAS, 2007b).

2.1.3.4 Development of Non-intrusive Monitoring

A key consideration for ONDRAF/NIRAS in the selection of non-intrusive monitoring techniques is the recognition that argillaceous rocks hamper the application of common geophysical techniques, due to signal attenuation. ONDRAF/NIRAS consider that careful selection of non-intrusive techniques, based on the realistic scope of their performance is therefore required.

Non-intrusive techniques are also envisaged as a major component of post-closure safeguard activities. Following repository closure, there may be a need to verify that no undeclared tunnelling takes place in the vicinity of an underground repository. Satellite imaging combined with active or passive seismic monitoring techniques are considered to provide a promising approach to achieve this objective.

2.2 Review of Applicable Technologies and Options for Monitoring

The requirement for passive safety of the repository following closure is usually taken to indicate that monitoring the repository through wires or fibre optic cables that would need to pass through the Engineered Barrier System (EBS) or around seals or bulkheads are unacceptable. Techniques exist for the remote transmission of data through-the-earth (TTE) telemetry – this has been referred to as "wireless" monitoring. In the context of wireless monitoring in a repository this could be the deployment of sensors within the near-field/Engineered Barrier System (EBS) that transmit data back to receivers located outside of the near-field. In contrast, in non-intrusive techniques the sensors would be located outside of the engineered barrier system and hence overcome the potential degradation in EBS performance that would result from conventional wired systems. Non-intrusive techniques also avoid the problems associated with the failure of monitoring sensors, which for conventional (intrusive) or wireless monitoring could only be renewed or replaced by disturbing the EBS.

Different non-intrusive techniques are suitable for monitoring the near-field, depending on the scale of the process to be monitored. Non-intrusive techniques carried out at the surface typically facilitate monitoring of large-scale, regional processes. Sub-surface non-intrusive monitoring tends to focus on smaller, repository scale processes, using techniques such as seismic tomography.

A number of geophysical techniques for non-intrusive monitoring of a repository were identified by Module 1 partners as candidates for further study. This section introduces the theory and application of these techniques and briefly outlines their advantages, limitations and the associated technical challenges. More detailed descriptions of a broader range of non-intrusive monitoring techniques can be found elsewhere (Albert, 2005; GSL and Golder Associates (UK) Ltd., 2004).

Several of the techniques described here, notably electrical resistivity imaging (ERI), seismic tomography and micro seismic/acoustic emission (MS/AE) monitoring were short-listed for further investigation under ESDRED Module 1. The applicability of these techniques for demonstration at a URL within Module 1 was assessed in detail (NDA, 2005b), taking account of different monitoring/measurement configurations, the expected performance and accuracy of each technique, availability of equipment for implementation of a full-scale demonstration, necessary preparatory work prior to carrying out measurements using the technique and the estimated costs of demonstrating each technique within ESDRED. The process by which seismic tomography was selected as the most appropriate technique for study in Work Package 5 is described in Section 2.3.

2.2.1 Electrical Resistivity/Impedance Imaging (ERI)

In this borehole-based technique, an external electric current is applied across a rock volume, and the resultant potential difference is measured. From this, the apparent resistivity of the material under investigation can be derived. Resistivity is indicative of material properties and conditions, so it is possible to determine the geological structure and changes in parameters such as moisture content, thermal fronts and gas migration from measurements of resistivity (NDA, 2005b). Any chemical change within the investigated area can be monitored, if it results in a change in the resistivity distribution. Methodologies employing linear electrode arrays or cross-borehole electrode set-ups can be deployed to derive resistivity measurements. ERI can also be employed as a surface-based technique (GSL and Golder Associates (UK) Ltd., 2004).

Geoelectric Resistivity Imaging is a synonymous name sometimes used to describe ERI. In some cases, this technique is also referred to as Geoelectric Tomography, although this is only an accurate description for electrode configurations where the electrical measurements can produce an image 'slice' through the sampled medium.

The presence of metal EBS components in the design concepts of the Module 1 partners is likely to complicate the acquisition and interpretation of ERI data, since these components may cause short circuits and spurious electrical noise or current flow. In addition, although ERI has been used to great effect in the study of underground environments in Canada and Germany, there are no known examples of its application in lined and backfilled tunnels, so its effectiveness in monitoring these environments is not well understood. It was therefore concluded that ERI would, to a large extent, only be applicable to the characterisation of the natural rock environment surrounding the galleries and tunnels of a repository, rather than the EBS itself (NDA, 2005b).

2.2.2 Seismic Tomography

A brief introduction to this technique and its application to the monitoring of geological repositories was provided in Section 1.3.2. The practicability of applying this technique is further discussed here.

Depending on the signal frequency employed, the distance between receiver and source locations, the separation between boreholes (and the spacing of sensors within these boreholes) and the type of medium under investigation, seismic tomography is potentially capable of resolving features on the centimetre scale (although this high resolution is more applicable to hard rocks, rather than the argillaceous media focused on within the Module 1 partners' programmes). Optimal resolutions are obtained using high frequency sources in hard rock and spacing sensors 1 m apart or less. The boreholes should be long enough to obtain sufficient ray coverage and the spacing of the receiver and source points should be smaller than half the wavelength used for the same reason. Experience indicates that fractures can be effectively imaged using seismic equipment in boreholes at a range of 10-20 m from the feature of interest.

The mechanism for coupling the signal generation with the surrounding medium and the shape of the contact area between the sensors and the borehole walls are also key considerations affecting data quality.

Seismic tomography is generally utilised to generate images of the rock mass in terms of signal velocity or attenuation, e.g., Jackson and McCann (1997). A full analysis of the acquired data can provide information on fracture and bedding orientations. Modifications to these properties caused by changes in stress fields, water content or porosity can be monitored by recording time-lapse surveys to monitor variation in the velocity of seismic waves through the rock mass. However, changes in seismic velocities over time are likely to be of low magnitude and, therefore, are challenging to detect. This problem may be compounded by the effects that changing conditions of the borehole walls and the shape of the contact area between the sensors and borehole walls over time may have on the reproducibility of data. For this reason, difference tomography or full waveform analysis (data processing methods which provide the optimal tomographic image resolution), may be preferred approaches for the study of repository system performance. In a clay-based medium, it may also be necessary to utilise anisotropic corrections in the waveform inversion process, since argillaceous rocks often have anisotropic velocity fields.

Under the ANDRA and ONDRAF/NIRAS proposed design conditions (Sections 2.1.1 and 2.1.3), it is considered that seismic tomography could only be utilised to study the natural rock environment surrounding repository galleries. This technique would therefore be applicable to study the stability of the galleries and their supporting structures (e.g., tunnel liners). Within the Nagra design (Section 2.1.2), it may also be possible to image within the gallery, for example, to monitor the performance of the buffer, although care would need to be taken in interpretation, since the presence of the waste packages could cause the presence of early arrivals in the seismic data.

2.2.3 Micro-seismic (MS) and Acoustic Emission (AE) Monitoring

Micro-seismic/acoustic emission (MS/AE) monitoring records the release of strain energy, generally due to brittle failure in the rock mass, but also associated with the movement or release of gas bubbles and/or sudden movements of fluids. This release of energy generally manifests itself as a seismic event. Events with a frequency below 100 Hz are generally termed “micro-seismic events”, whereas events with a frequency above 100 Hz are referred to as “acoustic emissions”. Events associated with the movement of gaseous or liquid species are often termed “hydraulic shock events”.

MS/AE monitoring could be employed to monitor strain energies arising due to the thermal effect of the emplaced waste and due to the generation and migration of gaseous and liquid species. The magnitude of the event, size of the failure surface (if any), the stress drop and the location of events, both spatially and temporally can be recorded using MS/AE monitoring, which allows the movement of thermal or other fronts to be mapped. Measurement accuracies are dependent on the sampling rates used to digitise the recorded data and, in the case of pinpointing the location of a seismic event, the precision with which the positions of the sensors are known. The sensors deployed as receivers for monitoring using seismic tomography may also be used to monitor MS/AE events, although this is somewhat dependent on the range of frequencies generated by seismic events, which is currently not well known for argillaceous environments. The velocity structure of the system under investigation will change over time, as a consequence of changes in saturation levels and thermal effects. These changes, which can be measured using seismic tomography, should be accounted for when monitoring MS/AE events.

To retain the passive safety of the repository, it would be necessary to deploy sensors for MS/AE in boreholes drilled in the rock surrounding the disposal drifts/galleries. These should ideally surround the feature to be monitored and should also be positioned at a number of distances away from this feature. Metal components in the EBS may act as wave guides, making it difficult to locate the source of seismic events. It is therefore likely that the ANDRA and ONDRAF/NIRAS repository design concepts would preclude the recording of MS/AE events generated within certain areas of the EBS. It may be possible to monitor MS/AE events in the backfill by deploying sensors which implement wireless data transmission within this region.

2.2.4 Seismic Reflection

In seismic reflection techniques, the energy produced by a seismic source propagates through the sub-surface and is reflected from the boundaries between features of different densities (and hence, seismic wave velocities). The reflected waves are recorded by seismometers, either geophones (in a dry environment) or hydrophones (in a fluid environment). By noting the time taken for a reflection to arrive at a receiver, the depth of different sub-surface features may be determined. Seismic reflection surveys may be undertaken using linear seismometer arrays (2D mode) or by implementing a grid of receivers (3D mode). 2D seismic reflection allows the features detected to be positioned in the plane beneath the survey line, but neglects out of-plane effects. In contrast, 3D seismic reflection employs more sophisticated signal handling and data processing techniques to reconstruct an image of the sub surface in 2D or 3D, and to estimate the correct 3D spatial location of the reflected energy.

3D seismic surveys may be repeated over time to indicate the evolution of a seismic feature, in which case, they are referred to as “time-lapse 3D” or “4D” seismic surveys. Seismic reflection techniques find widespread applications in the oil and gas industry, as well as in the mining industry, and may be applicable for non-intrusive monitoring of groundwater and gas migration in a repository following emplacement.

It is worth noting that IRSN carried out some high resolution 3-D seismic reflection tests at the Tournemire experimental station in France to investigate whether or not the method could detect secondary faults present in the mudrocks. Despite clear field evidence for the presence of these faults, which are mainly strike-slips with small vertical displacements, the seismic reflection method did not detect them (Cabrera, 2002).

2.2.5 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a surface-based technique where a pulsed electromagnetic signal (radiowave frequency) is transmitted via a tuned frequency antenna. The signal is reflected from sub-surface features and can be acquired in much the same way as described earlier for seismic reflection (Section 2.2.4). The technique is similar to seismic reflection, except that electromagnetic radiation is used instead of acoustic emissions. Reflections therefore originate from discontinuities in the electric permittivity, magnetic permeability and electric conductivity of the study area, rather than at discontinuities in the seismic wave velocity through the rock.

