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1. Introduction

The main goal of the collaborative, European Commission 7th Framework MoDeRn Project (**Mo**nitoring **De**velopments for safe **R**epository operatio**n** and staged closure) project is to take the state-of-the-art of broadly accepted, main monitoring objectives and to develop these to a level of description that is closer to the actual implementation of monitoring during a staged approach to disposal of radioactive wastes. To achieve this goal, 18 partners representing 12 countries and including 8 national radioactive waste management organizations have been working collaboratively within this EC project since 2009. The MoDeRn Project work programme addresses both Process (why monitor, developing a monitoring programmes, translating monitoring objectives into practice and using the results from monitoring) and Technology (technical requirements and constraints, state-of-the-art for monitoring technology, focused R&D and the development of techniques through demonstrations in underground research laboratories (URLs)).

The MoDeRn project aims to provide implementing organisations and other interested parties with a reference framework for the development and possible implementation of monitoring activities and provide a basis for stakeholder engagement during relevant phases of the radioactive waste disposal process i.e. during site identification, site characterisation, construction, operation and staged closure, as well as post-closure institutional control. Monitoring provides operators and other stakeholders with *in situ* data on repository evolutions, to contribute to operational safety, to help manage construction, operation and/or closure activities, and provides information on barrier performance and early evolution of the disposal system design. Monitoring provides information to inform decisions during the stages of repository development, operation and closure. When monitoring activities respond to stakeholder needs and provide them with results that can be readily understood, they will also contribute to transparency and help develop stakeholder confidence in the disposal process.

The partners, in developing this programme, recognised the significance of specific national contexts in defining monitoring requirements and the need for flexibility within the framework to capably address these requirements. The MoDeRn programme has also included engagement with both experts and public stakeholders to provide a wider perspective on monitoring and the ultimate purpose of the MoDeRn project is to utilise the outputs from this work as a basis for consultation on and development of monitoring programmes with stakeholders.

The MoDeRn partners recognise that it is necessary in the early stages of such development to pursue cautious and more intensive monitoring programmes until analyses of the results from monitoring can be used to inform appropriate monitoring programmes going forward. The partners also recognise the limitations to providing monitoring systems capable of functioning across the timescales for long-term safety cases, nonetheless, development of systems capable of monitoring the early stages of evolution will help to provide information to support decisions on whether to progress to the next stage of a step-wise process. The current programmes for developing and demonstrating monitoring systems within mock-up disposal cells will help the development of geological disposal programmes by:

- Advancing understanding of the capabilities (and limitations) of the monitoring systems being developed and tested;
- Providing implementers with information on the performance and early evolution of the design which can assist, through design development, in the performance and efficiency of planned repositories;
- Discussing and sharing of these programmes with stakeholders to enable better understanding of the monitoring disposal cell designs and the performance of those designs;
- Assisting further RD&D programmes to focus on technical areas where development needs have been identified;

Although many national programmes for geological disposal are at the early stages, where in many cases, sites and the geological environment for disposal have not yet been identified, the partner organisations recognise the need to assess, develop and refine available techniques at this stage. To successfully implement a programme for repository monitoring requires a competent technical programme focused on providing monitoring information in a clear and transparent manner.

The focus of the MoDeRn partners RD&D programme is in developing applicable state-of-the-art technologies in realistic situations in mock-up disposal cell in underground research facilities in order to replicate environments similar to that for actual disposal. This considers factors such as heat, humidity and pressure. From the results of these studies, the capabilities and limitations of particular systems and techniques are evaluated. Subject to the evaluation, improvements to performance and reliability can either be made during the project, if practicable, or be recommended as part of any future development or use.

It is important to minimise disturbance to the barrier systems, wherever possible, therefore the focus within the MoDeRn project has been to further the potential for applying non-intrusive and wireless techniques and researching and developing these techniques to improve their effectiveness for specific applications.

The intent within the technology programme is to deliver “best value for money” and in all of the demonstrator projects these have been built upon existing infrastructure or will be attached to infrastructure which is being developed and financed outside of the project. In most cases where mock-up facilities are developed the provision of a monitoring system would be an essential part of the information sought from such facilities, therefore utilising and developing state-of-the-art techniques (in some cases alongside more conventional techniques) provides additional benefits.

This report summarises a programme to develop non-intrusive monitoring of disposal cell mock-ups employing seismic tomography. It is one of a group of 5 research, development and demonstration (RD&D) programmes at underground research laboratories (URLs) within the MoDeRn Project, aimed at advancing the state-of-the-art of disposal facility monitoring. This has included a review by MoDeRn partners to evaluate the current state-of-the-art of monitoring technology which has also included workshops arranged with monitoring specialists from wider, but related, industries (oil, gas, mining and construction).

Summaries of the other MoDeRn RD&D programmes are listed below, summaries of these programmes and the results/findings can be found in “MoDeRn Technology Summary Report” (MoDeRn 2013) or in individual and more detailed reports on each programme as set out below:

1. Remote monitoring using high frequency wireless sensor networks at Grimsel Test Site (Ref: EC MoDeRn Project, 2013, D3.3.1)
2. Fibre optic sensing and acoustic emission at HADES URL at Mol in Belgium (Ref: EC MoDeRn Project, 2013, D3.4.1)
3. Wireless data transmission underground to surface at Mol (Ref: EC MoDeRn Project, 2013, D3.4.2)
4. Testing disposal cell monitoring systems under construction conditions at Bure URL in France (Ref: EC MoDeRn Project, 2013, D3.5.1)

An investigation into non-intrusive monitoring techniques applicable to geological disposal was conducted within EC ESDRED Programme, 2004 to 2008, identified seismic tomography as the most promising technique for monitoring the designs and host geologies considered. This programme of work monitoring a mock-up disposal cell at Mont Terri underground test site,

Switzerland, was continued after the end of the ESDRED programme by the Swiss Federal Institute of Technology, Zurich (ETHZ) and following completion of PhD studies the dissertation (Manukyan, 2011) has been completed and is accessible on the MoDeRn website (http://www.modern-fp7.eu/)together with an updated ESDRED Report (Ref: EC MoDeRn – ESDRED, 2012). Further work on seismic tomography funded by waste management agencies has been conducted under Project TEM (Testing and Evaluating Monitoring methods) at Grimsel Test Site (GTS), Switzerland. This work utilised a construction of a bentonite wall confined behind a low pH shotcrete pug which was constructed as part of a demonstration programme within the EC ESDRED programme. The monitoring boreholes for seismic tomography were installed under Project TEM. From May 2009, this work programme has continued within the MoDeRn project. A further PhD study (Marelli, 2011) has now been completed and can be accessed on the MoDeRn website. This report summarises the findings from the Marelli PhD and more detail on the research and analysis can be found in that report.

Figure 1: Location of the two underground laboratories in Switzerland where seismic campaigns were performed. Felslabor Mont Terri (FMT) is located in the North-West, whereas the Grimsel Test Site (GTS) is located in the South.

1.1 Objectives

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, EC ESDRED Project, 2008). The use of non-intrusive monitoring techniques avoids the possibility of reduction in passive safety of Engineered Barrier Systems (EBS) resulting from cables linking *in situ* monitoring systems with external data collection. 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 as monitoring activities must not affect the passive safety of the repository barrier system.

The need to ensure that monitoring of a repository does not affect the passive safety of the repository barrier system (IAEA, 2001), effectively 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 wireless data can be relayed.

The development and testing of non-intrusive monitoring techniques, in conjunction with conventional intrusive or wireless monitoring techniques, in 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. Furthermore, the experience gained from these applications, will enable the implementer to better understand any limitations and shortcomings of any monitoring technique and help to focus development of the monitoring systems in advance of their use in a disposal facility.

Analysis of repository concepts, monitoring objectives and potential non-intrusive techniques within the EC ESDRED Project (Ref: EC MoDeRn – ESDRED, 2012) (http://www.esdred.info), helped identify cross-hole seismic tomography as a promising technique to pursue. This report addresses the further development of seismic tomography of mock-up disposal barriers in granite, following on from the ESDRED project, which investigated this technique in a disposal cell mock-up in clay.

Controlled source seismic tomography (Marelli, 2012) is attractive because it not only complies with the non-intrusive requirements of a repository but also it offers high resolution imaging capabilities. Seismic imaging is based on the fact that any heterogeneity in the elastic properties of the medium (e.g., seismic wavespeed, density and attenuation) affects the wave propagation characteristics, and so diagnostic changes in the waveforms (traveltimes, amplitudes, pulse shape) could be observed. There are two broad categories of seismic imaging: reflector imaging and tomographic imaging. The main difference between the two is that mapping reflections can only delineate the geometry of discontinuities, whereas tomographic imaging can recover a detailed image of the subsurface elastic properties. Seismic tomography attempts to invert the elastodynamic equations of motion to deduce a subsurface model whose theoretical response fits the observed seismograms to some specified tolerance level and subject to certain constraints.

Traveltime tomography exploits the arrival times of selected seismic phases to create velocity images of the medium, whereas ray based amplitude tomography uses the maximum pulse amplitudes to deduce the attenuation characteristics. Full waveform inversion techniques exploit the full information content of the seismograms, amplitude as well as phase. Both categories of method have advantages and drawbacks. Traveltime (and ray amplitude) tomography, due to its intrinsic simplicity, is often regarded as the most stable and reliable method. In general, 2D traveltime tomography (say, in the plane formed by two boreholes) is less influenced by out of plane reflections that could strongly influence the later portions of the seismograms, especially in the presence of high contrast heterogeneities. In addition, it has relatively low computational demands, as even reasonably sized 3D inversions can be carried out on personal computers. Its resolution, however, is limited by the direct ray path coverage and the high frequency assumption (low frequency diffraction effects are ignored). Regions of low velocity in the subsurface are bypassed by first arriving rays and very sharp velocity contrasts tend to be underestimated, or even ignored in the resulting tomographic images (e.g., Wielandt, 1987).

