# Seismic Monitoring at the Underground Nuclear Research Laboratory in MOL, Belgium - 12461

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## ABSTRACT

Micro-seismic piezoelectric transmitters installed in the Boom Clay at HADES produce predominantly high frequency signals, above 5 kHz, which favour the generation of P waves. However, above 5 kHz shear (S) waves are not detected by the installation. Recent studies at HADES indicate that it is possible to detect S waves with the current setup when applying a low (5 kHz) cut-off filter. The results also show that S waves have frequencies mainly below 1 kHz, while P waves are detectable at all of the eight transmitted frequencies but show optimum resolution in the range of 7 to 23 kHz.

Although the system offers great potential for monitoring the evolution of a geological disposal site, further improvements in signal generation and treatment are necessary. One of these includes the design and testing of a new S-wave source at HADES planned in the framework of the EC MoDeRn project (http://www.modern-fp7.eu/).

## INTRODUCTION

HADES is an Underground Research Facility (URF) located at the Belgium Nuclear Research Center (SCK•CEN) in Mol, Belgium. It consists of approximately 250 m of galleries constructed in the Boom Clay, at a depth of 225 m below surface. Two shafts provide access to the URF, as shown in Figure 1.

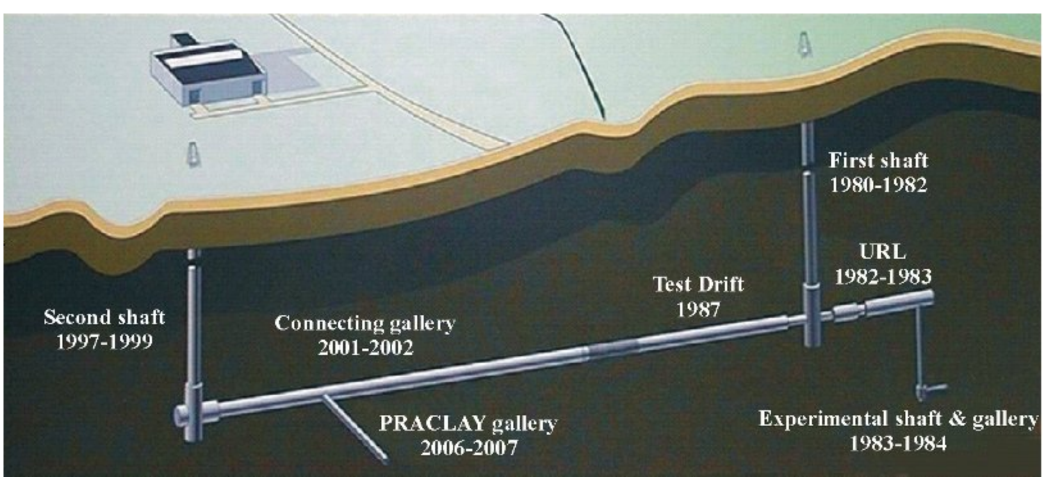


Fig 1. The underground research facility HADES – Mol, Belgium.

HADES is managed and operated by EIG EURIDICE, an economic interest grouping involving SCK•CEN and the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS). It carries out feasibility studies for the disposal of high-level and/or long-lived radioactive waste (HLW) in clay layers. In this way, EIG EURIDICE contributes to the national radioactive waste disposal programme managed by ONDRAF/NIRAS.

A new experiment in HADES is the PRACLAY in-situ heater test (Figure 2). This experiment, which is set to start in 2012 and to last for 10 years, simulates the effects of heating generated by high-level nuclear waste on the properties of the Boom Clay. The current seismic installation forms part a general monitoring plan to measure the effects of heating on the gallery lining and the Boom Clay.