Under ideal conditions, GPR surveys can produce useful results over an investigation depth of several tens of metres. The signal can penetrate soil, rock, concrete, ice and other common natural and man-made materials. However, since the penetration of radar signals is proportionate to the electrical resistivity, the practicability of this technique is severely limited in soft, conductive rocks, such as argillaceous media, and where saline (conductive) groundwater is present, since these conditions lead to attenuation of the electromagnetic signal. The degree of fracturing also has a pronounced effect on the attenuation of radar signals.

Radar reflection can also be carried out as a borehole-based technique, using either a single-hole (radar reflection) or cross-hole (radar transmission) set up of the electromagnetic source and the receiver. Cross-hole arrangements also facilitate tomographic measurements to obtain distribution maps of the velocity or attenuation of radar waves. Borehole radar measurements typically implement a signal frequency of 20-1000 MHz (Albert, 2005).

2.3 Basis for Selecting Monitoring Programme

2.3.1 Selection of Seismic Tomography for Demonstration in ESDRED

This section describes the process by which seismic tomography was selected for further research and development under Work Package 5.

A workshop for the Module 1 partners was held by the NDA on 8 October 2004 to assess the way forward for the implementation of appropriate non-intrusive monitoring systems for the three geometrical configurations described in Section 2.1. The aims of the workshop were to:

- Establish from the partners, the key monitoring functional requirements and specifications for each repository design (these topics are briefly discussed in Section 2.1 of this report).
- Assess parameters and ranges to be measured and the required accuracy (also outlined in Section 2.1).
- Identify issues affecting the selection of non-intrusive monitoring systems (see Sections 2.1 and 2.2).
- Focus on key areas for the development of monitoring, to progress the work programme.

Several non-intrusive techniques were considered as candidates for further research and development under ESDRED Module 1. These included ERI, GPR, seismic tomography (implementing travel-time or full waveform inversion analysis), MS/AE and single-hole seismic reflection.

The applicability and success of different geophysical methods is attributed to the degree of resolution and penetration that the technique can offer in a given host rock. Ideally, the resolution of an effective technique should be high enough to enable detection of small-scale changes in the near-field rock and EBS of a repository tunnel. An acceptable resolution for non-intrusive repository monitoring was deemed to be on the order of 1 m or less (Albert, 2005).

In general, the resolution of a technique increases as the proximity of the equipment to the object under investigation increases. However, a key requirement of non-intrusive monitoring is that it should not affect the passive safety of the repository. Therefore, features such as boreholes should be located sufficiently far from repository tunnels to avoid any influence on the barrier function of the rock mass. On this basis, a field of study with a scale of 50 m x 50 m, centred on an emplacement tunnel was identified as appropriate to fulfil the future requirements and constraints of a repository site. Observation boreholes would be sited approximately 25 m from the emplacement tunnel.

The partners agreed that, particularly for studies in argillaceous rock environments, ERI, seismic tomography and MS/AE techniques represented the most promising non-intrusive monitoring techniques. Given the high attenuation of radar signals in conductive materials and groundwater, GPR was not considered to be a suitable option for non-intrusive monitoring in an argillaceous medium.

Following the workshop, the NDA, in liaison with Module 1 partners, developed and compiled the design configurations, performance expectations, requirements for preparatory work and outlined cost estimates for carrying out non-intrusive monitoring research under Module 1, using each of the remaining techniques (NDA, 2005b).

A second workshop for the ESDRED Module 1 partners was arranged by the NDA for 9 February 2005. The objective of this workshop was to assess the feasibility of applying non-intrusive monitoring techniques and to consider the available options against the opportunity for further investigation of wireless monitoring, in order to support a decision on which technique to take forward for study.

Following discussion between the ESDRED Module 1 partners at this meeting, it was agreed that the use of seismic techniques for monitoring was preferable and feasible within the budget and timeframe of the programme. The resolution of ERI was considered to be too low and so this option was rejected from further consideration. In addition, the risk of anomalous, erroneous or noisy data arising from short circuits of the applied current through metallic components of the EBS was considered to be high for most of the Module 1 partners' repository concepts. MS/AE techniques were considered feasible within the scope of the ESDRED programme. However, monitoring of changes in temperature, water saturation, gas and fluid migration and/or stress would only possible using this technique if changes in these properties resulted in brittle failure events. This could limit the extent of data collection, particularly within the relatively short time frame of the project. Cross-hole seismic tomography was therefore selected as the favoured non-intrusive monitoring technique for obtaining useful and reliable information for the various conceptual repository designs and addressing the range of monitoring requirements expressed by Module 1 partners.

For a 50 m x 50 m field of study, only seismic waveform methods were considered potentially able to offer the required resolution. As indicated in Table 2.1, travel-time tomography has a reduced resolution compared with full waveform tomography, which was not considered sufficient to achieve the required resolution of the order of 1 m (this was later verified by the pilot study described in Section 1.3.3). Table 2.1 indicates that full waveform inversion analysis of seismic tomographic data from studies in the Opalinus Clay, for a borehole-borehole distance of 25 m, when using a source signal frequency of 2000 Hz is expected to produce tomographic results with a resolution of up to 1.5 m.

It was therefore decided to focus research on seismic tomography, with development of waveform inversion interpretation techniques, and to place the monitoring boreholes 20 to 30 m apart, in order to maximise the resolution of the technique, whilst avoiding any effect on the passive safety of the repository system (Nagra, 2005). It was considered that the observable changes to the conditions in a URL would be relatively small, so that it may only be possible to identify these changes through time-lapse surveys.

Table 2.1: Expected resolution as a function of distance, for seismic tomography in Opalinus Clay, using comparable sources (taken from Albert, 2005).

Borehole-borehole distance (m)	Velocity (m/s)	Expected max. frequency (Hz)	Expected resolution (m)	
			Waveform inversion (λ)	Travel-time inversion √ (λ*L)
10	3000	5000	0.6	2.4
25	3000	2000	1.5	6
50	3000	1000	3	12
100	3000	500	6	24

2.3.2 Selection of Mont Terri for Demonstration of Seismic Tomography

The information compiled by the NDA (and presented in NDA, 2005b) was used to provide the technical basis for the preparation and submission of two proposals for non-intrusive monitoring studies. Two sites were identified as candidates for the investigation of non-intrusive monitoring under ESDRED Module 1:

- The HADES URL at Mol, Belgium, specifically focusing on monitoring the PRACLAY experiment, (which is outlined in Section 3.1 of this report). A proposal for non-intrusive measurement studies around the PRACLAY gallery was developed by EURIDICE (Verstricht, 2005).

- The Mont Terri rock laboratory, for monitoring of the HG-A experiment in Gallery 04. A proposal for non-intrusive monitoring experiments at the Mont Terri rock laboratory was submitted by Nagra (Nagra, 2005).

Nagra proposed to concentrate on seismic tomography with development of waveform inversion interpretation techniques and to place monitoring boreholes outside the near-field, to avoid undesirable effects on long-term performance of the repository system. At the time of the proposal, the excavation of the HG-A experiment was already complete, so additional monitoring was feasible in the short term. The timescale for completion of this study was proposed as the end of 2007.

The suggestion for non-intrusive monitoring at the PRACLAY gallery proposed to complement standard monitoring measurements during the heating of a waste disposal gallery (simulating heat output from HLW/spent fuel) with those derived using non-intrusive micro-seismic and ERI techniques. At the time of the proposal, excavation of the PRACLAY gallery had not yet been completed. It was proposed that experiments would be undertaken during three monitoring campaigns between 2006 and 2009. The timescale for this project would limit the information which could be obtained on buffer performance within the scope of the ESDRED project.

Due to the limited budget for this monitoring task, it was only possible to carry out field experiments at one site. It was considered that the proposal for non-intrusive monitoring activities at Mont Terri offered the lowest associated programme risk. In addition, the argillaceous rocks at Mont Terri are more comparable with other Module 1 partners' geological environments. The layout at Mont Terri also made locating sensors and monitoring boreholes relatively straightforward (due to sub parallel galleries). On this basis, at a Module 1 meeting on 7 June 2005, the NDA recommended, and the Module 1 partners accepted, that field tests of non-intrusive monitoring should be carried out at Mont Terri. The results of a pilot study at this location are summarised in Section 1.3.3 and the experimental set-up is described in detail in Section 3.

2.3.3 Selection of ETH to implement non-intrusive monitoring at Mont Terri

Due to the specialised nature of the seismic studies to be undertaken under this non-intrusive monitoring project, and the requirements for technical expertise with specific experimental techniques and analytical software, several organisations capable of carrying out the experimental and analytical work were approached and invited to propose a work programme for implementation. Proposals were received from ETH, Augeos (a commercial spin-off company of the ETH group) and Deutsche Montan Technologie (DMT) in Essen, Germany.

ETH was selected to undertake the non-intrusive monitoring studies, with additional technical advisory support provided by Nagra. The key considerations underlying this decision included:

- ETH's extensive experience of seismic testing and implementing full waveform analysis of seismic data.
- Access to relevant software and waveform inversion codes.
- Cost of the proposed work programme.
- Proximity to the Mont Terri, leading to reduced travel-time and costs.
- Inclusion of a dedicated PhD student in the proposal, which contributes to training and development in this field.

3 - DESCRIPTION OF WORK PROGRAMME

This section provides a description of the HG-A programme at Mont Terri and the implementation of seismic tomography to monitor this programme.

3.1 Experimental Setup of the Seismic Tomography Experiments

A schematic drawing of the experimental geometry is shown in Figure 3.1.

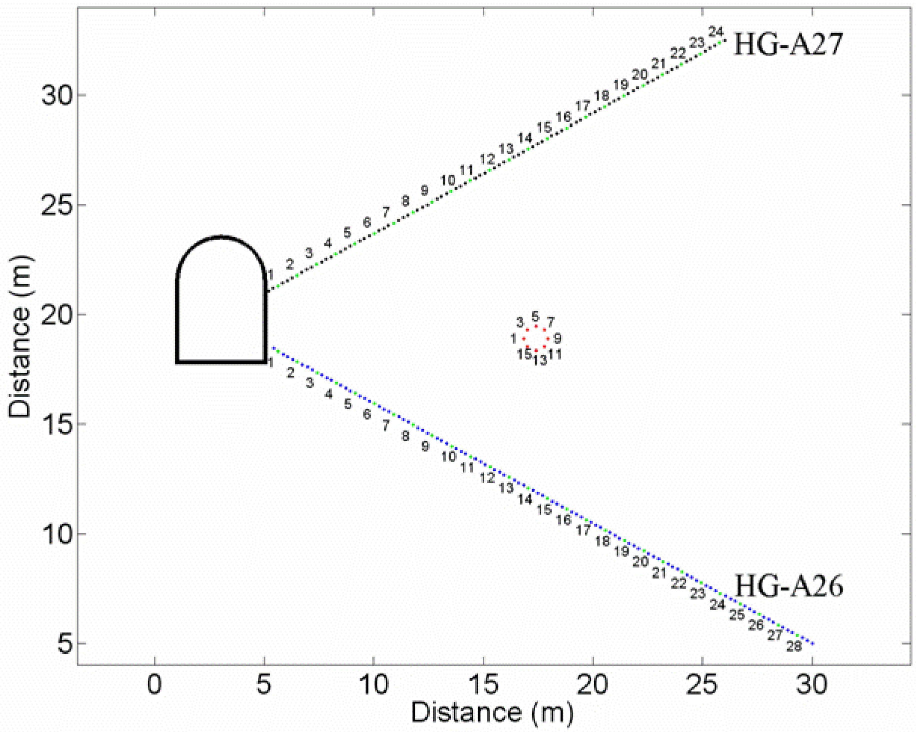

Figure 3.1: Geometrical setup of tomography experiment. Blue dots indicate source positions in borehole HG-A26, black dots indicate receiver positions in borehole HG-A27 and red dots indicate receiver positions on the wall of micro-tunnel HG-A. The source and hydrophone spacing is 0.25 m (full meters are labelled and marked with green dots).