Full waveform inversion entails iteratively refining a subsurface model so that the discrepancy between the synthetic data generated for the model and the observed data is minimized to a level commensurate with the expected noise. Generally, some degree of regularization in the form of smoothing and damping is imposed to stabilize the solution, because the problem is under-determined (i.e. more unknown model parameters than observations). Each iteration requires one or more forward modelling runs to simulate the response of the current structure. This can be computationally intensive, especially for 3D models. Choosing a suitable numerical forward modelling scheme, therefore, has a major impact on full-waveform inversion performance. Such numerical forward modelling can be performed either in the time or frequency domain (Marelli, 2011).

The main objectives from the research, development and demonstration activities, which are addressed in detail in the Marelli PhD (Marelli, 2011), are as follows:

1. An analysis of the data collected at a pilot monitoring test facility in Opalinus clay formation and a geophysical interpretation of the observed features, including source-receiver coupling in full-waveform inversion.
2. Laboratory measurements to determine the seismic velocities and other elastic properties of bentonite as a function of water saturation, temperature and confining pressure analogous to repository conditions.
3. A quantitative assessment of the required and available data quality for full-waveform inversion analysis of the mock-up disposal configuration (see Section 4)
4. Numerical analysis of nonlinearity issues associated with the inversion of high contrast bodies embedded in a high velocity medium.
5. An analysis of the validity of acoustic approximation in full-waveform modelling and inversion of cross-hole seismic data, addressing sharp interfaces and high contrast media.

1.2 Outline of this report

A summary of the research conducted and the findings from that research can be found within MoDeRn deliverable D2.3.1 Development Report of Monitoring Technology (EC MoDeRn Project, 2013). More detail on the research, development and demonstration programmes can be found in the PhD dissertations(Manukyan, 2011; Marelli, 2011). This report summarises the work conducted in progressing *in situ* demonstrations utilising seismic tomography.

Section 2 of this report summarises the key challenges for the work programme and the impact on the programme. This will include how the programme addressed the issues of repeatability, the limits of traveltime analysis, addressing non-linearity and the challenges of 3D interpretation of data.

Section 3 summarises the work that was necessary to address specific challenges in order to develop the monitoring system to meet the needs of a particular disposal system, particularly addressing the reliability of data and our capability to interpret effectively. It also advises where research has identified any limitations to the technique or where a conclusion is not possible at this stage.

Section 4 describes the experimental configuration of the demonstration programme giving some insight into the purpose of the demonstration. It explains the location of any sensors and any other factors in the configuration which impacted on the ability to optimise the location of sensors, receivers etc. It also explains the stages in the development of the experiment such as saturation, pressurisation etc. and would relate how monitoring would be conducted over those stages.

Section 5 summarises the results and key findings from the work programme, including the research, development and demonstration activities, the scope and limitations of the technique, the analysis of information and how that can be applied effectively.

Section 6 sets out the key conclusions and recommendation from the research and demonstration programmes and also highlights what would be required to apply this technique to a specific monitoring programme.

Section 7 identifies any issues which merit further research and development.

2. Key programme challenges

The most significant challenge in applying seismic tomography as a non-intrusive monitoring technique is in balancing the requirement for information (which is easier to obtain when the sensors are close to the source of investigation) with the need to locate the monitoring boreholes at an acceptable distance from the disposal cell to avoid any impact on the overall integrity of the geological barrier.

Regardless of the design of the site, it is very likely that the seismic velocities within the disposal cell will be substantially lower than in the surrounding host rock. Because the first arriving wave trains will predominantly “avoid” the disposal cell, they will provide no direct or only very limited indirect information about changes associated with the state of the disposal cell.

A powerful alternative to traveltime tomography is offered by full waveform inversions, where the information content offered by the entire seismic records is exploited. Although this technique has been known for more than 20 years, it has only recently received a lot of attention in the exploration industry. This is mainly due to the fact that substantial computing resources are required to perform the inversions.

Monitoring disposal cells with seismic waveform inversion methods requires a number of specific challenges to be addressed.

1. Changes within the disposal cell are expected to produce only very subtle changes of the seismic waveforms. Therefore, highly accurate and repeatable measurements need to be performed.
2. Seismic waveform inversions resolve changes of the elastic properties of the medium under investigation. These variations of the elastic properties need to be “translated” into physical processes. For example, water saturation of bentonite, which is typically employed for embedding high level radioactive waste, results in swelling and thus changes to the elastic parameters. To estimate the degree of water saturation from seismic measurements, it is necessary to perform controlled laboratory measurements to relate the degree of water saturation with the corresponding changes of the elastic parameters.
3. A typical monitoring setup of a disposal cell requires a 3D problem to be solved. To date, 3D elastic waveform inversions are not yet feasible, but 3D acoustic inversions (a simplified version of the elastic case) can be handled by modern computer clusters. Tests are required to assess whether the acoustic approximation is applicable to monitoring disposal cells.
4. The high seismic contrasts between the disposal cell and the surrounding host rock produce strong non-linearities. This may cause standard inversion algorithms to be unsuccessful.

3. Research & development to address challenges

The following programmes were progressed to address the challenges noted in Section 2.

3.1 Accuracy requirements of seismic data

Monitoring a repository will be conducted in the form of a series of repeated seismic measurements. Full waveform inversion techniques would be used to analyse the information offered by the differential changes in the waveforms between two series of measurements. These changes are expected to be very subtle. This imposes strong requirements on the repeatability of the experiments, that is, changes caused by slightly different experimental conditions during the individual measurements must be significantly smaller than the expected changes in the waveforms, caused by alterations within the repository.

Inconsistent waveform data could be caused by variations in

- the seismic source signature,
- seismic receiver properties,
- the data acquisition system, and
- the coupling of the sources and receivers to the host rock.

Section 5 outlines how all these factors that could influence the repeatability of the experiments, were tested. More detail can be found in (Marelli, 2012).

3.2 Changes in elastic properties for bentonite during saturation

Monitoring using seismic waveform inversions will identify changes to the elastic properties of the medium to be investigated. Most disposal concepts are based on embedding high-level radioactive waste or spent fuel in bentonite, which is expected to swell and seal the waste in the case of water infiltration. The water saturation and swelling process will result in changes to elastic properties of the bentonite. Until now, no quantitative relationships between the elastic properties and swelling pressure, water content and temperature have been established.

Section 5 summarises the extensive laboratory measurements performed to determine these relationships. More detail can be found in (Marelli, 2012).

3.3 Development of suitable tomographic inversion algorithms

Once suitable data acquisition strategies have been identified, and the relationships between physical parameters (pressure, temperature, water content) and the elastic properties (P- and S-wave velocities and density) of the target medium (bentonite) have been established, it is necessary to develop suitable tomographic inversion algorithms. Full waveform inversions are currently a hot topic in geophysical research and many groups worldwide are working on such problems (e.g., Plessix, 2008; Buske et al., 2009). There are several unresolved issues that are particularly relevant for applications related to radioactive waste monitoring. In the framework of the MoDeRn project, we have made significant progress in the following areas.

1. *Experimental design*
   We have established criteria for optimal temporal and spatial sampling of full waveform inversion experiments (Maurer et al., 2009). Furthermore, we explored, which types of sources and receivers are particularly useful for elastic waveform inversions (Manukyan et al., 2012).

2. *Validity of the acoustic approximation*
   Targets of interest in radioactive waste monitoring are best characterized by an elastic medium (possibly with some anisotropy and anelastic attenuation). Elastic waveform problems are computationally very challenging, and so far, only 2D problems could solved. However, typical monitoring setups may require a 3D problem to be considered. 3D problems can be tackled with acoustic inversions, which are a simplification of the fully elastic problem. We have checked, if such an acoustic approximation would be valid for radioactive waste monitoring problems (Marelli et al., 2012).
3. *Non-linearity issues*
   Seismic waveform inversion problems are well known to be highly non-linear. This problem is exacerbated in the presence of high velocity contrasts. We have performed extensive synthetic simulations to better characterise these non-linear effects (Marelli, 2011).
4. *Anisotropic inversions*
   Suitable host rocks may exhibit a high degree of anisotropy, which further complicates the elastic waveform inversion problem. We have successfully implemented an anisotropic and elastic waveform algorithm, and we have performed first synthetic inversions (Manukyan, 2011).
5. *Coupling problems*
   As explained in more detail in Section 5, coupling between seismic sources and receivers and the host rock is very critical. We have identified suitable procedures, with which the coupling variations can be minimised, but the coupling must be also considered during the inversions. Even if the coupling conditions remain constant between the two experiments, they are likely to have a significant effect on the waveforms. For that purpose, we have developed a suitable algorithm, with which the coupling factors can be determined reliably (Maurer et al., 2012).

All the algorithmic developments mentioned in subsection 3.3 are discussed in more detail within the PhD studies (Manukyan, 2011) & (Marelli, 2012) and in the final report of Work Package 2 (Ref: EC MoDeRn Project, 2013, Deliverable D2.3.1).

4. Experimental configuration

Grimsel Test Site

The physical properties of the granitic host rock have previously been explored using seismic methods. The various investigations revealed the presence and influence of numerous fractures and shear zones. Seismic P-wave velocities ranged from 4500 to 5500 m/s. (Holliger and Buhnemann, 1996) measured relatively high attenuation in the host rock, with Q factors of 30–50, possibly associated with microfracturing.

The experimental configuration is sketched in Figure 2. A 1-m-thick bentonite wall is assembled in layers at the end of a 3.5-m-diameter tunnel. Realistic closure of the repository is simulated with a 4-m-long low pH shotcrete plug. Water introduced at a number of locations induces bentonite swelling under controlled conditions. The experimental region is equipped with several types of sensor that monitor a variety of parameters, including pressure, water content, temperature, deformation, etc..

The swelling of bentonite is associated with substantial variations of its elastic properties; therefore, non-intrusive seismic monitoring was considered a viable option. For this purpose, six gently dipping boreholes were drilled at regular intervals around the circumference of the tunnel, shotcrete plug, and bentonite mass (Figure 2). The length and diameter of the boreholes were 25 and 0.085 m, respectively. During each seismic measurement campaign, seismic energy was released at 0.25 m intervals along the gently dipping boreholes 3, 4, and 5. The source employed in our tests was a P-wave sparker from Geotomographie GmbH, characterized by a nominally repeatable broadband spectrum up to several kHz.