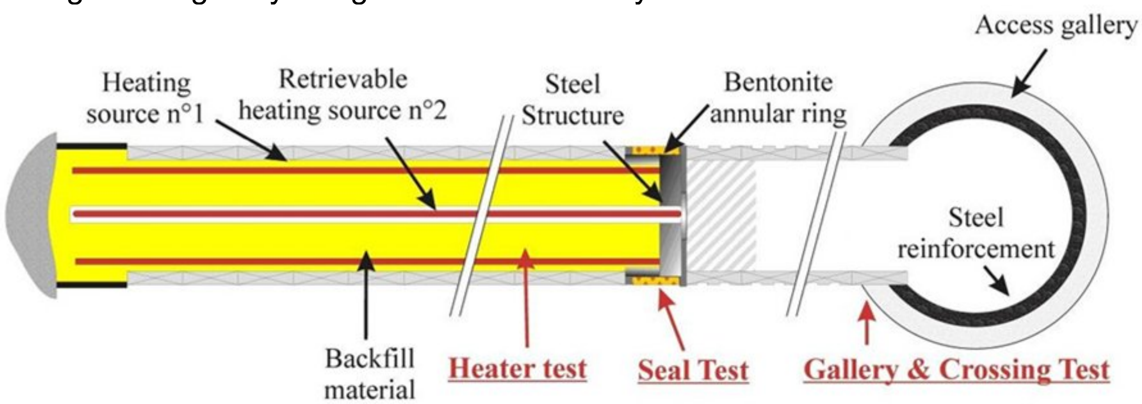


Fig 2. The PRACLAY heater experiment.

The installation of the monitoring system consisted of two phases: the first in 2006 prior to the construction of the PRACLAY gallery to monitor the far field; and the second after construction in early 2008 to monitor the near field around the gallery. The ongoing seismic measurements continue to provide information on the evolution of the EDZ around the PRACLAY gallery and in the Boom Clay. In the future, they will also assist in monitoring the thermally disturbed zone (TDZ) around the heater test.

## LAYOUT AND INSTRUMENTATION

The micro-seismic piezoelectric sensors consist of 23 transmitters (T) and 19 receivers (R). They are installed in three boreholes to depths varying between 0.5 m and 14 m (Figure 3) as well as at the interface between the gallery lining and the clay host formation (Figure 4).

The shape of the contact surface of the sensors fits the contact shape of the clay to provide a good acoustic contact. Finally, the sensors are made water tight and are sensitive to generate or receive P and S waves in a frequency range between 50 Hz and 100 kHz.

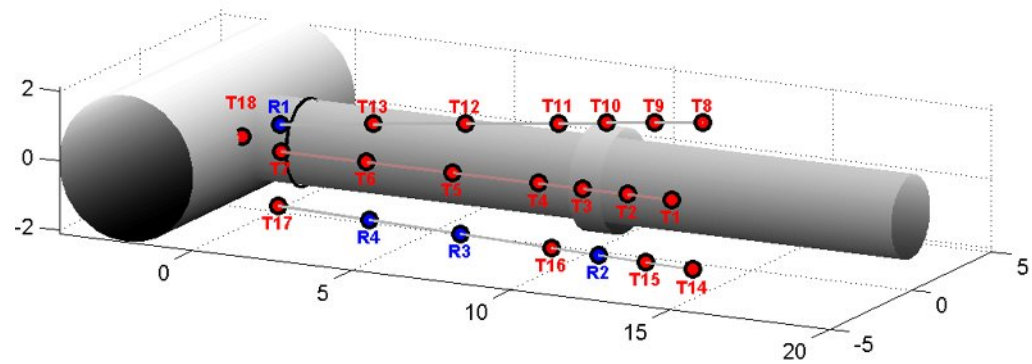


Fig 3. Transmitters (T) and receivers (R) installed in 2006 in 3 boreholes around the future PRACLAY gallery.