Investigations in the HG-A experiment focus on a 1 m-diameter micro-tunnel, which is back-filled with a coarse-grained sand mixture and closed with a hydraulic mega-packer. There is nothing in the tunnel to represent the wasteform or a metallic waste package. For the non-intrusive studies, the degree of saturation, gas storage and pressure build-up, and its effects on the geophysical data is monitored over the various phases of the HG-A experiment, using cross-hole seismic tomography. The aim of the experiments was to investigate differences in the seismic data due to variations within the micro-tunnel (both its content and physical condition).

Two inclined and diverging boreholes (HG-A26 and HG-A27) straddle the HG-A micro-tunnel. The boreholes have a finished diameter (after grouting and reaming) of 85 mm. Seismic waves were generated in borehole HG-A26 using a high-frequency sparker source (effectively a "giant spark plug"; Figure 3.3). The mechanical energy created by the ignition of the sparker was transferred via the fluid in the borehole to the host rock. Seismic data were recorded using a 24-channel hydrophone chain (a form of streamer;

Figure 3.4) emplaced in borehole HG-A27. The micro-tunnel diameter and the distances to the boreholes were chosen for practical development of the seismic tomography technique and to be representative of possible seismic monitoring set-ups that could be employed in a repository.

The sparker and the hydrophone chain required the boreholes to be water filled which created sealing problems for the upward-directed HG-A27 borehole. It was solved by employing a specially designed borehole sealing cap that includes connectors for the cables and water hose (Figure 3.5a and 3.5b). The hydrophone chain was positioned in the upper borehole using a hook and pulley at the end of the hole. Despite several technical improvements, sealing of the upward directed borehole HG-A27 turned out to be problematic. The problem was solved by placing the hydrophone chain in a plastic liner. This ensured a more consistent positioning of the hydrophones, and offered better options to seal the borehole collar (Figure 3.5c).

To gain additional insight about the effects of the different micro-tunnel infill materials on the seismic waveforms, eight vertical-component geophones were installed directly in the micro-tunnel (Figure 3.6). Such wired measuring devices would be not an option for an actual repository, but should the tunnel geophones produce useful data, the possibility of developing wireless and self-sustaining seismic sensors may be considered.

3.2 Measurement campaigns

3.2.1 Overview of the seismic experiments

Several surveys have been conducted to date (see Table 3.1). In each experiment the high frequency sparker source was fired every 0.25 m in the downward-directed borehole HG-A26, and the seismic waves were recorded on a 24-channel hydrophone array located in the upward-directed borehole HG-A27. The hydrophones were spaced at 1 m intervals. By shifting the hydrophone array three times at intervals of 0.25 m and repeating each shot, a 96-channel hydrophone array with 0.25 m element spacing was synthesized. Each shot was also recorded by the eight vertical-component geophones installed in the micro-tunnel.

Table 3.1 summarizes the measurement campaigns that have been undertaken to date and the measurement campaigns planned for the future monitoring of the gas injection experiment. After the pilot study MT_E1, additional tests were performed during survey MT_E2, while the micro-tunnel was still empty. Then, the micro-tunnel was filled with sand and closed with a mega-packer. After the emplacement of the sand, survey MT_E3 was conducted.

- On 9 October 2006, the micro-tunnel was saturated with water. Prior to the watering, survey MT_E4 was performed to check the repeatability of the measurements (to be compared with MT_E3). Survey MT_E5 was conducted after about 50% water saturation, and MT_E6 was carried out when the micro-tunnel was believed to be fully saturated, although is was discovered later that the micro-tunnel was only partially saturated during this test. Survey MT_E8 was undertaken 8 months later, when the tunnel was effectively water saturated. A further set of measurements was performed after a water over-pressurization of 5 bars (MT_E8). Gas injections are scheduled to be undertaken during in 2009 and it is planned to monitor this phase of the experiment with seismic measurements outside of ESDRED. This report will be updated to include the results of these campaigns and the analysis.

Figure 3.3: Sparker and capacitor discharging unit employed in this project.

Figure 3.4: 24 channel hydrophone chain employed in this project.

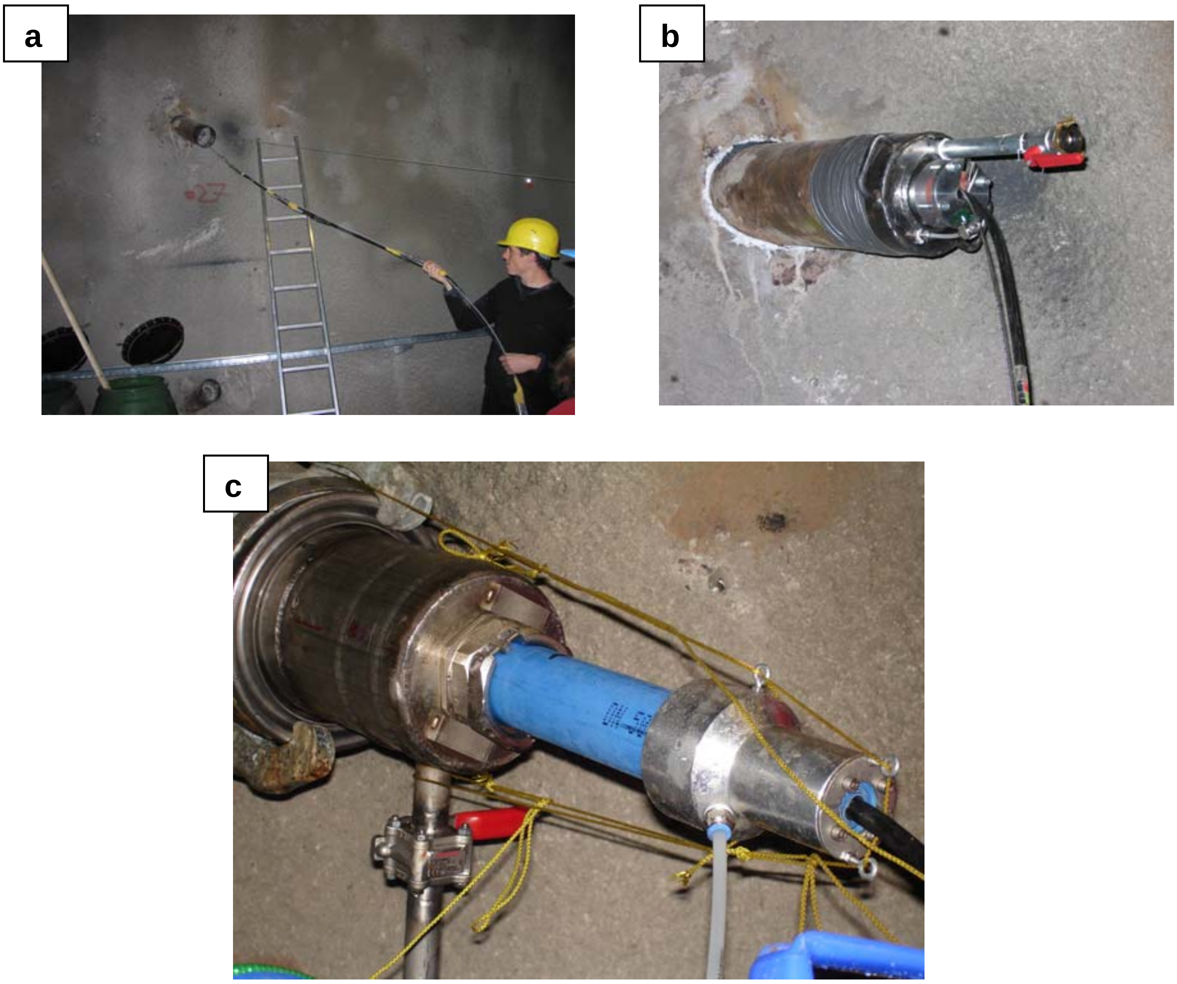

Figure 3.5: a) Insertion of the hydrophone chain into borehole HG-A27. b) Sealing cap of borehole HG-A27 (Photos provided by M. Johnson (NDA)). c) The improved sealing cap (Photos provided by B. Frieg, NAGRA).

Figure 3.6: Vertical-component geophones of the type installed in the micro-tunnel.

Table 3.1: Overview of the seismic experiments performed or planned during the HG-A experiment.

Date	Experiment ID	Description
Nov 23 – Nov 24, 2005	MT_E1	Pilot study (Maurer, 2006)
March 20, 2006	MT_E2	Empty tunnel
Sept 27, 2006	MT_E3	Tunnel filled with sand, dry
Oct 9, 2006	MT_E4	As for MT_E3
Oct 9, 2006	MT_E5	50% water saturated
Oct 9, 2006	MT_E6	Apparently 100% water saturated
June 13, 2007	MT_E7	Effectively 100% water saturated
Oct 13, 2007	MT_E8	After water injection experiments (5 bar)
Planned mid, 2009	MT_E9	Prior to gas injection
Planned mid, 2009	MT_E10	Shortly after gas injection
Planned end 2009	MT_E11	6 months after gas injection

3.2.2 Outline of PhD Project

Data acquisition and processing are being carried out in the framework of the PhD project conducted within the Applied and Environmental Geophysics Group (AUG) at ETH Zurich. Here is a brief summary of the main research objectives.

1. Development of a suitable data acquisition procedure (completed).
2. Travel-time analysis of the first arriving wave trains (completed).
3. Initial analyses of the effects on the seismic waveforms caused by changing experimental conditions (completed).
4. Development of an anisotropic time-domain forward modelling algorithm suitable for simulating seismic waveforms (completed).
5. Development of an anisotropic frequency-domain 2.5D modelling algorithm suitable for tomographic waveform inversions (underway).
6. Development of a waveform inversion algorithm that simultaneously inverts for the elastic medium parameters, source signature and variable receiver coupling (underway).

