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Seismic Monitoring of a Simulated Radioactive Waste Repository During Water Saturation

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SUMMARY

In the framework of a radioactive waste disposal and monitoring program as part of the EC Integrated Project ESDRED, we have conducted for the NDA (UK) in co-operation with Nagra (Switzerland) high resolution (0.2 - 4 kHz frequencies) seismic experiments in an anisotropic clay unit at the Mont Terri underground rock laboratory in Switzerland. The objective was to explore the possibilities and limitations of seismic measurements for remotely monitoring, at distances of tens of metres, the changing properties of material filling a small scaled-down version of a repository (1 m diameter tunnel) embedded in a clay formation. Recordings using vertical-component geophones attached to the inside wall of the microtunnel revealed significant waveform variations for different fill materials (empty and sand-filled) and experimental conditions (dry, wet, and pressurised). Initially, the presence of water weakens the clay, but at a later stage the seismic measurements indicate swelling of the clay material, which likely causes healing in the excavation damage zone. On the basis of our results, it is judged worthwhile to develop wireless seismic sensors that could be employed for non-intrusive monitoring during the water saturation of a repository.

Introduction

Countries worldwide are seeking solutions for the permanent removal of high-level radioactive waste from the environment. A critical aspect of the disposal process is the need to be confident that when the waste is placed in a repository it is safely isolated from the biosphere. Seismic measurements offer a potentially powerful means for non-intrusive monitoring a repository.

It is assumed that immediately after its closure, a repository and its surrounding excavation damage zone (EDZ) will be dry, but that the EDZ and surrounding material will saturate quite quickly as groundwater infiltrates the volume. It is therefore important to know how the material properties of the host rock, and particularly the EDZ, will change as the water infiltrates. This is the motivation for conducting a series of controlled seismic measurements at the Mont Terri underground rock laboratory in Switzerland as part of the EC ESDRED Project.

Experimental set up

The Mont Terri rock laboratory is located in the Swiss Jura Mountains. The host rock is the Opalinus clay formation, which has an extremely low permeability. It has been identified as a potential host rock for high level radioactive waste in Switzerland because of its swelling and self sealing properties under water infiltration (e.g. Loew 2004). A distinguishing, feature of Opalinus clay is its high degree of elastic anisotropy (e.g. Nicollin et al. 2008), with slow and fast P-wave velocities of about 2500 and 3300 m/s, respectively.

Our experimental set up at the Mont Terri rock laboratory is sketched in Figure 1. It represents a scaled version (smaller by a factor of ~2.5) of a high-level radioactive waste repository and possible monitoring scheme. A 1 m diameter microtunnel (mimicking the repository) was drilled 13 m into the Opalinus clay host rock. Two inclined boreholes (25 and 29 m long) were drilled for crosshole monitoring purposes perpendicular to the axis of the microtunnel.

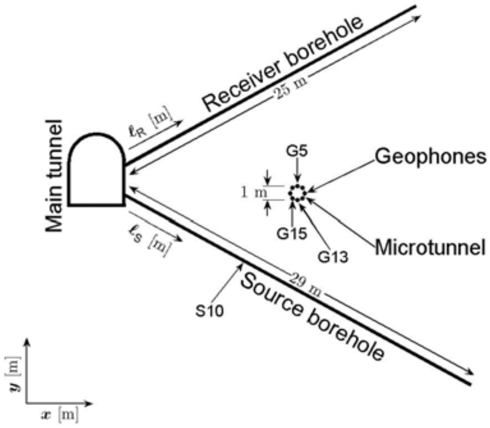

Figure 1 *Experiment set up at the Mont Terri test site, showing source and receiver boreholes and microtunnel with instrumented geophones.*

Initially the microtunnel was empty. Then, it was filled with sand and sealed with a megapacker system. Subsequently, it was water saturated and slightly over-pressured. The various stages of tunnel fill and water saturation were accompanied by seismic measurements. A high frequency sparker seismic source was placed in the lower borehole and sequentially fired at 0.25 m intervals. The seismic waves were sensed on a 24-element hydrophone streamer placed in the upper borehole and recorded on a multi-channel acquisition system. In addition to the borehole hydrophone array, 8 vertical-component geophones with a natural frequency of 100 Hz were installed at regular intervals around the circumference of the microtunnel in the plane spanned by the two boreholes (Figure 1). Several seismic measurement campaigns were carried out at different stages of the water-saturation and pressurisation experiment.

Temporal evolution during saturation

For analysing the temporal evolution within and near the repository, we focus here on the geophone recordings around the periphery of the microtunnel. More specifically, we consider geophone G13, which is placed at the very bottom of the microtunnel, and geophone G5, which is attached to the tunnel ceiling (Figure 1). Figure 2 shows 3 receiver gathers (all shots fired along the source borehole) for each of these 2 geophones. For comparison purposes, the traces are time-aligned on the first breaks. Furthermore, the trace amplitudes are strongly amplified, colour coded (blue = "up", red = "down") and even clipped to enhance important features in the sections. Figure 3 shows the corresponding summed frequency spectra for the first 3 ms of the receiver gathers in Figure 2.

