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Appraisal of Waveform Repeatability and Fidelity for Crosshole Seismic Monitoring of Potential Radioactive Waste Reposit

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SUMMARY

An experimental study into the viability of remote crosshole seismic monitoring of potential nuclear waste repositories has been undertaken. Full-waveform repeatability measurements to assess source, receiver and coupling effects were carried out at the Grimsel hard rock laboratory in Switzerland. Numerical modelling simulations showed that changes in the anomalous feature to be monitored (bentonite plug) resulted in measurable changes in the seismic waveforms. However, the use of waveform inversion to extract changes in medium properties requires that the changes not be overshadowed by recording variations. We found that a sparker source was highly repeatable up to frequencies of several kilohertz for propagation distances out to several tens of meters. In contrast, we observed large variations of the hydrophone coupling to the host rock when the hydrophone streamer was removed and re-inserted into the boreholes. Our investigations have outlined a quantitative methodology to assess the data quality requirements for successful monitoring. We suggest that seismic full-waveform tomography can be used to monitor radioactive waste repositories provided that careful attention is paid to receiver coupling differences.

Introduction

Permanent removal of high-level radioactive waste from the environment is one of the most important and pressing technical challenges of today. Enclosing the waste by multiple engineered barriers and emplacement in deep geological repositories is widely accepted as a safe means of isolating it from the biosphere for the necessary 10^5 - 10^6 years. However, effective monitoring that does not compromise the engineered and natural barriers may also be required. To address this issue, we are investigating the viability of crosshole seismic methods for remotely monitoring high-level radioactive waste repositories. In particular, we are examining the suitability of seismic sources and receivers for accurate and highly repeatable measurements.

Experimental setup

The Grimsel Test Site (GTS), located in the central Swiss Alps, is dedicated to diverse studies associated with the storage of radioactive waste (GTS will not be used for waste disposal). Since the official opening of GTS in 1984, a wide variety of geophysical, geological, hydrogeological and rock mechanical experiments has been conducted in the tunnels and numerous boreholes of the underground laboratory (Kickmaier and Thury, 2002).

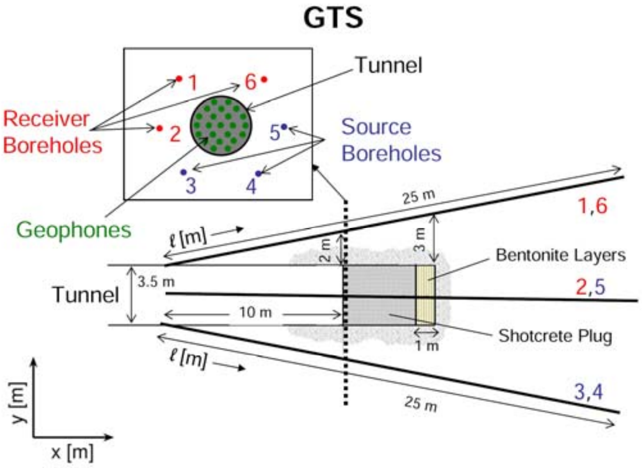

Figure 1 *The Grimsel Test Site experiment setup.*

Several European radioactive waste agencies have initiated and implemented experiments at GTS devoted to the non-intrusive monitoring of swelling bentonite. This clay is characterised by pronounced swelling and very low hydraulic conductivities when it is water-saturated (Villar et al., 2005). The experimental configuration at GTS is sketched in Figure 1. A 1 m thick bentonite wall is assembled 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, material deformation etc.

Since the swelling of bentonite is associated with substantial variations in its elastic properties (Wersin 2003; Villar et al., 2005), non-intrusive seismic monitoring was considered to be a viable and useful option to sense any changes. For this purpose, six gently dipping boreholes were drilled at regular intervals around the circumference of the tunnel, shotcrete plug and bentonite mass (Figure 1). The length and diameter of the boreholes were 25 and 0.085 m, respectively. During multiple seismic measurement campaigns, 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 characterised by a nominally repeatable broad-band spectrum up to several kHz, depending on its coupling to the host rock (Lovell and Hornby, 1990). The seismic waves were detected and recorded by an acquisition system that included 24 geophones mounted on the concrete plug, three multi-element hydrophone chains placed in gently dipping boreholes 1, 2 and 6, and a composite 24-bit dynamic range recording unit that allowed 120 individual channels to be simultaneously sampled at a timing interval of 20 μs. Each hydrophone chain was equipped with 24 pressure sensors 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 synthesised by shifting the hydrophone chains in increments of 0.25 m along the boreholes and repeating the shots.

Numerical simulations

To quantify waveform changes caused by medium changes within and around the simulated repository at GTS, we first performed some numerical modelling experiments. For the sake of simplicity and computational efficiency, we restricted the simulations to two dimensions. End-member scenarios were considered for this synthetic experiment: a dry and a fully water-saturated bentonite block (Table 1). We used a Ricker-wavelet source pulse with a 3 kHz centre frequency, corresponding to dominant P-wavelengths of ~1.73, ~0.94, ~0.17 and ~0.67 m for granite, shotcrete, and dry and wet bentonite.