7. Inversion of the borehole hydrophone data for determining the Opalinus Clay properties (yet to be carried out).

8. Inversion of the tunnel geophone data for determining changes within the micro-tunnel (yet to be carried out).

A PhD thesis of the AUG group typically includes 3 journal article publications embedded between a general introduction and a conclusion/outlook chapter. A first journal publication on the experimental setup, anisotropic travel-time inversions and initial data analyses is currently being prepared. A second publication will focus on the development of the anisotropic 2.5D modelling and inversion schemes. The third journal publication will report on the tomographic waveform inversions of the Mont Terri data sets. These methodological publications will be submitted to peer-reviewed international geophysical journals. Further publications may be written for engineering journals, which will focus on the results of the project rather than the methodology.

4 - DATA ANALYSIS

4.1 Waveform quality appraisal

4.1.1 Source and receiver spacings

Initially, in survey MT_E1, source and receiver spacings of 0.5 m were used. During experiment MT_E2, the impact of decreasing the spacings from 0.5 to 0.25 m on wavefield sampling was checked. Figure 4.1 demonstrates that subtle changes of the waveforms can be traced much better with 0.25 m sampling. For example, in Figure 4.1a at a distance of about 4 m only a single trace shows slight anomalies near the first arriving wave train, but Figure 4.1b reveals that this anomaly extends over several traces.

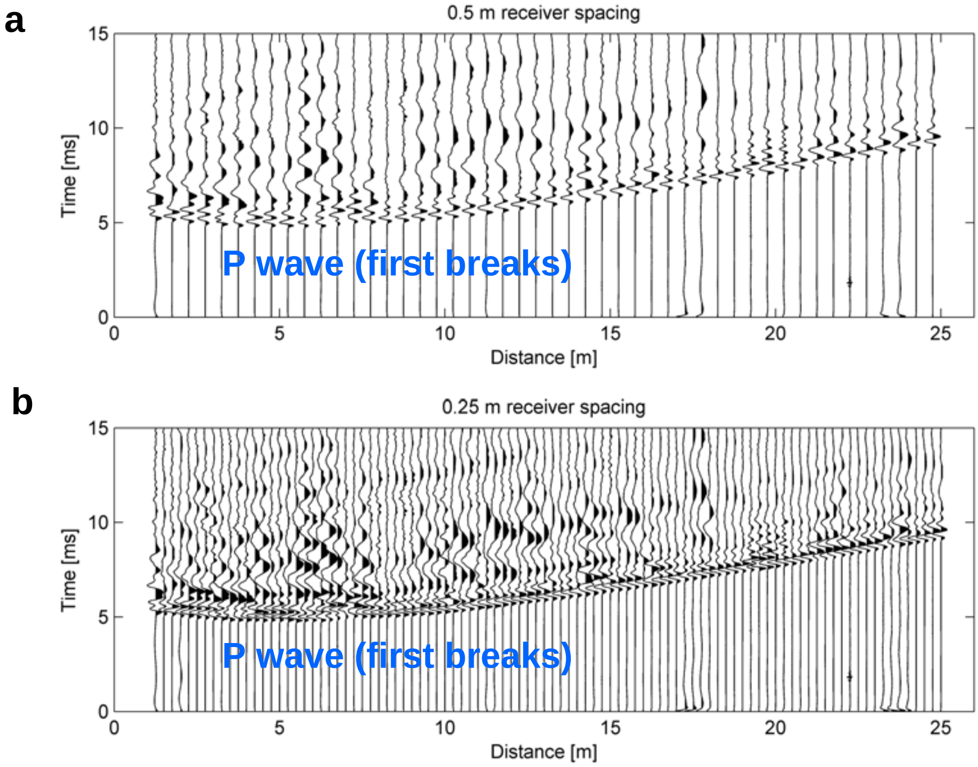

Figure 4.1: Shot gather from campaign MT_E2 with a) simulated 0.5 m receiver spacing. b) same as a), but all traces included (0.25 m spacing).

4.1.2 Reciprocity check

Initial inspections of the data revealed that shot gathers (all recordings of a single shot) and receiver gathers (all recordings of a single receiver) exhibit substantially different spatial continuity.

As shown in Figure 4.2a, the shapes of the seismograms vary quite erratically between adjacent receivers. By contrast, recordings of a single receiver and all shots (Figure 4.2b) exhibit much better continuity. By means of a reciprocity test, i.e. placing the source in the receiver borehole and the hydrophone streamer in the source borehole, it was investigated, if these discrepancies were caused by variable receiver coupling or if they are the result of the geological layering. The reciprocal shot gather is shown in Figure 4.2c. It is at best moderately similar to the corresponding receiver gather in Figure 4.2b. This indicates that both the geology and the receiver coupling influence the recordings and must be considered in future full-waveform inversions.

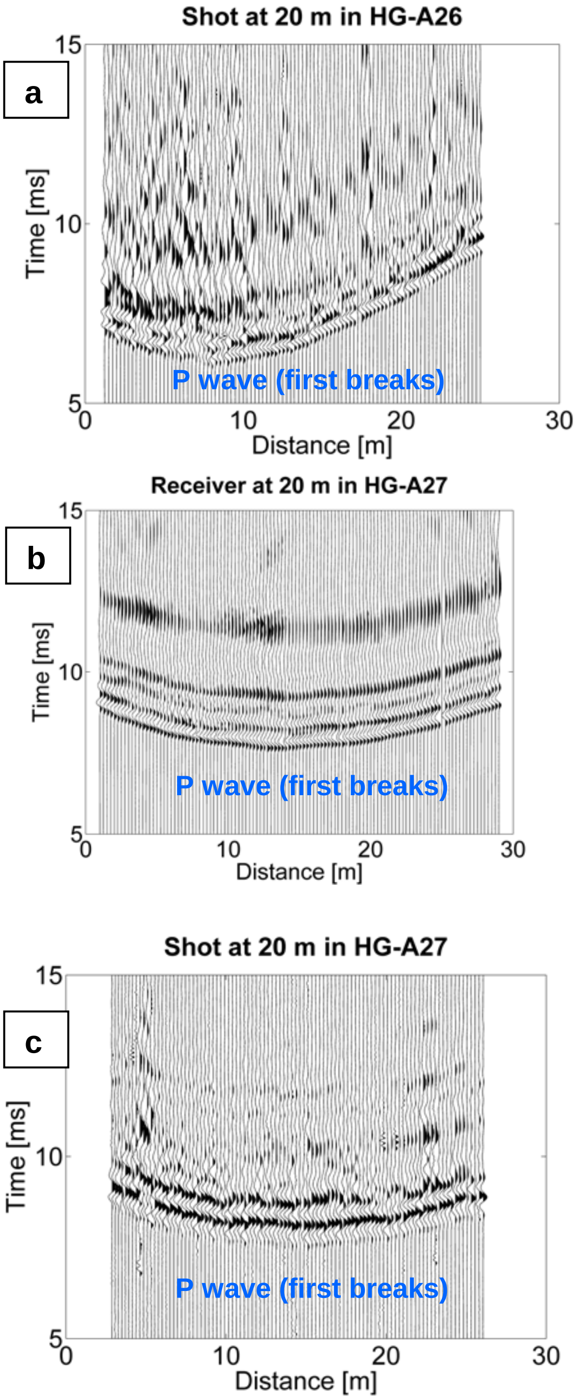

Figure 4.2: Results of reciprocity tests. a) shows a shot gather from a shot at a distance of 20 m in borehole HG-A26, b) shows a receiver gather from a hydrophone at 20 m distance in borehole HG-A27 and c) shows a shot gather from a shot at 20 m distance in borehole HG-A27.

4.1.3 Source repeatability

Monitoring with seismic tomography requires highly repeatable measurements. Both the source pulse (including its coupling) and the coupling of the receivers must be consistent throughout all experiments. Source repeatability is demonstrated in Figure 4.3. Four shots were fired at the same position then the source was moved to the next position and the process continued until the source borehole was fully occupied. The entire process was carried out four times, on every occasion that the hydrophone streamer was shifted by 0.25 m. This experimental set-up results in 16 seismograms being recorded at each geophone for the same source position (four times 4 back-to-back shots). Figure 4.3a shows recordings of one geophone (G5) for the source at a distance of 20 m. The 16 traces show a high consistency, both visually and as determined by cross-correlation analysis. This confirms the excellent repeatability of the sparker source.

Figure 4.3b shows recordings for 4 shots fired at the same position and a hydrophone placed at a distance of 20 m. The source and the hydrophone were not moved between the individual shots. Again, the signals are very consistent over the timescale of the experiment.

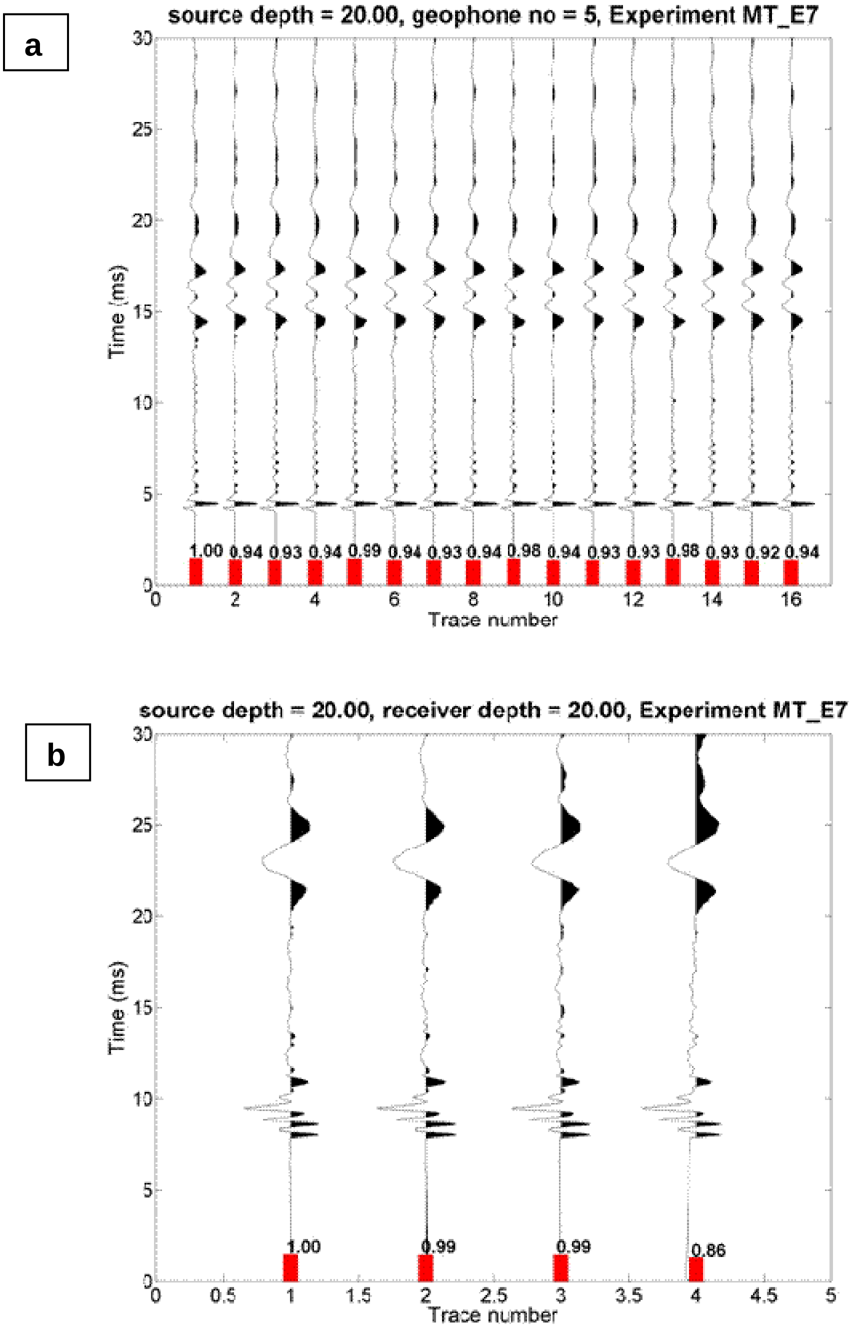

Figure 4.3: a) Recordings from tunnel geophone 5 during experiment MT_E7. b) Recordings from a hydrophone at a distance of 20 m recorded during experiment MT_E7. Numbers at the bottom indicate cross-correlation coefficients with respect to first trace of each figure.