Figures 2a and 2b depict the seismograms when the microtunnel was sand-filled and dry and Figures 3a and 3b show the associated spectra. The overall wavelet shapes of the G13 and G5 recordings are comparable, although the spectral peak of G5 is lower because of weaker coupling to the ceiling than to the floor of the microtunnel. The seismic traces in Figures 2a and 2b are dominated by a "ringing" pattern, which is likely caused by seismic energy bouncing up and down within the microtunnel. It is noteworthy that the first arrival polarity is "up" for G13 and "down" for G5, thereby indicating that the first arriving wavetrain travelled around the microtunnel (diffraction) and hit G5 from the top.

Immediately after saturating the microtunnel, a "new" phase in the form of a V-shaped arrival pattern appears in the G13 recordings (Figure 2c). Numerical modelling using realistic parameters for the Opalinus clay and the microtunnel indicates that this pattern represents shear waves. In fact, the shear waves are also present in Figure 2a, but they are obscured by the strong "ringing", which has decreased in Figure 2c. This is an indication that the overall impedance contrast between the microtunnel and host rock has decreased, which is to be expected when water replaces air in the interstitial sand pores. The recordings at G5 change markedly between Figures 2b and 2d. They are dominated by low frequency phases in the latter (see also Figure 3d). This is due to clay-water interaction, which weakens the clay and thus loosens the geophone anchorage. Due to gravitational sand loading on G13, this effect is less pronounced in Figures 2c and 3c.

Receiver gathers and their frequency spectra observed approximately one year after saturation are displayed in Figures 2e/2f and 3e/3f, respectively. Seismograms and spectra for the two geophones are now remarkably similar. Most of the first arrival polarities in Figure 2f have changed to "up" because the seismic velocities within the microtunnel have increased and the minimum time paths are now straight through the tunnel rather than around it. Furthermore, the spectral amplitudes for higher frequencies (> 3 kHz) are significantly increased (Figures 3e and 3f). This is a clear indication that the swelling of the clay led to a tighter coupling of the geophones and likely to a healing of the EDZ.

Characterization of the EDZ

Figure 4a shows seismic traces for source S10 and geophone G15 (Figure 1) for the different experiments presented in Figures 2 and 3. Since G15 is nearest to the source hole, the changes in the first arrivals can only be attributed to changes in the microtunnel EDZ. Trace 2 (immediately after saturation) shows a minor delay with respect to trace 1 (dry), which can be explained by the weakening of the clay. In contrast, the first arrival of trace 3 (one year after saturation) appears significantly earlier as a result of the EDZ healing process. We attempt to quantify information about the EDZ by analysing the arrival time differences Δt between traces 1 and 3 for all shots. Using a straight ray approximation, the traveltime difference Δt can be written as $\Delta t = s(r)\left(1-\frac{1}{\beta}\right)/v$, where v is the velocity of Opalinus clay in the microtunnel 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 the ray that passes through the EDZ. By varying β and *r* systematically, we attempt to find