Figure 2 shows the results for a shot position at about 20 m along the source borehole (red dot in the figure). Wavefield snapshots at 3.6 ms for the dry and wet bentonite scenarios are presented in Figure 2a and 2b, and simulated seismic sections for a hydrophone in borehole 2 are displayed in Figure 2d and 2e. Differences between the dry and the water-saturated scenarios, magnified by a factor 2, are displayed in Figure 2c and 2f. The snapshots and seismic sections clearly show that the simulated repository causes a large amount of scattering. It is 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 wavefields but also in the reflected wavefields.

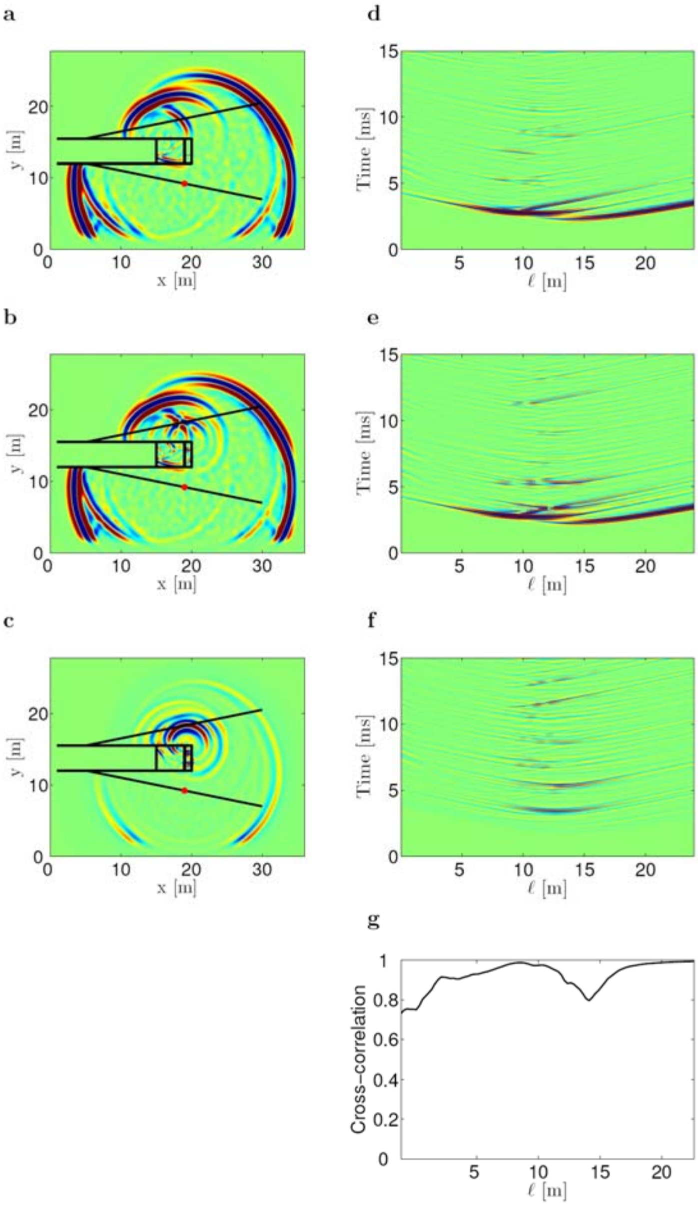

Figure 2 *Numerical simulation results show snapshots of pressure wavefields at 3.6 ms for (a) dry bentonite and (b) fully water saturated bentonite. (c) shows a difference snapshot (exaggerated by a factor of two). Source position is indicated by the red dot. (d) and (e) show seismic sections as they would be recorded in the receiver borehole, and f) depicts their differences. (g) displays the cross-correlation coefficients (using a time window of 5 ms after the first breaks) for the seismograms shown in (d) and (e).*

To quantify differences in the waveforms, zero-lag cross-correlation coefficients between the traces of Figure 2d and 2e are plotted in Figure 2g. The coefficients range from 0.75 - 1.0. Analyses using other shot positions yielded similar results. These cross-correlation coefficient variations are the result of changes in the seismic properties (density, P and S wavespeed) between the bentonite block and the surrounding host rock. Bentonite has a significantly lower wavespeed than 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 regardless of the water-saturation conditions, and little affected by the target zone itself (Figure 2g); the varying cross-correlation coefficients are related to changes in the later parts of the waveforms. This consideration suggests that tomographic analyses based on first arrivals will be of only limited use. Full-waveform tomography will likely be required to detect changes within the repository.

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

Table 1 *Material properties considered for the numerical simulations.*

Repeatability tests

The simulation results in Figure 2 clearly indicate that changes of the seismic waveforms caused by changes within the repository are rather subtle. It is therefore critical that repeatability differences in the seismic measurements be significantly smaller than any seismic changes caused by the repository. By means of two experiments we have investigated the repeatability of the sparker source and the hydrophone receivers.