4.1.4 Receiver coupling

4.1.4.1 Repeatability of tunnel geophone recordings

Experiments with the dry, sand-filled micro-tunnel were carried out twice (MT_E3 and MT_E4, see Table 1). This was to check that the geophone response remains stable between experiments. Figure 4.4a demonstrates that this is indeed the case. In fact, this test is again clear verification that the source characteristics remain stable between experiments.

4.1.4.2 Repeatability of borehole hydrophone recordings

Unfortunately, the hydrophone repeatability is more problematic. Figure 4.4b shows recordings for a single hydrophone for experiments MT_E3 and MT_E4. The signal characteristics change significantly, although the experimental conditions remain unchanged. These variable coupling conditions must be considered during the waveform inversion to be carried out later.

The difference concerning the coupling consistency between tunnel geophones and borehole hydrophones is also documented in Figure 4.5. Figures 4.5a and 4.5c show receiver gathers for tunnel geophone G9 recorded during experiments MT_E3 and MT_E4, and Figures 4.5b and 4.5d display the corresponding receiver gathers for a hydrophone in HG-A27 at a distance of 10 m along the borehole. As expected, there are virtually no differences for the tunnel geophone recordings between experiments MT_E3 and MT_E4. However, the corresponding sections for the borehole hydrophones exhibit significant variations.

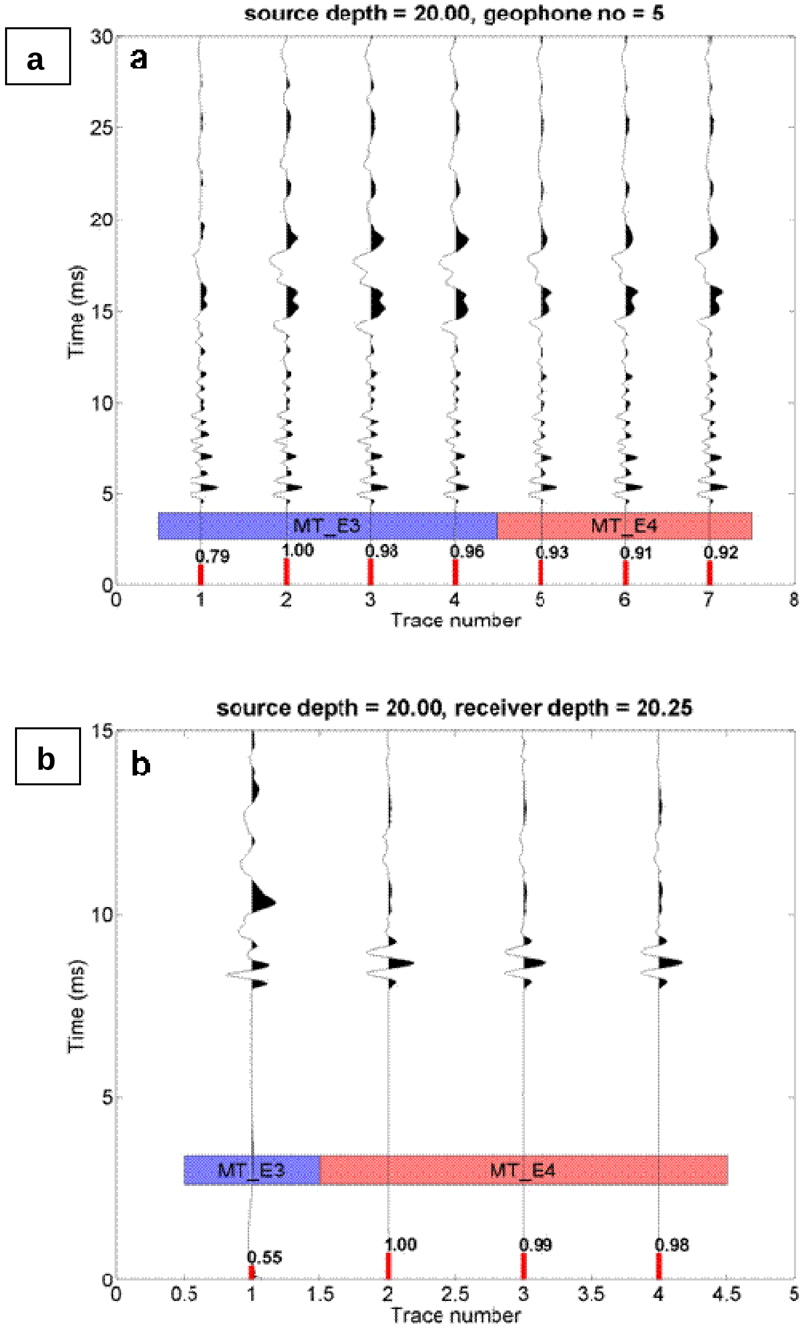

Figure 4.4: a) Recordings from tunnel geophone 5 during experiments MT_E3 (traces 1 to 4) and MT_E4 (traces 5 to 7). b) Recording from a hydrophone during experiments MT_E3 (trace 1) and MT_E4 (traces 2 to 4). Numbers at the bottom indicate cross-correlation coefficients with respect to trace 2 of each figure.

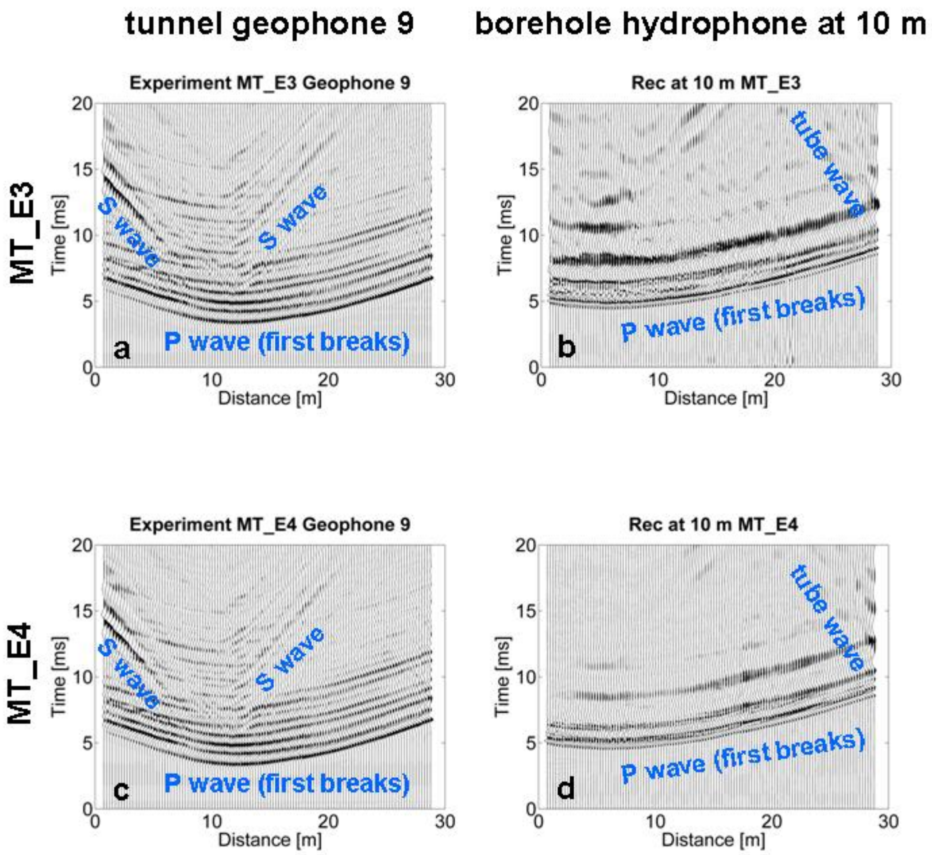

Figure 4.5: Receiver gathers for geophone 9 (left panels) and hydrophone at a distance of 10 m (right panels) for experiments MT_E3 (top panels) and MT_E4 (bottom panels).

4.1.5 Frequency content

Initial inspection indicated that the recorded data were characterized by a surprisingly wide band of frequencies. However, seismic sections generated by sources at exactly the same position and recorded by a fixed-location hydrophone streamer revealed the presence of incoherent high frequency energy. This was examined quantitatively by performing a coherency analysis of data generated 4 times at every source position and recorded with the geophones in the micro-tunnel and the hydrophones in borehole HG-A26. The cross-correlation is a measure of the similarity of the two waveforms (e.g. Tokhi *et al.*, 2003).

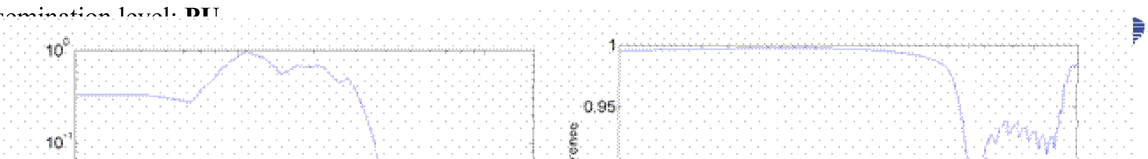

Figure 4.6: Frequency content (left panel) and coherence (right panels) for tunnel geophones (top panels) and hydrophones (bottom panels) for repeated shots of experiment MT_E7.

The averaged amplitude spectrum for all sources and tunnel geophones is plotted in Figure 4.6a, and the corresponding averaged coherence results are displayed in Figure 4.6b. The corresponding graphs for the borehole hydrophones are shown in Figures 4.6c and 4.6d. Suitable frequencies to use for imaging should exhibit both high amplitudes and high coherence values. Such a frequency band extends from approx. 0.5 kHz to 3 kHz for the tunnel geophones and from approx. 1 kHz to 3 kHz for the hydrophones. Knowledge of these frequency bands is critical for designing the waveform inversion algorithms. The relatively narrow frequency band of high coherence for the hydrophones (Figure 4.6.d) is surprising and the subject of ongoing investigations.