The seismic waves were primarily recorded by an acquisition system that included three multi-element hydrophone chains (from Geotomographie GmbH) placed in gently dipping boreholes 1, 2, and 6, and a composite 24-bit dynamic range Geometrics Geode recording unit that allowed 96 individual channels to be simultaneously sampled at a timing interval of 20 μs. The three hydrophone chains were each equipped with 24 hydrophones spaced at 1 m intervals. These sensors were expected to provide a flat response from approximately 0.2 to 7.0 kHz. During the surveys, a 0.25 m hydrophone spacing was synthesized by shifting the hydrophone chains by 0.25 m along the boreholes and repeating the experiments.

To ensure rigidity and accurate relative positioning, the hydrophone chains were placed in PVC pipes. In addition to the hydrophone data, information from twenty-four 100-Hz vertical-component geophones rigidly mounted (cemented within small holes) to the front wall of the shotcrete plug was also recorded by the Geode system.

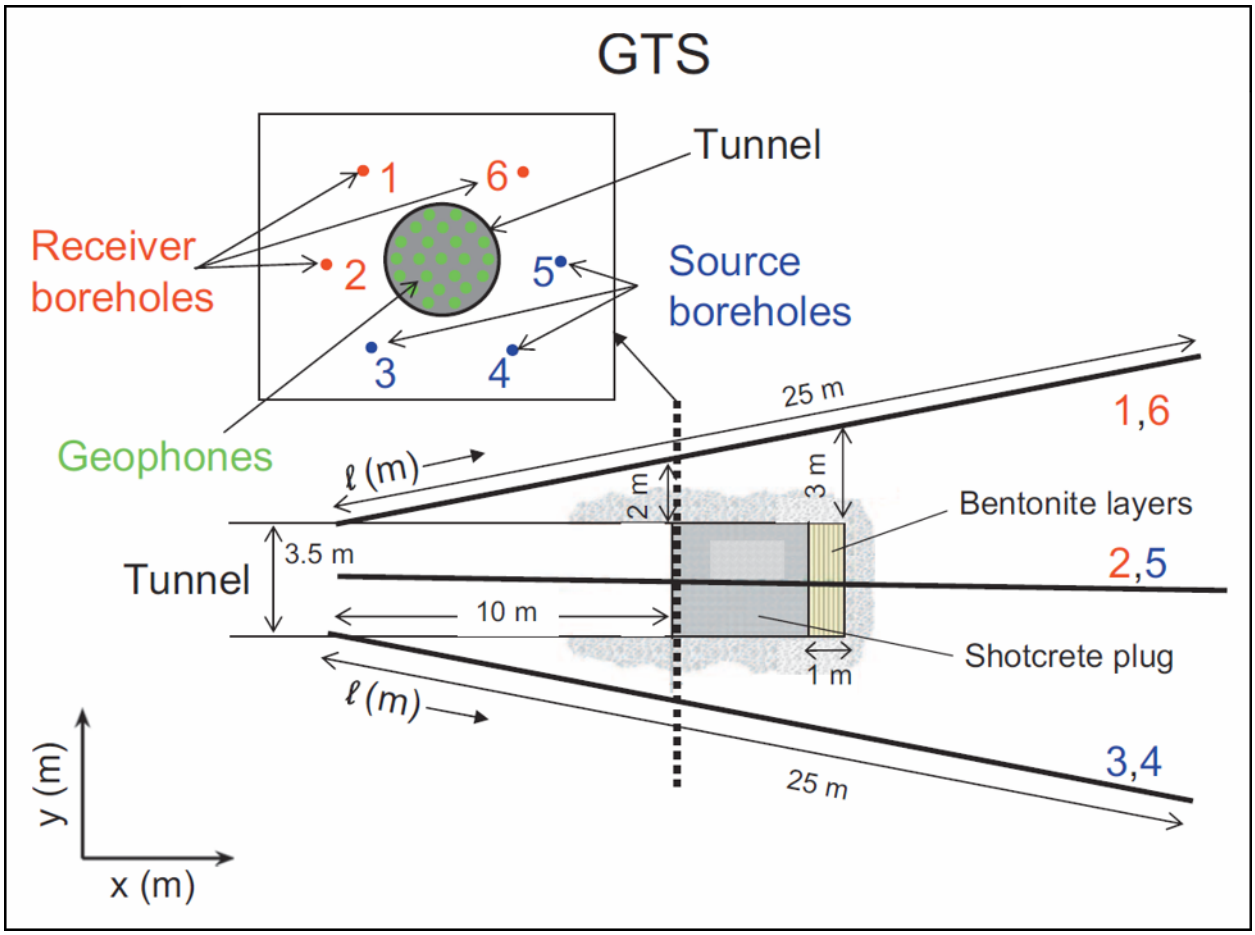

Figure 2: Experimental configuration at the Grimsel Test Site. The cross-section perpendicular to the tunnel axis at the top left corner shows the relative orientations of the six boreholes (blue for source and red for receiver) and the distribution of vertical-component geophones (green dots) mounted on the outer wall of the shotcrete plug. The lower drawing shows the borehole inclinations and the relative positions of the tunnel, shotcrete plug, and bentonite layers.

Mont Terri Test Site

For some of our experiments, we also considered a second test site located in the Swiss Jura Mountains. The Mont Terri laboratory is located in the Opalinus clay formation, which is currently the preferred host rock in the Swiss radioactive waste disposal concept. A distinguishing feature of Opalinus clay (the host rock) is its high degree of elastic anisotropy, with slow and fast P-wave velocities of 2300–2500 and 3100–3300 m/s, respectively.

The experimental setup at Mont Terri is sketched in Figure 3. It is part of the so-called HG-A experiments being conducted by the Swiss Radioactive Waste Management Agency, Nagra. A 13 m long micro-tunnel with a diameter of 1.0 m, mimicking a 30–40% scaled repository, was constructed in the Opalinus clay formation. For crosshole monitoring purposes, two moderately dipping boreholes (25 and 29 m long) were drilled perpendicular to the axis of the micro-tunnel. During the experiments, both boreholes were water filled. Initially, the micro-tunnel was empty. It was then filled with sand and sealed with a mega-packer system. Subsequently, the micro-tunnel was water-saturated and slightly over-pressured. As a last phase, gas injections were performed.

All phases of the experiment have been accompanied by seismic measurements. Seismic energy was released sequentially in the lower downward dipping borehole at 0.25 m intervals using the same sparker source as at the Grimsel test site. The primary data acquisition system

and recording strategy were essentially the same at both the sites; 24 hydrophones, spaced 1 m apart were progressively shifted 0.25 m in the upward dipping borehole to simulate 0.25 m spacing. At Mont Terri, the temporal sampling interval was either 64 or 32 μs, and two different installation procedures were employed. During the first six experiments, the hydrophone chain was inserted with a hook and pulley system. For the remaining experiments, the hydrophone chain was placed in a rigid PVC pipe as described for the Grimsel test site. In addition to the hydrophones, eight 100-Hz vertical-component geophones were planted at roughly equal distances around the interior of the micro-tunnel in the plane spanned by the two boreholes (Figure 3).

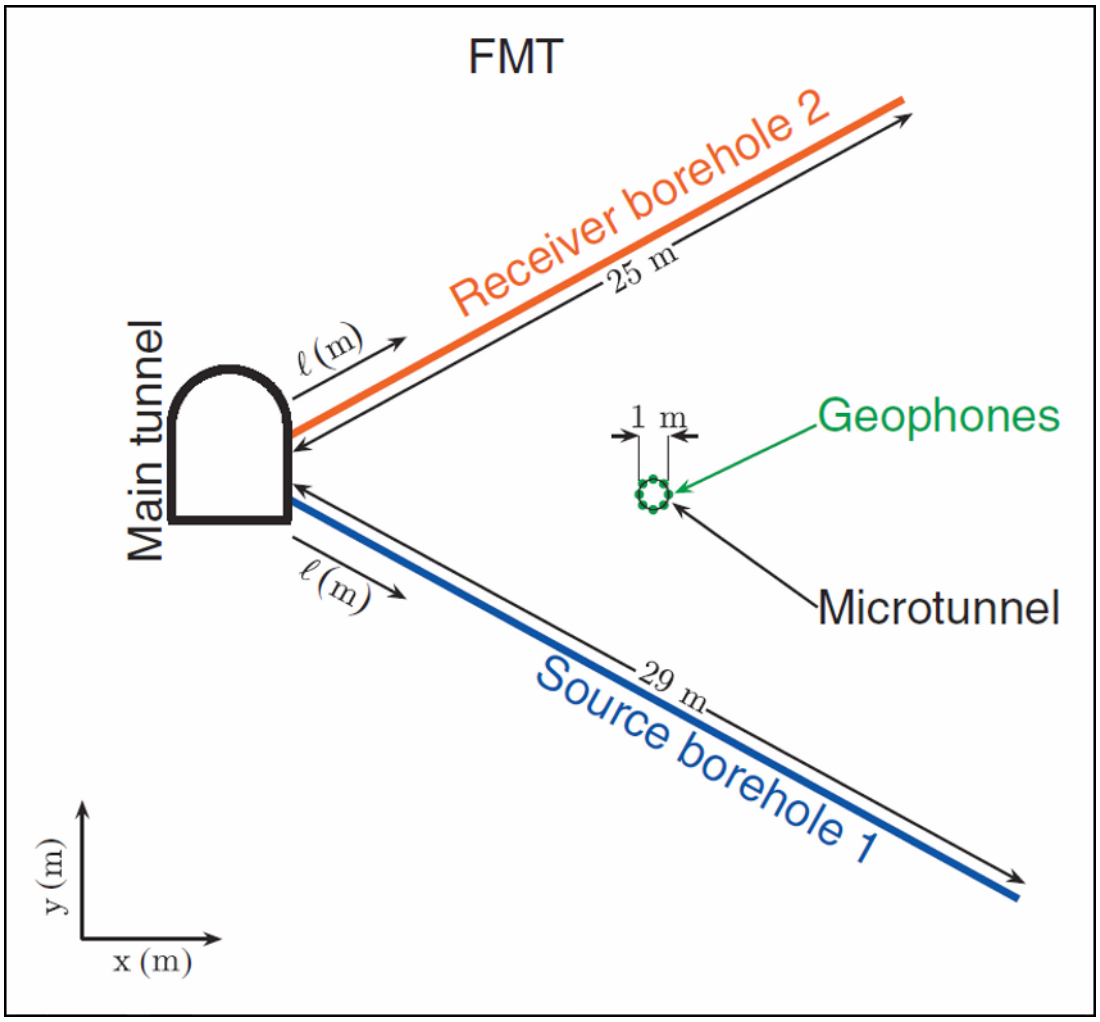

Figure 3 Experimental configuration of the HG-A experiment at the Mont Terri Rock Laboratory. Two boreholes extend from the side of the main tunnel (blue for source and red for receiver). Vertical component geophones (green dots) are rigidly mounted equidistant around the monitored micro-tunnel.