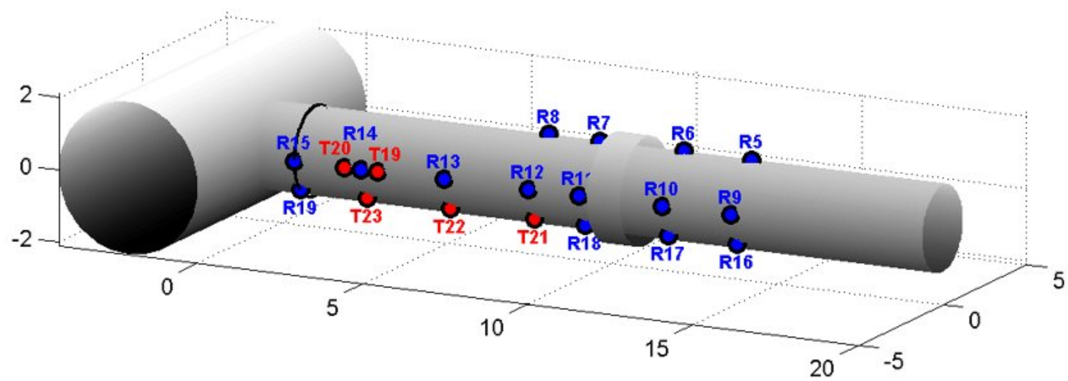


Fig 4. Transmitters (T) and receivers (R) installed at the extrados of the PRACLAY gallery in 2008.

## DATA ACQUISITION

The data acquisition (DAQ) system combines micro-seismic transmission and ultrasonic acoustic-emission (AE) measurements. It includes both a digital signal generator and a transient recorder built-in and controlled by an industrial personal computer, as schematically shown in Figure 5. The sampling frequency is 500 kHz. The DAQ system is accessible via an internet connection and operates fully automatically.

AE monitoring is active from 8 pm to midnight. These measurements run in the frequency range of approximately 1 kHz to 50 kHz, with a high-pass filter set at 1 kHz to filter out the low frequency background noise. The micro-seismic transmitter-receiver measurements run with all appropriate transmitter-receiver combinations (Figures 3 and 4) between midnight and 5 o'clock in the morning. Both measurements are performed daily and outside normal work hours to avoid work-related disturbances.

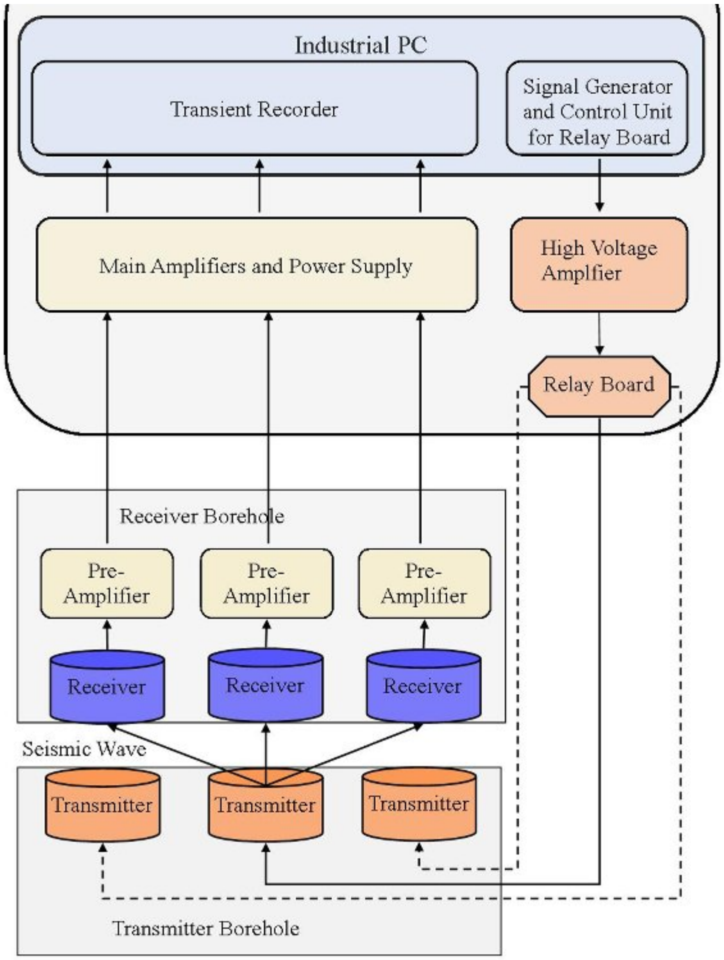


Fig 5. Data acquisition system.