4.1.6 Summary and consequences of waveform quality appraisals

Extensive instrumental tests and waveform analyses have led to several important conclusions for implementing an active seismic monitoring system in a radioactive waste repository. The sparker source is capable of producing significant energy and well-repeatable signals in a frequency band up to 3 kHz. This corresponds to minimum wavelengths of less than a metre in the Opalinus Clay host rock, and even shorter wavelengths in the micro-tunnel. Considering that the spatial resolution of waveform inversions (discussed in the next section) is roughly half a wavelength, it can be concluded that the sparker source is a suitable tool for active monitoring of the HG-A experiment.

Problems have been identified with the coupling of the hydrophones to the host rock. Slight changes of the positioning of the hydrophone chain seem to lead to significant changes of the waveforms. There are two possible solutions to this problem for monitoring of the HG-A experiment. The sensors could be firmly grouted into the borehole, which would guarantee constant coupling conditions. Alternatively, variable coupling can be considered during the waveform inversion process, by treating the coupling of the individual hydrophones as additional unknowns during the inversions. The latter option will be further investigated in the framework of a PhD project at ETH Zurich.

4.2 Anisotropic travel-time inversions

Initially, anisotropy effects were accounted for in the computation of seismic travel-time tomograms by application of a correction scheme (Maurer, 2006). These travel-time inversions were repeated with a truly anisotropic inversion code (Zhou and Greenhalgh, 2008). This software inverts the travel-times of the first arriving P-waves for the elasticity tensor. We have also converted the results to the more intuitive Thomsen parameters (Thomsen, 1986) *delta* (δ) (Figure 4.7a) and *epsilon* (ε) (Figure 4.7b), the slow (Figure 4.7c) and fast (Figure 4.7d) P-wave velocities (parallel and perpendicular to the symmetry axis, respectively) and the S-wave velocities parallel to the symmetry axis (Figure 4.7e). Additionally, the data were inverted for the orientation angle of the symmetry axis (Figure 4.7f), which is the axis perpendicular to the modelled plane of isotropy in which wave speed remains constant.

The Thomsen parameters are contained in the model for weak anisotropy, which is applicable for materials such as the Mont Terri Opalinus Clay:

(1) $$v(\theta) = v_{\min}(1 + \delta \sin^2(\theta - \varphi)\cos^2(\theta - \varphi) + \varepsilon \sin^4(\theta - \varphi)).$$

$v(\theta)$ is the P-wave velocity as a function of the ray angle θ, v_{min} is the slowest velocity, φ is the direction of v_{min}, and δ and ε are the Thomsen anisotropy parameters. At small angles $(\theta - \varphi)$ parameter δ dominates, whereas ε dominates at large angles $(\theta - \varphi)$. In the case of $\delta = \varepsilon$, equation (1) reduces to a purely elliptical anisotropy:

(2) $$v(\theta) = v_{\min}(1 + \varepsilon \sin^2(\theta - \varphi)).$$

The degree of anisotropy in seismic velocities (Figures 4.7a and 4.7b) seems to vary significantly in the Opalinus Clay and the velocities are generally higher further away from the main tunnel. This latter is probably the combined effect of the excavation damage zone of the main tunnel and changes in the lithology of the Opalinus Clay. The overall modelled variation of the direction of the symmetry axis is fairly constant. Most of the values lie within a few degrees. As with the initial tomogram shown in Maurer (2006) travel-time tomography is unable to detect and delineate the micro-tunnel.

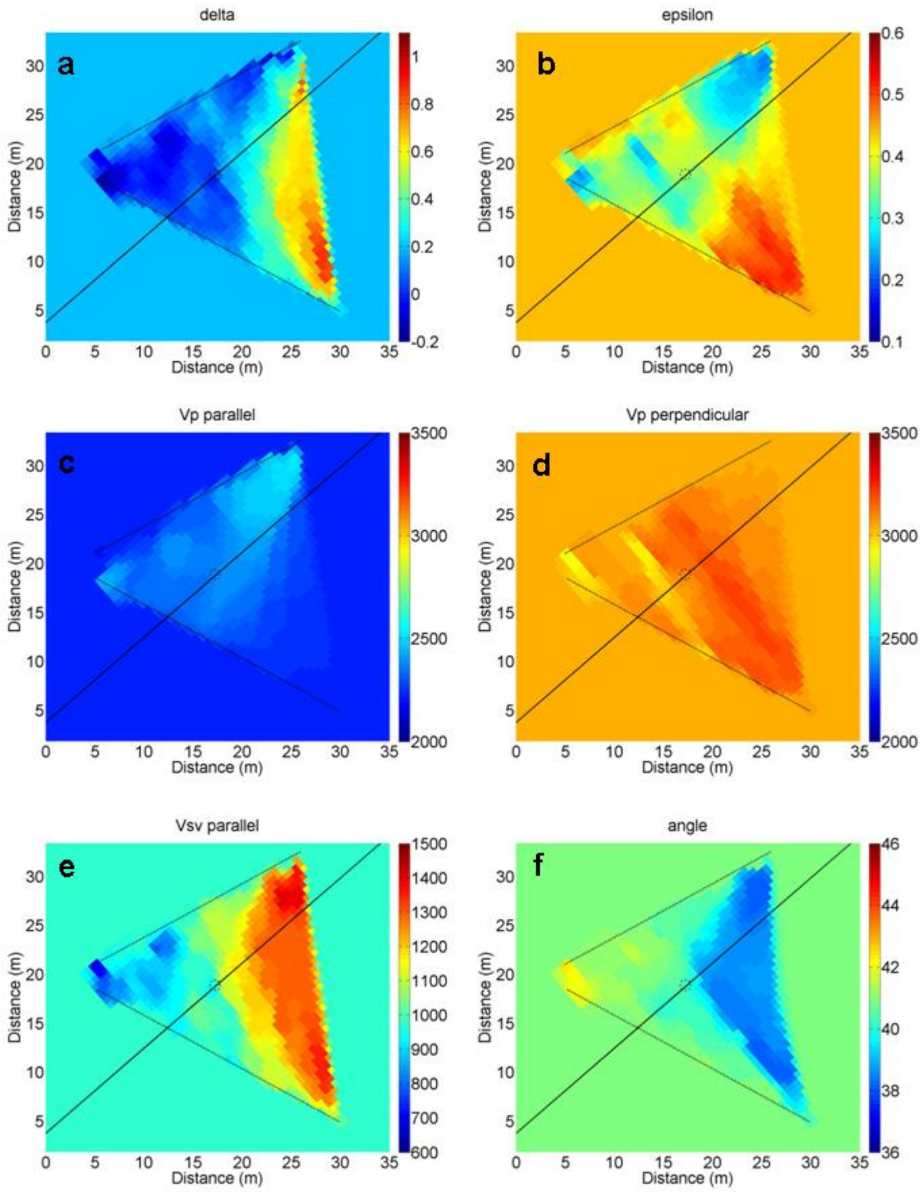

Figure 4.7: Results from anisotropic travel-time inversions. The individual parameters are indicated at the top of each tomogram.

4.3 Tunnel geophone analyses

Recordings from the micro-tunnel geophones show significant differences as the experimental conditions are varied. We see variations not only in the travel-times but also in the polarity and character of the first arrivals. Figure 4.8 displays early portions of seismograms from geophones G15 and G7, with the source at the 10 m position S10 (see Figure 4.9), for six experiments MT_E2, MT_E3, MT_E5, MT_E6, MT_E7 and MT_E8.

For experiment MT_E2 (empty micro-tunnel), the geophones were only poorly coupled to the micro-tunnel, yielding unreliable seismograms. Figure 4.8a shows that G15 seismograms are very similar for experiments MT_E3, MT_E5, and MT_E6, indicating that the micro-tunnel excavation damage zone (EDZ) changes little as a result of nearly saturating the sand filling in the micro-tunnel. In contrast, the G15 arrival times and waveforms for experiments MT_E7 and MT_E8 are quite different from those of experiments MT_E3, MT_E5, and MT_E6. A likely reason is that for the last two experiments the micro-tunnel was fully saturated for a long time, allowing water to enter its EDZ. This probably led to swelling of the clay (Bossart and Nussbaum, 2006), which in turn resulted in water being pushed under pressure into the micro-tunnel EDZ; such an increase in water content would result in increases seismic velocities within the micro-tunnel EDZ.

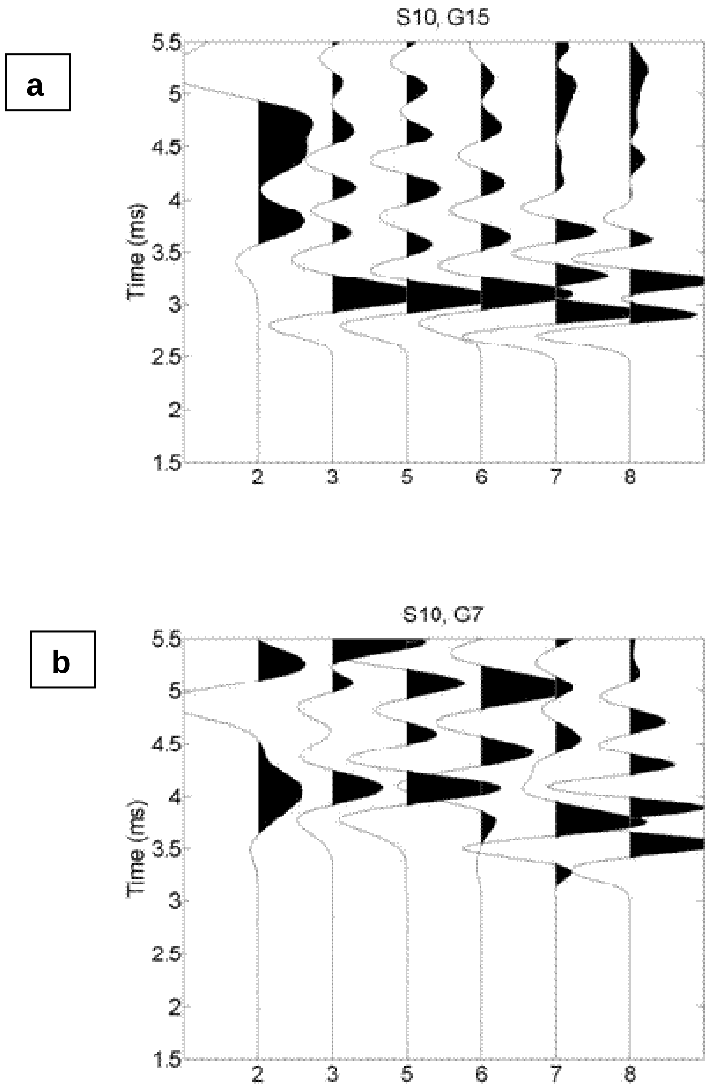

Figure 4.8: Portions around the first break from seismograms recorded with geophones (a) 15 and (b) 7. Traces correspond to experiment numbers MT_E2 (empty), MT_E3 (sand filled, dry), MT_E5 (partially saturated), MT_E6 (nearly fully saturated), MT_E7 (fully saturated), MT_E8 (after first gas injections).