5. Results of demonstration activities

5.1. Accuracy requirements of seismic data

To quantify waveform changes expected to be caused by physical property changes within and around the simulated repositories at the Grimsel and Mont Terri sites, numerical modelling experiments were performed. For the sake of simplicity and computational efficiency, we restricted the simulations to two dimensions. For the Grimsel experiment, our 2D setup would correspond to, for example, a source placed along borehole 5 and hydrophones placed along borehole 2 (Figure 2). At Mont Terri, the geometry of the boreholes is essentially two-dimensional (Figure 3). Synthetic seismic traces were computed for Grimsel using a viscoelastic finite-difference time-domain modelling code described by Bohlen (2002). For Mont Terri, synthetic seismic traces were calculated using an elastic-wave version of the same code that was modified to incorporate anisotropy.

End-member scenarios were considered for the Grimsel site synthetic experiment: a dry and a fully water-saturated bentonite block (Table 1). P-wave velocities for granite were based on traveltime inversions of observed data (Maurer and Green, 1997), whereas the remaining P- and S-wave velocities and densities for granite, shotcrete, and dry and wet bentonite were based on information supplied by Peter Blümling (NAGRA). No excavation disturbance zone was included in the Grimsel model.

For the Mont Terri experiment, a sand-filled micro-tunnel was modelled that was either dry or water-saturated (Table 2). Elastic parameters for the Opalinus clay were derived from the anisotropic traveltime inversion as described in (Manukyan, 2011), and its density was provided by Nagra. The properties of dry and wet sand were estimated from the literature (Zimmer et al., 2007). An EDZ was included in the Mont Terri model with dry and water-saturated velocities decreasing linearly from normal Opalinus clay values at a radius of 1.5 m to about 60% of normal values at the surface of the micro-tunnel. On the basis of seismic sections recorded at the two test sites, Ricker-wavelet sources were chosen with centre frequencies of 3 and 2 kHz for Grimsel and Mont Terri, respectively. These correspond to dominant P-wavelengths of 1.73, 0.94, 0.17, and 0.67 m for granite, shotcrete, and dry and wet bentonite, and 1.17 – 1.55 m for Opalinus clay and 0.25 and 0.95 m for dry and wet sand.

Material	V_P (m/s)	V_S (m/s)	□ (kg/m^3)
Granite	5200	2700	2600
Shotcrete	2820	1810	2200
Bentonite (dry)	500	260	1400
Bentonite (saturated)	2000	500	1600

Table 1 Rock properties used for Grimsel simulations. The velocity values for granite indicate the median velocities of the model, on top of which 5% stochastic fluctuations were added.

Material	V_P (m/s)	V_S (m/s)	□ (kg/m^3)
Opalinus Clay	3110 / 2340	1110	2500
Sand (dry)	500	240	1855
Sand (saturated)	1900	240	2155

Table 2 Rock properties used for Mont Terri simulations. The two values for Opalinus clay indicate the P-wave velocities parallel and perpendicular to the axis of isotropy.

Figure 4 shows the results for a selected shot position at each site. Wavefield snapshots at a time t = 3.6 ms for the dry and wet bentonite scenarios at Grimsel are presented in Figure 4a and b, and simulated seismic sections for a hydrophone in borehole 2 are displayed in Figure 4d and e. Corresponding diagrams for the dry and wet sand scenarios at Mont Terri are given in Figure 4h and i (t = 7.4 ms) and 4k and 4l. Differences between the dry and the water-saturated scenarios at the two sites, magnified by a factor 2, are displayed in Figure 4c, f, j, and m.

The snapshots and seismic sections clearly illustrate that the simulated repositories at both test sites cause a large amount of scattering. It is also noteworthy that a substantial part of the seismic energy is reflected from or near the simulated repository boundaries, demonstrating that useful information is contained not only in the transmitted but also in the reflected wavefields. This is especially important at Grimsel, where information in measurement planes not intersecting the repository can be collected. Differences in the seismic traces occur along most of the length of the receiver boreholes, indicating that the boreholes should extend well outside the monitored regions for optimum results.

To gain further insight with regard to the data accuracy required for performing reliable waveform inversions, changes in the seismic traces simulated for the dry and wet conditions need to be quantified. A suitable tool for this task is cross-correlation. Unless specified otherwise, we have used 5 ms time windows starting at the first break of each trace for computing the normalized cross-correlation coefficients of simulated and observed seismic traces. As shown in the synthetic seismic sections (Figure 4), this time window includes most of the relevant information for the Grimsel and Mont Terri sites.

Zero-lag cross-correlation coefficients for traces in Figure 4d, e, k, and l are plotted in Figures 4g and n, respectively. The coefficients range from 0.75–1.0 for Grimsel traces, whereas larger variations of 0.1–1.0 are observed for the FMT traces[1]. Analyses using other shot positions yielded similar results.

These variations of cross-correlation coefficient are caused by changes in the seismic contrast between the anomalous features (i.e., bentonite plug, EDZ, and micro-tunnel) and the surrounding host rock. The anomalous features have lower velocities than the host rock at both sites, so waves passing through them are somewhat delayed. At Grimsel, the bentonite has a significant contrast with the granite, both when dry (1:10.4; Table 1) and when fully saturated (1:2.6). Hence, the early part of the recorded wavefield is expected to be dominated by waves diffracted around the anomalous feature in both dry and water-saturated conditions and little affected by the target zone itself (Figure 4g).

[1] A cross-correlation coefficient of 1.0 indicates a perfect match between two traces, a value of 0.0 is obtained, when the two traces are completely uncorrelated, and a value of -1.0 is obtained, when the two traces are identical but one of them exhibits a polarity reversal. That is, the cross-correlation coefficient can vary between -1.0 and 1.0.

When the micro-tunnel at Mont Terri is filled with dry sand, the velocity ratio with normal Opalinus clay is considerable. In contrast, the velocity ratio is quite small (average of 1:1.4) for water-saturated sand conditions. As a consequence, the transmitted seismic paths through the Mont Terri micro-tunnel are expected to affect the early part of the recorded wavefield in the water- saturated scenario, but not when the sand is dry. This is clearly borne out in the cross-correlation plot (Figure 4n).

Success or failure of waveform-based inversion relies on its capability to exploit the waveform differences shown in Figure 4f and m. This requires data accuracy and repeatability to be significantly better than these differences. The cross-correlation coefficients plotted in Figure 4g and n indicate that this is a challenging task. In particular, for Grimsel, it will be necessary to generate highly repeatable seismic sections, such that small variations of the source signal and/or the receiver coupling would result in cross-correlation coefficients of 0.95 or better for repeat experiments under the same conditions. Furthermore, the 2D simulations shown in Figure 3a-g tend to overestimate the effects of the swelling bentonite. In a realistic 3D configuration, the overall magnitude of the waveform perturbations would probably be smaller, making the monitoring task even more challenging.

Based on the results of synthetic experiments in Figure 4, it is concluded that repeatability of "identical" equipment should yield cross-correlation coefficients of better than 0.95 over a wide frequency band. This threshold will be used as a yardstick for the analysis of observed data at Grimsel and Mont Terri.