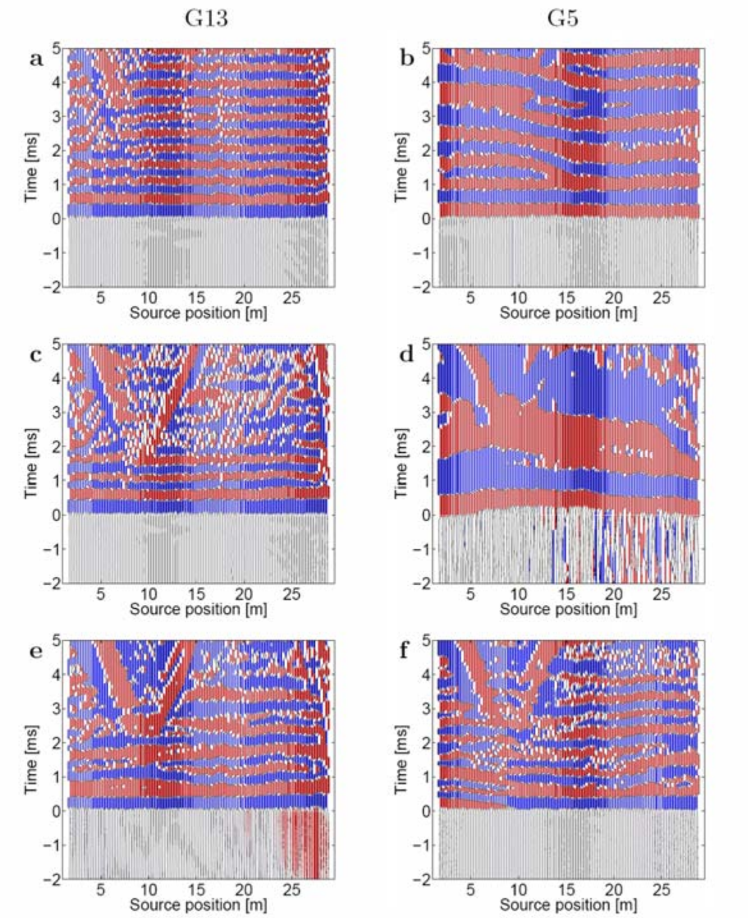

Figure 2 *Geophone gathers aligned with the first arrival for the top G13 (a, c, e) and the bottom G5 (b, d, f) geophones.*

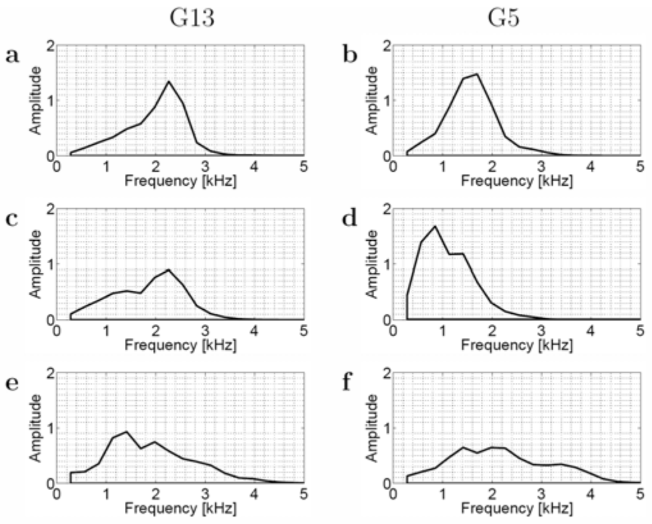

Figure 3 *Frequency content of first 3ms of the geophone gathers depicted in Figure 2.*

an optimal combination of the two parameters that explains all observed traveltime differences. As shown in Figure 4b, there exists a clear trade-off between β and *r* that minimises the misfit, such that à priori information on one of the two parameters is required for a unique solution. Nevertheless, the trade-off curve in Figure 4b provides constraints for narrowing the likely range of EDZ properties.

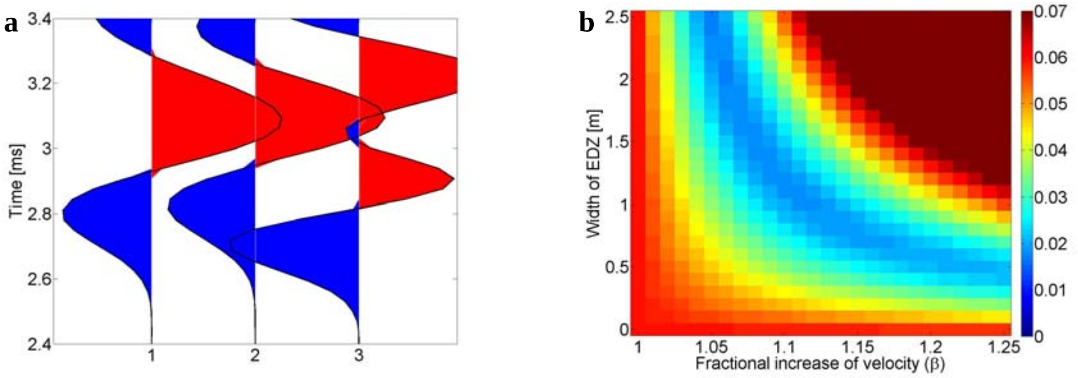

***Figure 4** a) Seismic traces for source S10 and geophone G15 (Figure 1). Traces 1, 2 and 3 correspond to experiments depicted in the first, second and third rows of Figure 2 respectively. b) RMS errors [ms] between observed traveltime differences of traces 1 and 3 for all source positions, and predicted differences using a straight ray approximation.*

Discussion and conclusions

Our measurements have demonstrated that seismic sensors placed near or within the simulated repository provide valuable information about its actual state, which would be difficult to obtain with other methods. However, placing geophones within the repository may be incompatible with the requirement that monitoring should be truly non-intrusive (i.e. no wires should lead into the sealed zone). A possible option would be to install wireless geophones. Such devices do not currently exist, but recent developments of wireless transmission technology (e.g. Akyildiz and Stuntebeck 2006) may make them feasible. Since water saturation of the EDZ and its surroundings are expected to occur within a relatively short time, it should be possible to operate regular sensors during this period. At a later phase, non-intrusive monitoring using crosshole tomography with a borehole configuration comparable to that shown in Figure 1 could be a viable option.

Acknowledgements

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