Significant waveform and travel-time changes from experiment to experiment at geophone G7 (top of the micro-tunnel) can be attributed to the superposition of two waves which follow slightly different paths (Figure 4.8b): one wave passes directly through the micro-tunnel and therefore is influenced by the fill material; the other wave is diffracted around the micro-tunnel and is thus influenced primarily by the EDZ. The first wave to arrive depends on geophone location (i.e. top, side or bottom of the micro-tunnel) as well as the state of the micro-tunnel and its EDZ. Waves travelling directly through the micro-tunnel strike the upper vertical-component geophones from below, whereas waves travelling around the micro-tunnel wall strike the upper geophones from above, thus providing the potential for polarity changes and marked amplitude variations that depend on the arrival times of each wave segment. Such polarity changes and amplitude variations are illustrated in Figure 4.8b. Our interpretation of Figures 4.8a and 4.8b are supported by Figure 4.10, which shows complete geophone gathers for G15 (left column) and G7 (right column) for experiments MT_E3 (top), MT_E5 (middle), and MT_E7 (bottom). These gathers show the uniform polarities and amplitudes of first arrivals at G15 and the variable character of first arrivals at G7, the latter depending on source positions and experimental conditions.

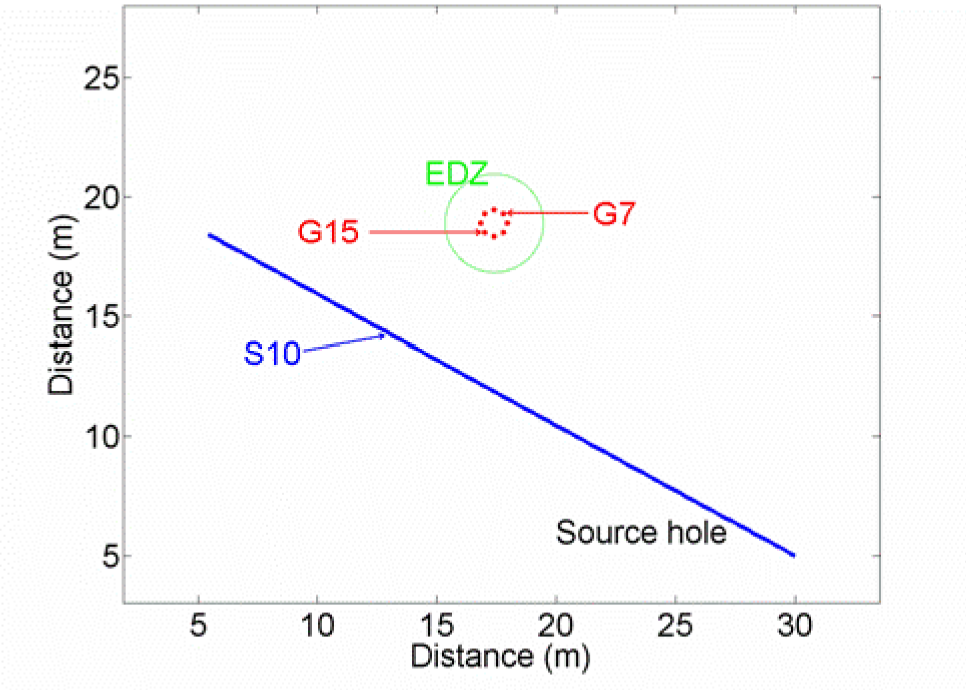

Figure 4.9: Experimental setup showing positions of the source at 10 m length along the borehole (S10), geophones 7 (G7) and 15 (G15) and a sketch of the micro-tunnel EDZ.

Since differences observed at geophone G15 can only be attributed to changes in the micro-tunnel EDZ, we have attempted to determine information about this zone from the corresponding travel-time data. Using a straight ray approximation, the travel-time difference Δt of first arrivals between the experiments 2 and 5 can be expressed by the equation:

(3) $$\Delta t = s(r)\ (1 - 1 / \beta) / v,$$

where v is the velocity of Opalinus Clay in the micro-tunnel EDZ under dry conditions, β is the fractional increase of velocity in the EDZ caused by the presence of water, r is the width of the EDZ, and $s(r)$ is the length of ray that passes through the EDZ (Figure 4.11a).

By varying β and r systematically, we attempted to find an optimal combination of the two parameters that explained all observed travel-time differences. As shown in Figure 4.11b, there exists a clear trade-off between β and r minimising the misfit, such that *a priori* information on one of the two parameters is required for a unique solution.

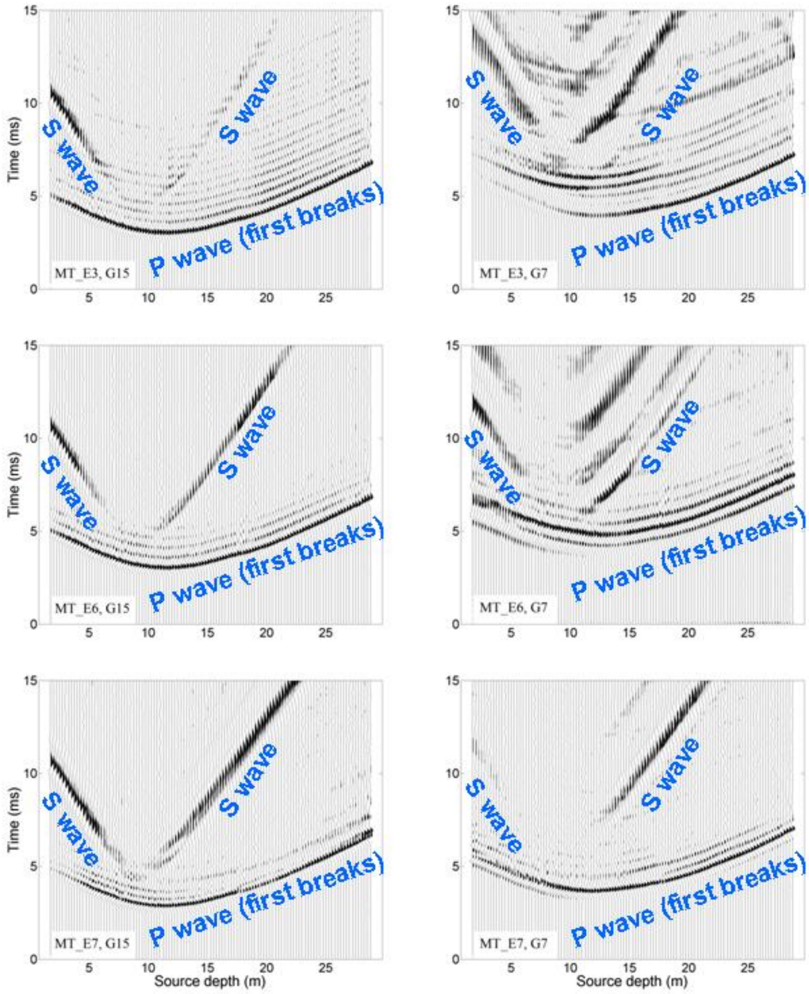

Figure 4.10: Receiver gathers for G15 (left panels) and G7 (right panels) under different experimental conditions. They correspond to experiments with a dry sand-filled (MT_E3), nearly fully water-saturated sand-filled (MT_E6), and fully water-saturated sand-filled (MT_E7) micro-tunnel (from top to bottom).

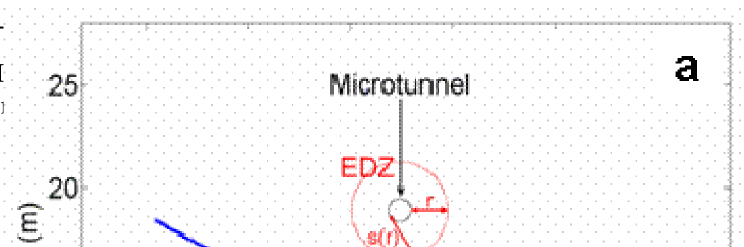

Figure 4.11: a) Straight-ray approximation: First arriving wave propagating from the source to the geophone along an approximately straight line has a lower velocity inside the EDZ (red section of the ray). b) RMS errors [ms] between observed travel-time differences (experiments MT_E3 and MT_E7) for all source positions, and the predicted differences based on equation (3).

4.4 Initial modelling results

The velocity structure shown in Figure 4.7 was used as input for an elastic waveform simulation (Bohlen, 2002), which mimics radiation of seismic waves in a representative medium.

Figure 4.12 shows first results of the modelling study. It includes a geophone gather for geophone 13. The simulations are able to explain the first arriving P-waves accurately. Prominent later phases include converted S-waves (initially radiated as P-waves and then converted to S-waves when hitting the micro-tunnel). Some of them can be associated with each other in the observed and simulated sections. Further work will focus on attempting to use iterative forward modelling to achieve a better match. In particular, attention will be focussed on modelling the significant changes in the geophone gathers shown in Figure 4.10. Finally, the match between observed and simulated seismograms will be improved by performing full waveform inversions.

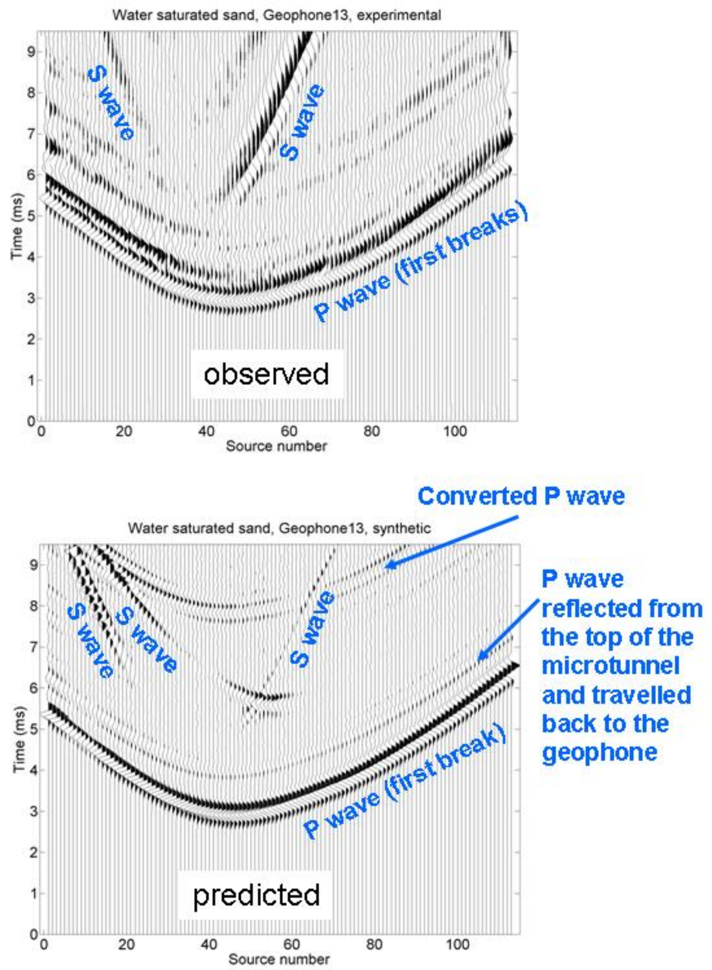

Figure 4.12: Comparison of observed data and predicted data for the model shown in Figure 4.7, using a 2D time-domain elastic modelling code.