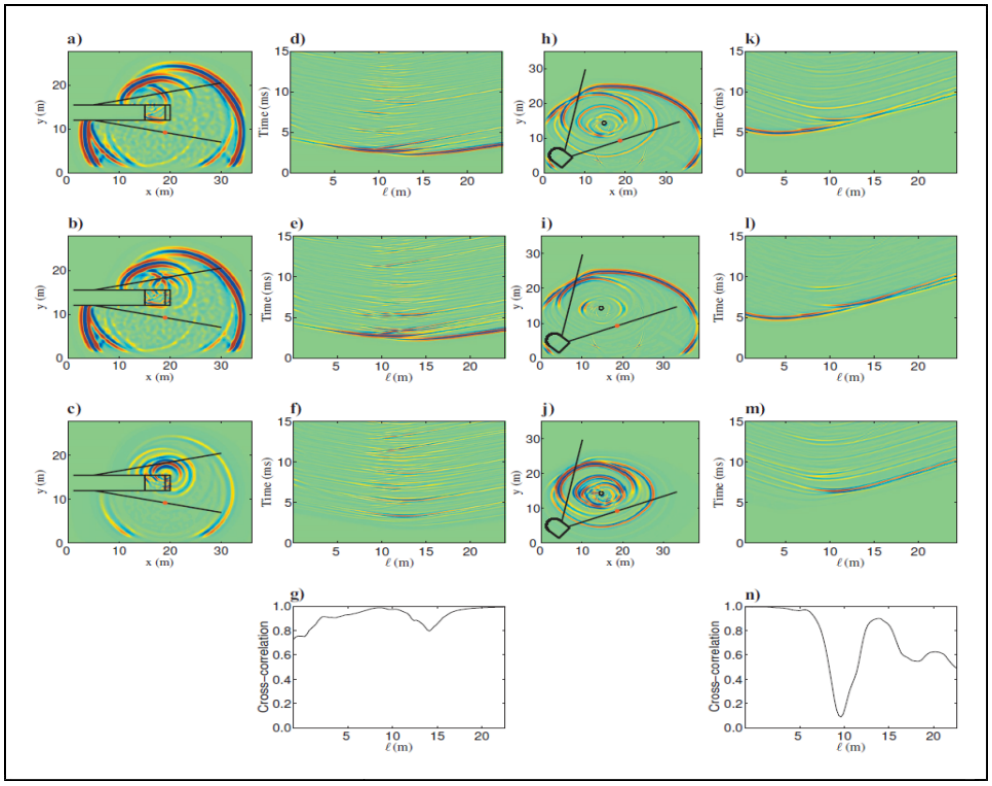

Figure 4: Simulation results for (a–g) Grimsel and (h–n) Mont Terri. Snapshots of pressure wavefields at 3.6 ms for (a) dry bentonite and (b) fully water- saturated bentonite at Grimsel Test Site. (c) Difference between (a) and (b) with amplitudes magnified by a factor of two. Source position is indicated by the red dot in each diagram. Seismic sections as they would be recorded in the receiver borehole are shown in (d) and (e), and the difference seismic section is presented in (f) with amplitudes amplified by a factor of two. (g) Crosscorrelation coefficients (using a time window of 5 ms after the first breaks) for the seismic sections shown in (d) and (e). (h) to (n) are like (a) to (g), but for Mont Terri with snapshots at 7.4 ms and a dry and water-saturated micro-tunnel.

5.2. Repeatability tests

Repeatability of seismic experiments is governed by several factors, including the

- source signal,
- coupling of the source to the medium,
- coupling of the receiver to the medium, and
- fidelity of the receiver and acquisition system

To study the effects of these different factors, extensive tests were performed at the Grimsel and Mont Terri sites. The Grimsel experiments were conducted when the bentonite block was partially saturated and the Mont Terri experiments were conducted during a phase of slight over-pressurization of the micro-tunnel (the actual state of the simulated repositories is not critical for the repeatability tests).

Source repeatability

For this set of experiments, a single source position at a distance of 13.5 m in borehole 5 was considered at Grimsel and a single source position at a distance of 18 m at Mont Terri. Recordings from firmly grouted vertical-component geophones at the front of the shotcrete plug (Grimsel) and within the micro-tunnel (Mont Terri) were considered.

Ten repeat shots at exactly the same locations were fired consecutively and compared (Figure 5a and 5b). To quantify the repeatability, the 10 traces at each site were stacked to form a master trace and cross-correlation coefficients between the master trace and the individual traces were computed. The resulting cross-correlation coefficients demonstrate excellent repeatability of the source signal and geophone recordings; the average of the cross-correlation coefficients shown at the bottom of each trace is >0.99.

The dominant lower frequency phases visible in the later portions of the Grimsel traces are probably the result of resonances around the shotcrete plug, but for our purposes it is only important to note that the Grimsel signals also include significant high-frequency energy up to ~3 kHz (see summed amplitude spectra of the individual traces represented by the red curve Figure 5c). The Mont Terri signals have significant energy up to ~4 kHz (Figure 5d).

To estimate repeatability of the seismic traces as a function of frequency, coherence spectra were computed. The coherence values lie between 0 (no similarity at a particular frequency) and 1 (perfect similarity at a particular frequency). Note that coherence is not computed for frequencies that have amplitudes less than 5% of the maximum amplitudes.

The averaged coherence spectra over all 45 (10 x 9/2) combinations of the 10 traces from Grimsel and the 10 traces from Mont Terri are shown by the blue lines in Figure 5c and 5d. These figures indicate that the sparker source produces highly repeatable signals that are consistently recorded by the firmly attached geophones over a wide frequency band. After removal and reinsertion of the sparker in the boreholes, the experiments were repeated. The results were essentially identical. We conclude that the sparker source and firmly attached geophones produce the required repeatability for high-precision seismic monitoring.

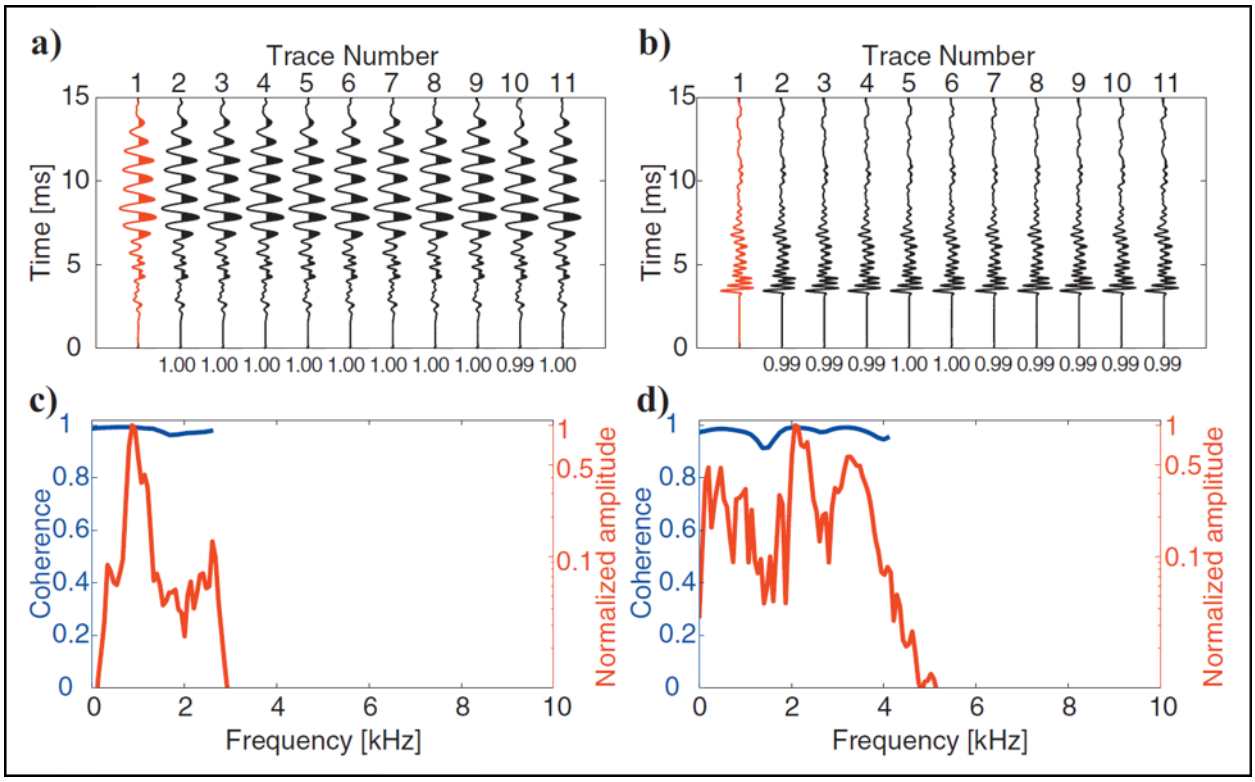

Figure 5: Results of source and geophone repeatability tests. (a) and (b) show seismic traces generated by 10 repeat shots recorded using geophones at Grimsel ((a) and (c)) and Mont Terri ((b) and (d)). Stacked master traces are shown in red at the left of both sections. The numbers below the traces are the cross-correlation coefficients with the master traces. Summed amplitude spectra (red curves, logarithmic scale) and coherence (blue curves, linear scale) are shown in (c) for Grimsel and (d) for Mont Terri. The two coherence curves are truncated above the lowest frequencies for which the amplitudes are less than 5% of the respective maximum amplitudes.

Hydrophone repeatability

In the next step, the same shots as in Figure 5 were considered, but the responses of typical hydrophones at a distance of 9 m in borehole 5 at Grimsel and at a distance of 23.5 m at Mont Terri were analysed. The unfiltered traces are displayed in Figure 6a and 6b.

Compared to the excellent repeatability of the geophone recordings (Figures 5a and 5b), the cross-correlation coefficients for the hydrophone data in the moderately dipping hydrophone boreholes are substantially inferior for the Grimsel data (average cross-correlation coefficient of ~0.92) and slightly inferior for the Mont Terri data (average of ~0.99). These lower values are primarily caused by energetic, but largely incoherent high-frequency signals. It is notable that there is no clear amplitude decay towards higher frequencies in the Grimsel spectrum of Figure 5c.

The averaged coherency spectra in Figure 6c and 6d (blue lines) show uniformly high values over the frequency range 0.5 - 3.0 kHz for Grimsel and 0.5 - 4.0 kHz for Mont Terri. Figure 6e and 6f show the corresponding 0.5 - 3.0 kHz and 0.5 - 4.0 kHz bandpass filtered traces together with the cross-correlation coefficients based on recomputed master traces. The corresponding recomputed frequency and coherence spectra are given in Figures 6g and 6h. For the bandpass-filtered traces, the average cross-correlation coefficients are ~0.99 for Grimsel and >0.99 for Mont Terri, which is judged to be adequate for monitoring purposes. On the basis of these observations, seismic traces shown in subsequent figures were bandpass filtered using the frequency ranges indicated, unless otherwise specified.

Coupling of the hydrophones to the host rock was further investigated via two simple experiments at each site. Initially, the hydrophone chains were installed in the observational boreholes and the sparker was fired at several positions within the source boreholes. Then, the hydrophone chains were removed, disassembled, reassembled, and reinserted to the same nominal positions. With these experiments, the aim was to determine to what extent very small changes in hydrophone position (i.e., variations of at most ~1.0 cm) and seating in the boreholes affected the waveform shapes. At both test sites, significant changes were observed in the waveforms (Figure 7a and 7b) due to the coupling differences associated with small variations of hydrophone position and seating on the floor of the borehole. The corresponding zero-lag cross-correlation coefficients between traces recorded using the original and reinserted traces (Figure 7c and 7d) quantified the differences in Figure 7a and 7b. The coefficients ranged from 0.2-0.8 for Grimsel and from negative values to 0.8 for Mont Terri, all of which were clearly unacceptably low.

