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Borehole-to-tunnel seismic measurements for monitoring radioactive waste

Edgar Manukyan, Hansruedi Maurer, Stefano Marelli, Stewart A. Greenhalgh, and Alan A. Green
Institute of Geophysics, ETH Zurich, Zurich, Switzerland (edgar@aug.ig.erdw.ethz.ch)

Countries worldwide are seeking solutions for the permanent removal of high-level radioactive waste (HLRW) from the environment. A critical aspect of the disposal process is the need to be confident that the deposited waste is safely isolated from the biosphere. Seismic monitoring represents a potentially powerful option for non-intrusive monitoring. We conducted a series of seismic experiments in the Mont Terri underground rock laboratory, where a 1-m-diameter microtunnel simulates a HLRW repository downsized by a factor of ∼2.5. The host rock at the laboratory is Opalinus clay. We had access to two water-filled boreholes, each approximately 25 m long (diameter 85 mm), with one inclined upwards and the other downwards. Both were oriented perpendicular to the microtunnel axis. Seismic signals were generated in the down-dipping borehole with a high frequency P-wave sparker source every 25 cm and received every 25 cm in the upward-dipping borehole on a multi-channel hydrophone chain. Additionally, the seismic waves were recorded on eight (100 Hz natural frequency) vertical-component geophones, mounted and distributed around the circumference of the microtunnel wall within the plane of the boreholes. The experiment was repeated with different material filling the microtunnel and under different physical conditions. So far, six experiments have been performed when the microtunnel was:
a. air-filled with a dry excavation damage zone (EDZ),
b. dry sand-filled with a dry EDZ,
c. 50 % water-saturated sand-filled with partially water-saturated EDZ (experiments were conducted immediately after half water-saturation),
d. water-saturated sand-filled with partially water-saturated EDZ (immediately after full water-saturation),
e. water-saturated sand-filled with water-saturated EDZ (water was in the microtunnel for about 9.5 months), and
f. water-saturated sand-filled and pressurized to 6 bars with water-saturated EDZ.

The results of our seismic experiments yield several important conclusions.
1) Travel time inversion of cross-hole data is not able to detect the microtunnel.
This is due to the small size and central location of the microtunnel. Consequently, waveform inversions need to be performed.
2) The geophone recordings around the periphery of the tunnel are strongly affected by changes within the microtunnel.
For example, between the individual experiments there are changes in the polarity of the first arriving waves for some of the geophones. This is because the recorded wavefield is a superposition of two waves. One wave passes directly through the microtunnel and is, therefore, influenced by the fill material. The other wave is diffracted around the microtunnel and is thus influenced primarily by the EDZ. The first wave to arrive depends on the geophone location (top, bottom, side of tunnel) as well as the state of the microtunnel and its EDZ.
3) Water infiltration changes the elastic properties of the microtunnel very rapidly.
Repeated shots within 30-40 minutes intervals show significant waveform changes for some of the geophones during experiments (c) and (d).
4) Water infiltration changes the coupling conditions of the geophones significantly.
For experiment (d), the frequency content on some geophone traces decreases significantly, and there is a remarkable increase of higher frequencies for experiments (e) and (f). This is due to the clay-water interaction, which first weakens the clay and thus loosens the geophone anchorage. Later, the water penetrating into the EDZ leads to swelling of the clay, which firmly fixes the geophones.

5) Analyses of the geophones installed within the microtunnel allow elastic properties of the EDZ to be delineated. A simple analysis of the first-arrival traveltimes allows us to determine a relationship between some properties of the EDZ (elasticity, radius).