4.5 Waveform inversion strategy

Although travel-time tomography is usually an effective technique for determining seismic velocities between boreholes, it only incorporates a small portion of the information contained in the seismic recordings (i.e. the travel-times of the first arriving energy). In contrast, because full-waveform inversion schemes exploit all information contained in the recordings, they usually provide higher-resolution details of the velocity structure (e.g. Pratt, 1999). Figure 4.13 shows the results of applying travel-time and full-waveform tomography to a synthetic cross-hole radar data set (radar waves are the electromagnetic equivalent of seismic waves; Ernst, Holliger and Maurer, 2005). There are two low-velocity features in the true model (Figure 4.13a). The relatively large feature is well delineated in the travel-time tomogram of Figure 4.13b, whereas the smaller one is barely visible. By comparison, the full-waveform tomogram has allowed both features to be well resolved (Figure 4.13c). Note that the size of the small feature in Figure 4.13 as a fraction of the dominant georadar wavelength is comparable to the size of the micro-tunnel as a fraction of the dominant seismic wavelength in the Mont Terri experiments.

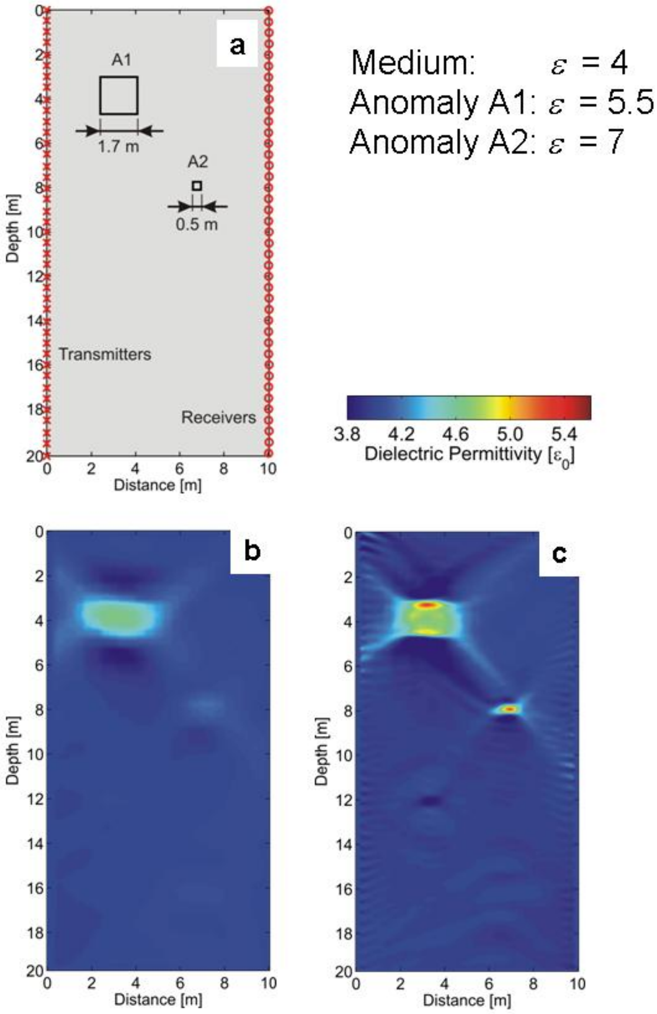

Figure 4.13: Comparison between the results of travel-time and full-waveform tomography based on a synthetic cross-hole radar data set (Ernst, Holliger and Maurer, 2005). a) Geometry of the true model. b) Results from travel-time tomography. c) Results from full-waveform tomography.

Seismic waveforms generated in borehole HG-A26 and recorded either in borehole HG-A27 or with the tunnel geophones are affected by the properties of the Opalinus Clay and the infill material of the micro-tunnel. Furthermore, the source signature, its radiation pattern and coupling, as well as the receiver characteristics and coupling, need to be known for accurate predictions of the seismic waveforms observed.

In a first step, the material properties of the Opalinus Clay will be determined. For that purpose, data set MT_E2 will be considered. Without any *a priori* information it would be quite challenging to find a reliable model of the host rock. However, there exists extensive information on the general layering of the Opalinus Clay. All the *a priori* information will be added as constraints for the inversion of the data set MT_E2. Besides determining the Opalinus Clay properties, the inversion will also yield estimates of the source signature and the coupling conditions of the hydrophones and the tunnel geophones to the host rock.

Once a reliable Opalinus Clay model is available, the waveforms recorded with the tunnel geophones will be employed for identifying temporal changes. Unknown quantities to be solved for in these inversions will include (i) material parameters of the micro-tunnel infill material and (ii) material properties of the EDZ surrounding the micro-tunnel. Coupling conditions of the tunnel geophones and the source signature are expected to remain constant (i.e. values determined with data set MT_E2 will be used throughout).

As shown in Figure 4.8, variations of the waveforms of the tunnel geophones are quite substantial. By contrast, variations of hydrophone data caused by the changes in the micro-tunnel are expected to be rather subtle. Figure 4.5 indicates that changes observed in the hydrophone data are most likely the result of variable hydrophone coupling. As a first step, data sets MT_E3 to MT_E11 will be inverted only for the hydrophone coupling parameters. Source signatures and material parameters will be taken from the inversions of the MT_E2 data set. If the observed and predicted waveforms exhibit significant discrepancies that cannot be explained solely by variable coupling conditions, the hydrophone data will be included in the inversions for the micro-tunnel infill material as well. These aspects are the subject of the ongoing PhD and will be completed outside the timescale of ESDRED project. However, on completion of the work this report will be updated to include the findings of the monitoring programme and PhD.

5 - CONCLUSIONS AND RECOMMENDATIONS

Seismic tomography experiments at the Mont Terri rock laboratory and investigations in the framework of a PhD project at ETH Zurich have allowed a preliminary evaluation of the applicability of seismic tomography as a repository monitoring technique. The experiments have been used to investigate key issues associated with the application of seismic tomography and to develop recommendations for further research. Some of these issues will be addressed through the ongoing PhD. Other issues will need to be addressed by further developments to seismic tomography technology or through further specification of monitoring objectives and strategies.

In this section we identify the achievements, outstanding issues and recommendations from the research conducted under ESDRED Module 1, Work package 5 – Testing Non-intrusive Monitoring Systems.

5.1 Achievements

1. A review of the requirements of monitoring in national waste disposal projects and an assessment of available monitoring techniques against these requirements was conducted. This led to identification of seismic tomography as the most promising technique for conducting non-intrusive monitoring for the designs and host geologies considered.

2. The sparker source proved to be a suitable option for non-intrusive monitoring of the HG-A experiment with seismic tomography. It produced well-repeatable waveforms in a frequency band up to 3 kHz. This will allow waveform inversions to be conducted with sufficient spatial resolution.

3. Anisotropic travel-time tomography using data sets from the Mont Terri test site allowed the elastic properties of the Opalinus clay host rock to be delineated. A high degree of anisotropy (up to 30%) could be identified.

4. Additional geophones placed within the HGA micro-tunnel proved to be of significant value to the project. Data recorded by the geophones allowed the changes within the micro-tunnel and in the excavation damage zone around the micro-tunnel to be identified.

5. Results from cross-hole travel-time inversions were unable to detect differences associated with saturation of the micro-tunnel. This indicates that full waveform analysis is required for non-intrusive repository monitoring. Development of an anisotropic frequency-domain 2.5D modelling algorithm suitable for tomographic waveform inversions is being progressed. This work will however be completed outside of the ESDRED project programme. NDA commit to provide a revised report on completion of the work on non-intrusive monitoring, this will include data from the gas injection measurement campaigns, scheduled to commence mid 2009, and results of the full waveform inversion analysis.

5.2 Outstanding Issues

1. Extensive instrumental tests showed that repeatability of the measurements with the hydrophone chain is insufficient. It seems that only minor position changes of the sensors result in significant changes of the waveforms recorded. There are two possible approaches that could be used to overcome this problem. The sensors could be firmly grouted into the boreholes. This should improve the repeatability of the measurements. Alternatively, the tomographic inversion codes could be modified such that they account for varying coupling conditions. For logistical reasons, the former option was not feasible for the Mont Terri HG-A project, but it could be considered for the design of repository monitoring systems. Allowing for variability in coupling conditions will be considered during development of the full waveform inversion code being undertaken as part of the PhD project.

2. This study highlighted the importance of waveform inversions. Algorithms for this relatively new technique have been already published in the geophysical literature, but to our knowledge no codes exist that account for anisotropy and variable coupling conditions. This requires development of new algorithms, which is currently underway, but will be completed outside the timescale of ESDRED project. A revised report will be issued on completion of the analysis.

3. Following development, the new algorithms need to be applied to the data sets collected at the Mont Terri test site.

4. The relatively narrow frequency band of high coherence for the hydrophone records will be investigated.

5. Implementation of non-intrusive monitoring requires further research on the objectives and strategies associated with monitoring programmes. In particular, how monitoring could be implemented within the framework of a decision-making programme needs to be specified, and a monitoring programme (what, when, where, why and how) should be developed within the framework of specific repository systems.

5.3 Recommendations

1. On the basis of our investigations, seismic tomography has been identified as a potentially useful option for non-intrusive monitoring. It is recommended that more research should be undertaken for further improving the usefulness of this technique. In particular, linking the tomogram and waveform data to specific processes will be an important part of future research.

2. Our study highlighted the importance of seismic sensors emplaced directly in the repository. It is recognized that wired sensors, as they are installed in the HGA micro-tunnel at Mont Terri would be unsuitable for a sealed repository. Therefore, a monitoring programme employing seismic tomography should consider collection of data and calibration of the tomographic data with data collected from the disposal cell.

3. Monitoring temporal changes via seismic waveform tomography requires precise knowledge of the background medium in which the repository will be embedded.

This requires calibration measurements. Accordingly, seismic tomography experiments should be performed prior, during and after excavation of the disposal cell. Identical experimental configurations should then be used for the subsequent monitoring phases.

4. Further work should be undertaken to identify monitoring objectives, strategies and decision-making processes, in order to identify requirements on monitoring techniques and guide technology development.

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