In a next step, traces recorded by sensors adjacent to each other were investigated. Figure 8a presents recordings from a shot fired in borehole 5 and recorded in borehole 2 at distances from 12.5-14.25 at Grimsel, and Figure 8b displays traces recorded at distances from 3.25-5.0 m at Mont Terri. For optimum visual comparison, the first breaks of the traces are in each case aligned. Since the 0.25 m receiver spacing was achieved by shifting the 1 m spaced hydrophones repeatedly in increments of 0.25 m, the first four traces in each of Figure 8a and 8b were recorded with the same hydrophone and the last four traces were recorded by an adjacent hydrophone. In most of the experiments the hydrophones were moved together with the PVC pipe. As a consequence, the positions and coupling conditions of the hydrophones within the pipe were not expected to change, but small variations of the recordings may have been due to changes of the geology along the boreholes and minor changes of the overall wavepaths. Cross-correlation coefficients for adjacent traces (numbers at the bottom of the traces in Figure 8a and 8b) for the first four and last four traces range from 0.53 to 0.88; these differences are likely due to changing geological conditions. In contrast, cross-correlation coefficients between traces 4 and 5, corresponding to two different hydrophones, are only 0.17-0.24. This indicates that the individual hydrophones have different responses and/or that this is again the result of the significant effects of slightly different sensor position and seating. From our observations it is not possible to separate these two effects.

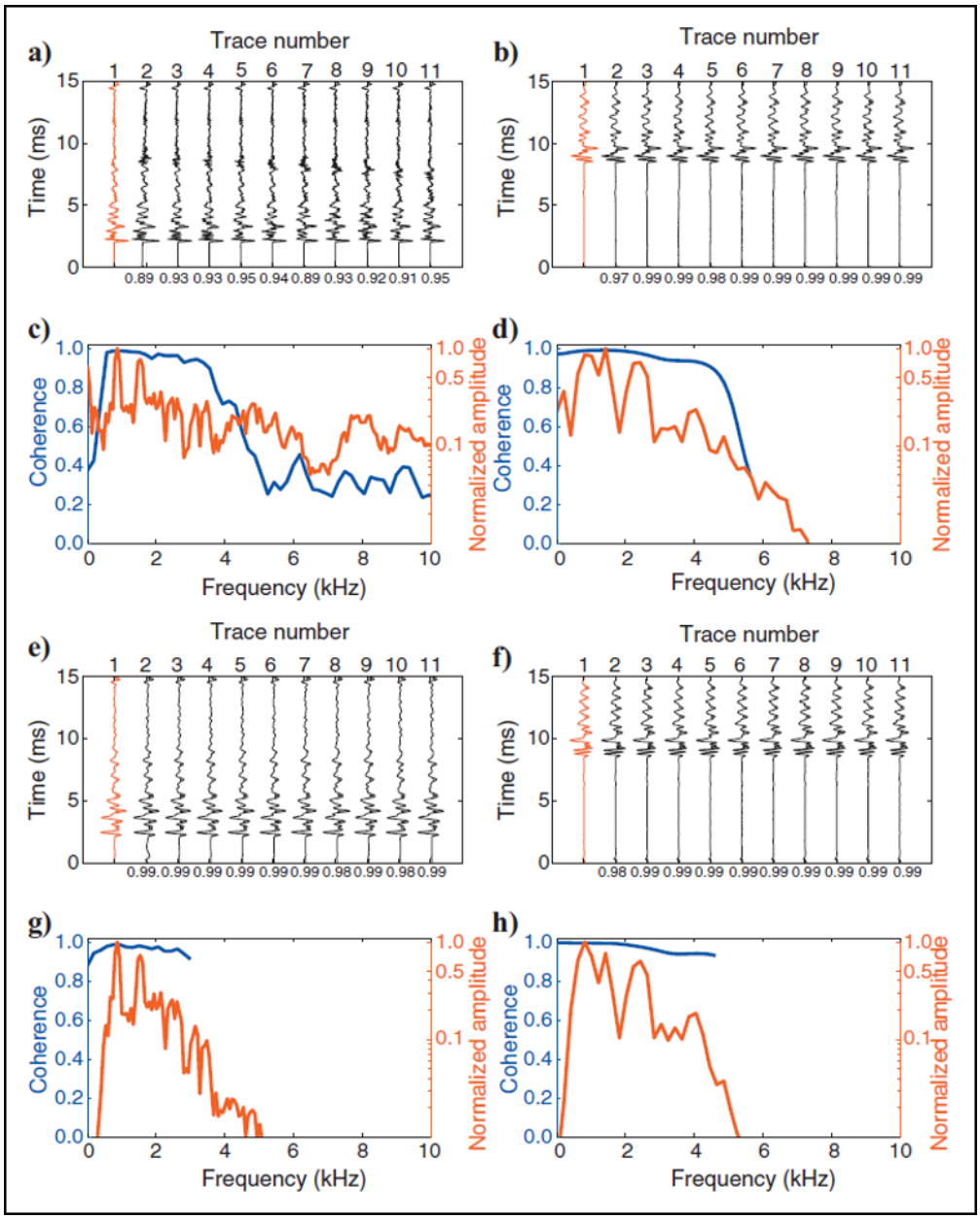

Figure 6: (a) to (d) are the same as Figure 5 (a-d), but for hydrophones at each site. (e) to (h) are the same as (a) to (d), but the traces have been bandpass filtered (corner frequencies of 0.5-3 kHz for Grimsel and 0.5-4 kHz for Mont Terri). Coherence curves are truncated above the lowest frequencies for which the amplitudes are less than 5% of the respective maximum amplitudes.

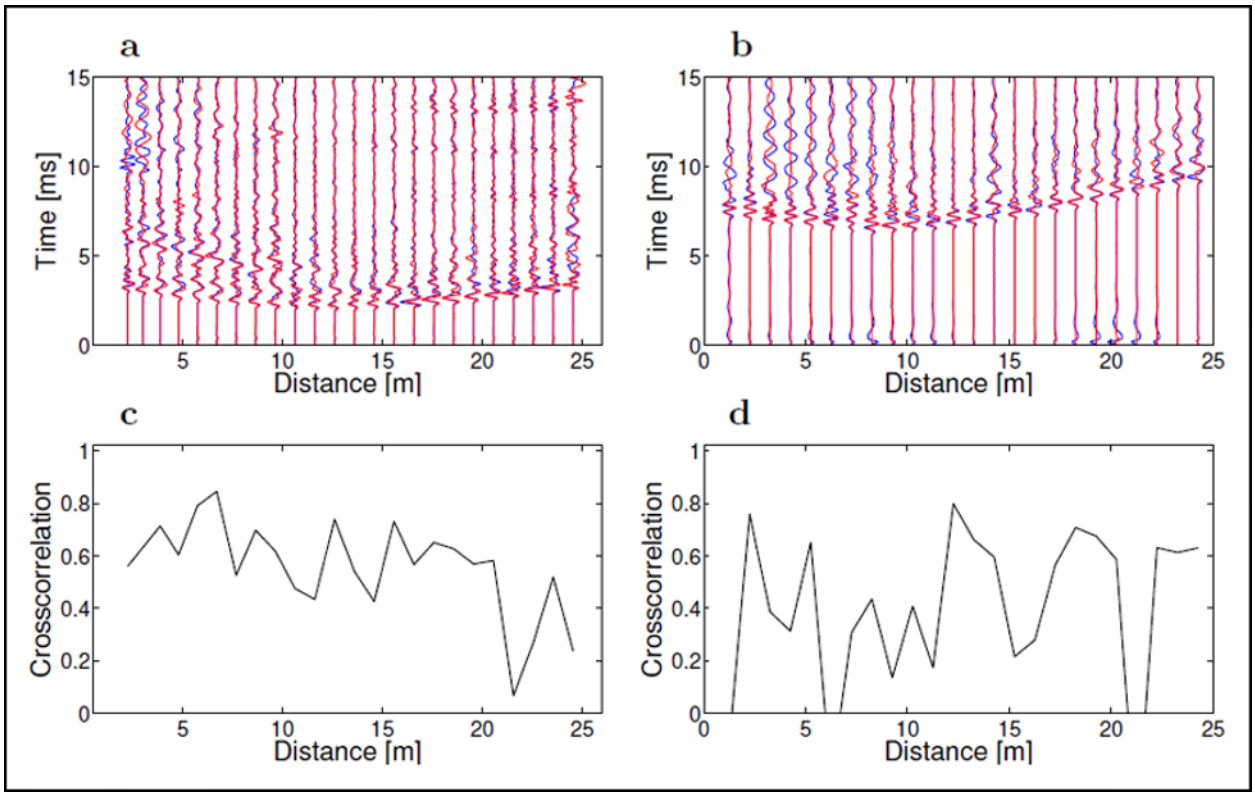

Figure 7: Shot gathers for repeated experiments before (red traces) and after (blue traces) re-inserting the hydrophone chain at (a) Grimsel and (b) Mont Terri. (c) and (d) show the distribution of the corresponding cross-correlation coefficients for 5 ms after the first breaks.