Ten repeat shots at exactly the same locations were fired consecutively in borehole 5. The average coherence spectrum obtained from raw traces recorded on a receiver in borehole 2 shows good repeatability in the 0.5 - 3 KHz frequency range. To quantify the repeatability, the 10 raw traces were band-pass filtered in this range, stacked to form a master trace and cross-correlated individually with the master trace. The resulting cross-correlation coefficients (Figure 3b) demonstrate excellent repeatability of the source signal and hydrophone recordings: the average of the cross-correlation coefficients at the bottom of each trace is ~0.99.

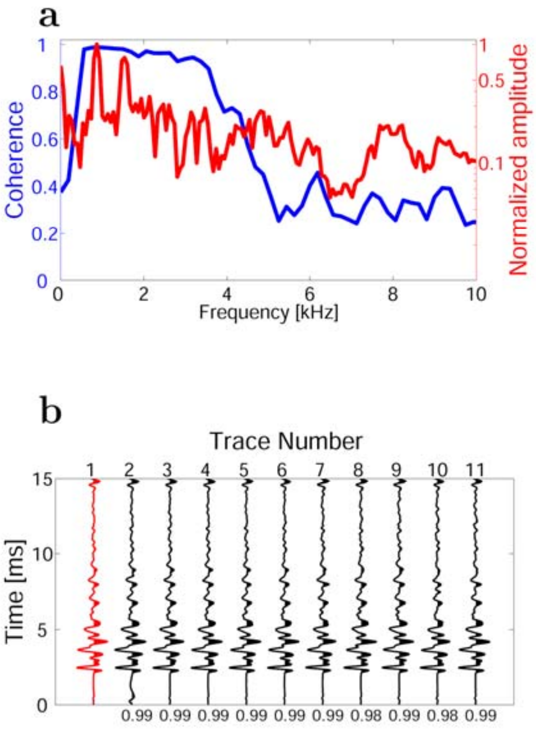

Figure 3 *Results of source repeatability tests. (a) Summed amplitude spectra (red curves, logarithmic scale) and coherence (blue curves, linear scale) for 10 repeat shots. (b) Seismograms from the same 10 shots after 0.5 - 3 kHz filtering. Numbers below the traces are normalised cross-correlation coefficients relative to the stacked master trace shown in red.*

Coupling of the hydrophones to the host rock was further investigated via the second experiment. Initially, the hydrophone chain was installed in observation borehole 2 and the sparker was fired at several positions within source borehole 5. Then, the hydrophone chain was removed, disassembled, reassembled and reinserted to the same nominal position. We observe significant changes in the waveforms (Figure 4a) 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 hydrophones (Figure 4b) quantify the differences in Figure 4a. The coefficients range from 0.2-0.8, which is clearly unacceptably low for monitoring purposes.

Conclusions

Numerical simulations show that realistic changes in a high-level radioactive waste repository (such as fluid saturation of the bentonite fill and damage zone) can produce measurable changes in the seismic waveforms recorded outside the volume of interest. Such changes can be detected provided that the data quality meets stringent requirements in terms of repeatability, reliability and bandwidth; comparison of traces recorded during repeat experiments under the same source, receiver and site conditions should yield cross-correlation coefficients of > 0.95 and the meaningful frequency bandwidth content should be at least 2 - 3 kHz.

The seismic sparker source (i) is highly repeatable for frequencies up to 5 kHz, (ii) is not susceptible to coupling problems and (iii) provides significant energy in a frequency band of several kHz. In contrast, variable coupling of hydrophones to the host rock has a major effect on the transfer function of the acquisition system. Minor differences in hydrophone positioning and seating result in substantial changes of the seismic sections.

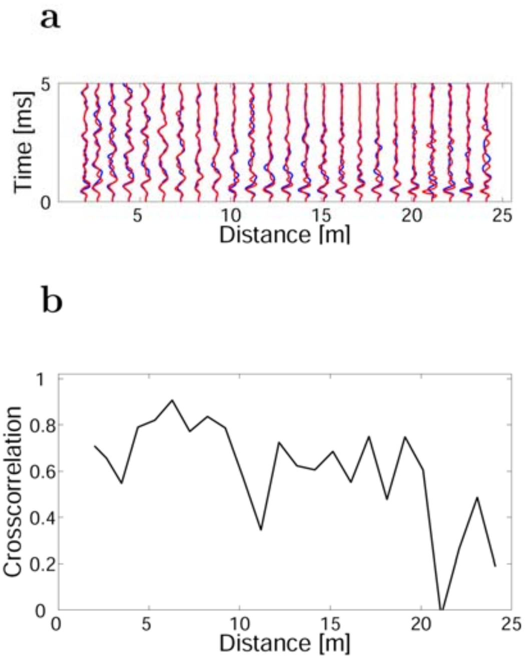

Figure 4 *a) Shot gathers for repeat experiments before (red traces) and after (blue traces) re-inserting the hydrophone streamer. b) corresponding cross-correlation coefficients.*

If the sensor coupling problem can be resolved, for example, by firmly grouting geophones into the observation boreholes, then crosshole and/or hole-to-tunnel seismic methods are likely to provide useful information for the remote monitoring of high-level radioactive waste repositories over repository-scale distances.

Acknowledgments

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