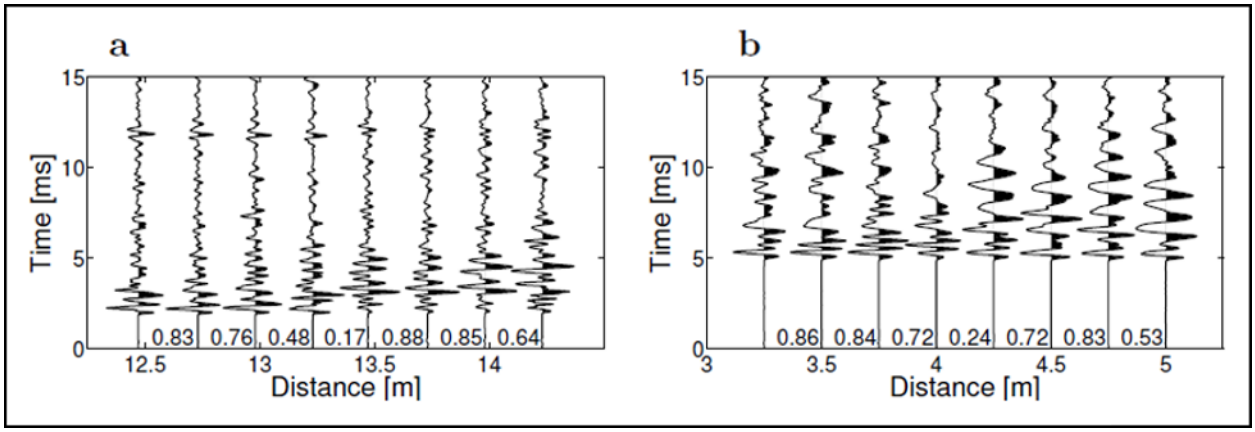

Figure 8: Effect of hydrophone chain shifting and different hydrophone transfer functions at (a) Grimsel and (b) Mont Terri. The eight traces in each diagram are a subset of shot gathers recorded using two hydrophone elements separated by 1 m, but shifted three times by 0.25 m. The numbers between the traces are cross-correlation coefficients of adjacent traces. Note the relatively high coefficients (≥0.48) for adjacent traces of the same hydrophone and low coefficients (≤0.24) for adjacent traces of different hydrophones.

5.3. Geophone tests

The poor repeatability of the hydrophones (Figure 7) suggests usage of firmly grouted geophones instead. Besides offering stable coupling conditions, multi-component geophones provide vectorial information, which is important for elastic waveform inversions. Therefore, it was decided to install a string of multi-component geophones in the upper borehole at Mont Terri (Figure 3).

A special purpose geophone string including 48 3-component 100 Hz geophones was manufactured by the Dutch company Omniquest. Figure 9 and 10 show some details of the installation procedure. A detailed description of the entire project can be found in Cornée (2010). Here, it is focused on only on improvements of the coupling conditions.

Figure 11 shows a comparison of repeated recordings using a shot position at 15 m distance from the lower borehole collar and a receiver position 20 m away from the upper borehole collar (Figure 3). Trace no. 1 of the experiment was recorded with a hydrophone as described in section 5.2. Traces numbers 2 to 5 were recorded with the geophone string at various stages of the cementation procedure. Within the first week after cementation, an increase in the high frequency content and a slight decrease in the first arrival traveltimes were observed. This indicated that the cement had hardened to a sufficient degree, leading to improvements in geophone coupling and hence the quality of the recorded data.

Figure 9: Single 3-component geophone that was installed at Mont Terri.

Figure 10: Installation of Geophone string at Mont Terri.

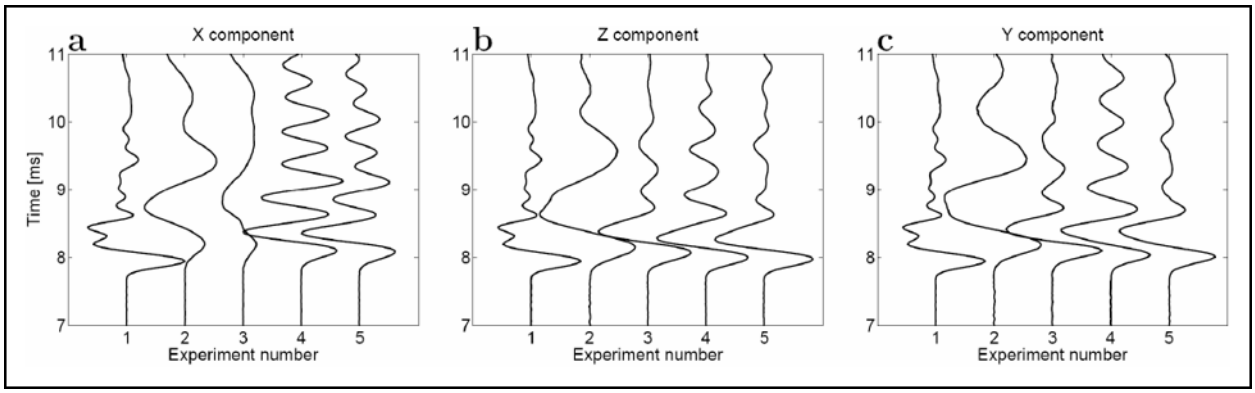

Figure 11: Seismic sections for different experiments using a source at 15 m distance in the lower borehole and the receiver at 20 m distance in the upper borehole. a), b), and c) show data recorded by geophones along the receiver borehole (x component), perpendicular to the receiver borehole in the plane of boreholes (z component) and perpendicular to the plane containing the boreholes (y component), respectively. Experiment numbers correspond to (1) hydrophone streamer (it records pressure, and is replicated in all panels), (2) geophone array immediately before cementing, (3) geophone array immediately after cementing, (4) geophone array 13 hours after cementing, (5) geophone array 5 days after cementing.

5.4. Determining elastic bentonite properties with laboratory measurements

The swelling of bentonite, in which high-level radioactive waste should be embedded, is one of the key targets of seismic near field monitoring. In order to quantify the effects of water saturation, temperature and pressure on the elastic bentonite properties, extensive laboratory measurements were performed. The full details of the investigations are documented in Tisato and Marelli (2012). Here, the discussion is restricted to the most relevant aspects of this study.

Four different sets of samples with water saturations from approximately 10% to 50% were initially prepared. Due to instrumental limitations, it was not possible to vary both temperature and pressure. Therefore, a first set of measurements was performed at a constant pressure of about 2 MPa. The resulting P- and S-wave velocities are shown in Figure 12. The individual curves demonstrate that (i) the seismic velocities primarily depend on the water content and (ii) that the velocities decrease linearly with increasing temperature.

In a second set of measurements the temperature was kept constant at room temperature, and the seismic velocities were measured under different confining pressures. The results are shown in Figure 13. As expected, both the P- and S-wave velocities increase with increasing pressure. Compared with the varying temperature measurements, shown in Figure 12, the velocities are more influenced by pressure than the water content. In particular, within the pressure range between 1 and 20 MPa, which is most significant for high-level radioactive waste repositories, the velocities vary considerably as a function of pressure.

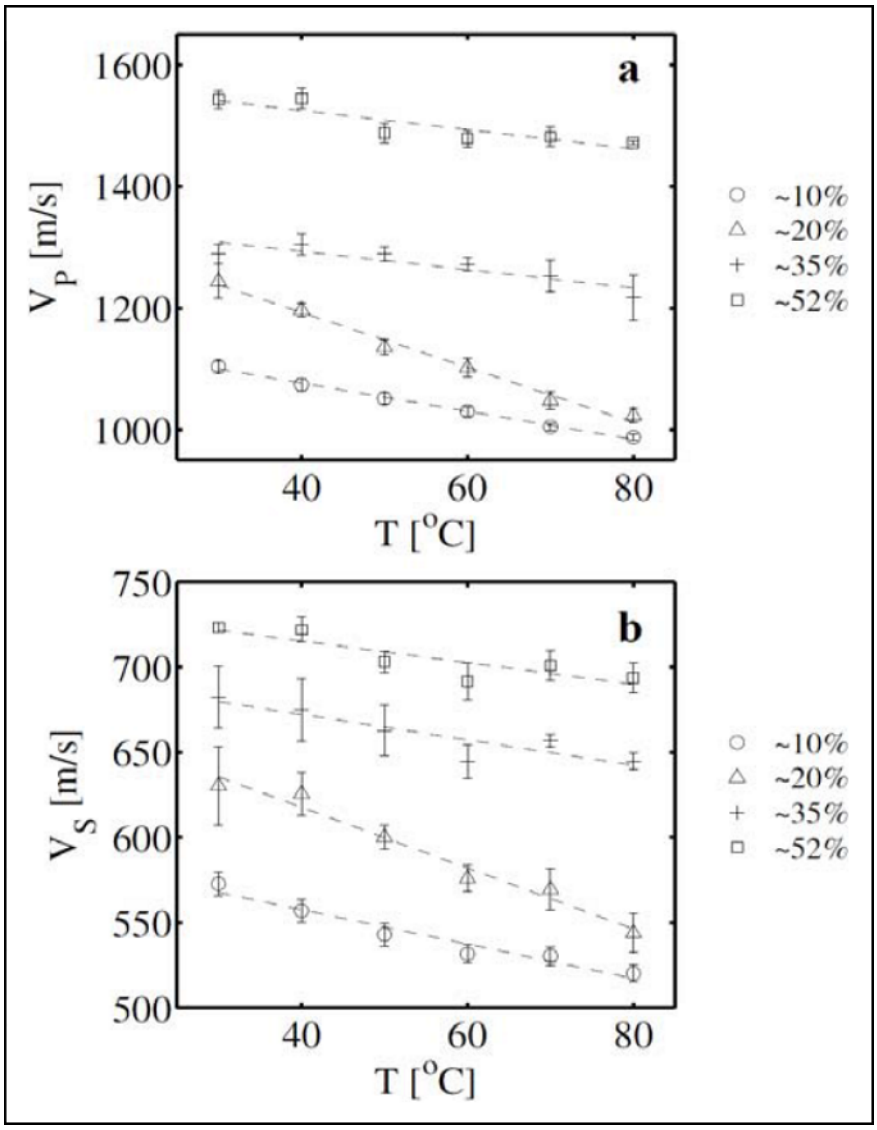

Figure 12: Seismic P- and S-wave velocities of bentonite as a function of temperature, for different percentages of water content .

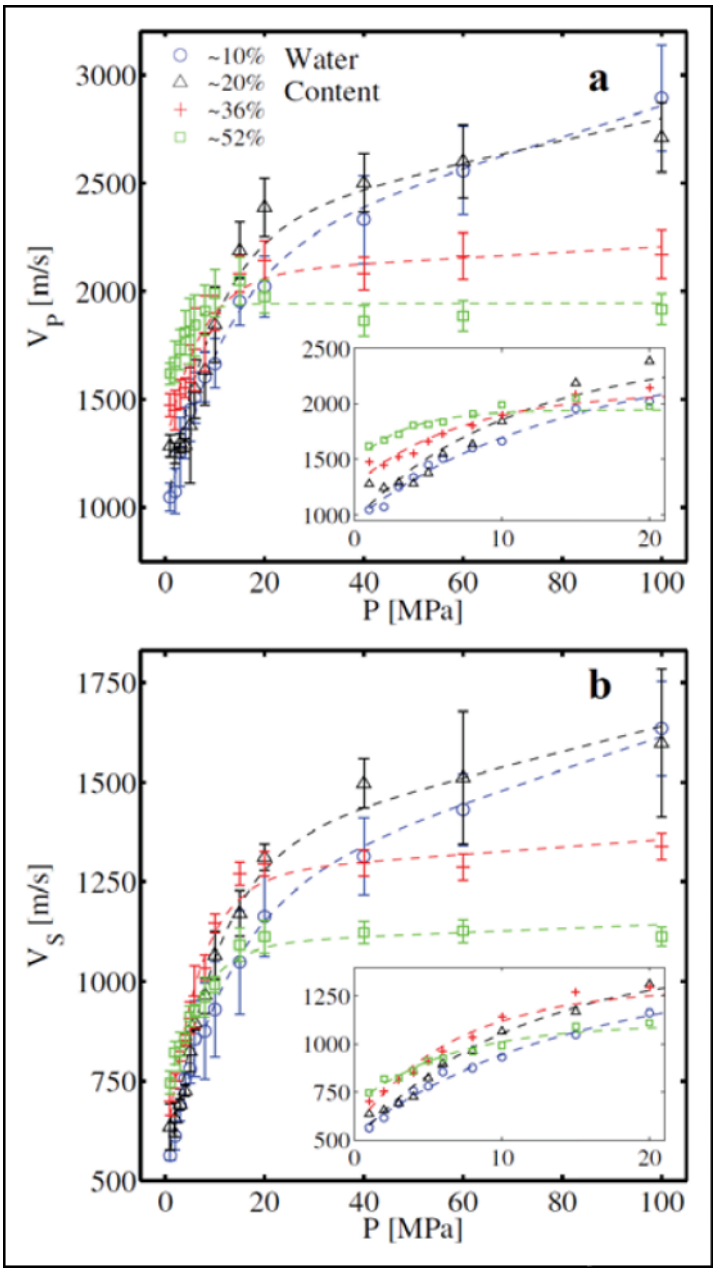

Figure 13: Seismic P- and S-wave velocities of bentonite as a function of pressure for different percentages of water content. The insets show expanded views of the pressure range 0 to 20 MPa.

6. Conclusions and recommendations

1. Numerical simulations revealed that changes in a potential radioactive waste repository, such as water saturation processes, lead to significant changes to seismic waveform data, if the data quality and repeatability is sufficiently high.
2. The numerical simulations indicated that the effects of repository changes on the waveform occur over relatively large areas. Consequently, the observational boreholes should be long enough and should extend well beyond the actual repository.
3. Extensive measurements have been performed at the Grimsel and Mont Terri test sites. It could be shown that the sparker source, manufactured by Geotomographie GmbH, provided useful results. The measurements are highly repeatable, the source pulse is sufficiently powerful, and frequencies up to several kHz can be generated.
4. Results from hydrophone streamers are less satisfactory. The main problem is their poor repeatability. Most of our measurements were performed with hydrophone streamers from Geotomographie GmbH, but we also tested several other products. The results were essentially the same.
5. Firmly grouted geophones seem to offer a reasonable alternative to hydrophones. They allow a high repeatability of the measurements. A possible problem could include the frequency bandwidth of geophones. In particular, it is not entirely clear how they perform at very high frequencies, which may be critical for resolving small-scale features.
6. Controlled laboratory experiments revealed that the elastic properties of bentonite vary significantly as a function of (i) water saturation, (ii) pressure and (iii) temperature. The laboratory measurements will form an important means for correctly interpreting seismic waveform tomography results.

On the basis of our results, we judge seismic waveform tomography to be a promising option for non-intrusive monitoring of radioactive waste repositories. Once the outstanding problems are resolved (see section 7), we recommend performing further monitoring experiments, preferably at a realistic scale. Since different host rocks will impose different challenges on such seismic experiments, it is further recommended to simultaneously perform experiments in different potential host rock environments (granitic rocks, clays, salt). Finally, we propose to identify alternative non-intrusive techniques that could complement seismic measurements. Although seismic waveform tomography is in our view still the most promising techniques, we see potential benefits from geoelectrical or electromagnetic methods, which may provide diagnostic information on the electrical properties/characteristics of the host rock.

7. Issues for further research and development

Although our research yielded several new insights on how to conduct seismic waveform experiments, there are still open questions that require further research. Here, we highlight the most urgent areas, where further knowledge is required.

a) ***Choice of receivers***

After having realized the unsuitability of hydrophone streamers, it needs to be determined which types of sensors offer the best alternative for seismic monitoring purposes. Geophones may be possible alternative (see section 5.3), but other types of sensors should be tested as well. In particular, piezoelectric receivers and Micro Electrical Mechanical Systems (MEMS) could be reasonable alternatives.

b) ***Longevity of equipment***

Monitoring may be required over periods of tens to hundreds of years. This requires equipment that provides stable and consistent results over such long periods. The longevity

of seismic equipment that is temporarily or permanently installed in boreholes or firmly grouted into the host rock, has not yet been studied sufficiently.

c) ***Firmly grouting sources and receivers***
Related with the longevity problem, it is also not clear if the sources and receivers should be firmly grouted, or if retrievability should remain an option.

d) ***Further development of the tomographic inversion algorithms***
As described in more detail in the Work Package 2 report D2.3.1. several improvements of the waveform inversion algorithms could be achieved, but further research is required, before all the important effects of a realistic monitoring experiment can be considered adequately.

e) ***Waveform inversions of observed data sets***
An important aspect of field data inversions is the pre-processing of the observed seismograms. Conceptually, only minimal pre-processing should be applied, in order to preserve the information content of the seismic data. However, the data likely include features that cannot be easily predicted with the forward modelling codes included in our waveform inversion codes (e.g., guided waves travelling along the boreholes). Therefore, appropriate pre-processing steps need to be identified.

8. References

Bohlen, T., 2002, Parallel 3-D viscoelastic finite difference seismic modelling: Computers & Geosciences, **28**, 887-899.

Buske, S., I. Lecomte, T. Nemeth, S. Operto, and V. Sallares, 2009, Imaging and inversion --- Introduction: Geophysics, **74**, WCA1-WCA4.

Cornée, S., 2010, Consistency of cross-hole seismic data acquisition and sensitivity information content analysis for monitoring radioactive waste repositories, Master thesis, ETH Zurich, Switzerland.

EC MoDeRN - ESDRED, 2012, Testing Non-intrusive Monitoring Systems Evaluation & Final Report

EC MoDeRn Project, 2013, Deliverable D2.3.1, RTD Final Report

EC MoDeRn Project, 2013, D3.3.1, Grimsel test Site: Report on completed wireless network demonstration activities.

EC MoDeRn Project, 2013, D3.4.1, Report on completed demonstrator activity at Hades URL, Belgium

EC MoDeRn Project, 2013, D3.4.2, Wireless data transmission, underground to surface at Hades URL, Belgium

EC MoDeRn Project, 2013, D3.5.1, Report on testing disposal cell monitoring systems under construction conditions at Bure URL in France.

Holliger, K., and J. Buhnemann, 1996, Attenuation of broad-band (50-1500 Hz) seismic waves in granitic rocks near the earth's surface: Geophysical Research Letters, **23**, 1981-1984.

Manukyan, E., 2011, Seismic monitoring and elastic full waveform inversion investigations applied to the radioactive waste disposal issue, PhD thesis, ETH Zurich, Switzerland.

Manukyan, E., S. Latzel, H. Maurer, S. Marelli, and S. A. Greenhalgh, 2012, Exploitation of data-information content in elastic-waveform inversions: Geophysics, **77**, R105-R115.

Marelli, S., 2011, Seismic imaging of temporal changes in underground radioactive waste repositories: surveillance requirements and full waveform inversion issues: PhD thesis, PhD thesis, ETH Zurich, Switzerland.

Marelli, S., H. Maurer, and E. Manukyan, 2012, Validity of the acoustic approximation in full-waveform seismic crosshole tomography: Geophysics, **77**, R129-R139.

Maurer, H., and A. G. Green, 1997, Potential coordinate mislocations in crosshole tomography: Results from the Grimsel test site, Switzerland: Geophysics, **62**, 1696-1709.

Maurer, H., S. Greenhalgh, and S. Latzel, 2009, Frequency and spatial sampling strategies for crosshole seismic waveform spectral inversion experiments: Geophysics, **74**, Wcc79-Wcc89.

Maurer, H. R., S. A. Greenhalgh, S. Marelli, E. Manukyan, and A. G. Green, 2012, Receiver coupling effects in seismic waveform inversions: Geophysics, **77**, 1-7.

Plessix, R.-E., 2008, Introduction: Towards a full waveform inversion: Geophysical Prospecting, **56**, 761-763.

Tisato, N., and S. Marelli, 2012, Laboratory measurements of the longitudinal and transverse wave velocities of compacted bentonite as a function of temperature and confining pressure: Applied Clay Science, **submitted**.

Wielandt, E., 1987, On the validity of the ray approximation for interpreting delay times, *in* G. Nolet, ed., Seismic tomography: Reidel Publishing Company.

Zimmer, M. A., M. Prasad, G. Mavko, and A. Nur, 2007, Seismic velocities of unconsolidated sands: Part 2 - Influence of sorting- and compaction-induced porosity variation: Geophysics, **72**, E15-E25.