## SIGNAL GENERATION

### AE Signals

The system is set to trigger mode to perform AE monitoring. A ring buffer first writes signals measured in sampled receivers and then scans the channels to select those signals with a minimum trigger level. When the receiver amplitude is higher than the trigger level we have a triggered channel. The trigger condition may be reached on one or more channels. Finally, the digitized waveforms are stored when two or more channels meet the trigger condition.

The histogram in Figure 6 shows the daily event counts of AE activity for the period between February 2008 and September 2009 with 19 receivers. The green bars show the number of events with at least 2 triggered channels. The red bars show all hits in 600 days. The distribution of the green bars has an average of about one event per day. Approximately half of the days show no event at all (the big green bar at zero). From a total number of 7258 triggered events, 576 have two triggered channels and only about 170 of them are real AE events.

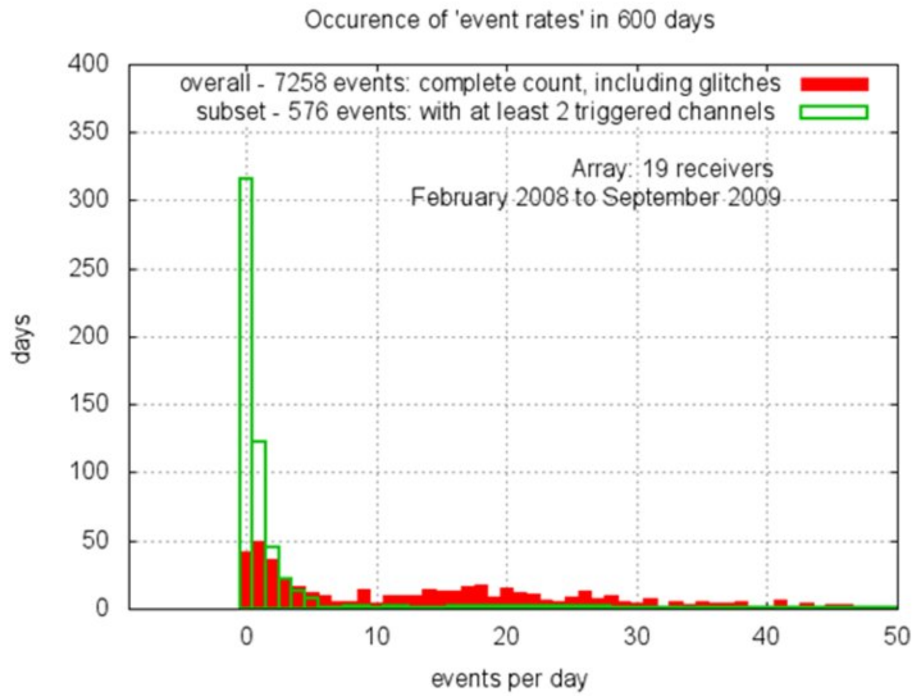


Fig 6. Observed AE event rates in 2008 and 2009.

**Transmission-Receiver Signals**

Each transmitter-receiver measurement uses eight transmission signals, all containing a different frequency content. A computer program calculates the shape of the transmitted signals, which consist of a broadband ramp signal generated by a step function and seven sinusoidal signals with center frequencies between 5 000 and 50 000 Hz, as shown in Figure 7. Measurements are performed with all transmitters, which are connected to the high-voltage amplifier using a relay device. At every measurement all receivers are active and all received signals are stored.

Finally, individual seismic signals recorded at HADES with the current seismic installation are too weak because of the high damping characteristics of the Boom Clay. This requires stacking the signals 256 times to sufficiently improve signal-to-noise ratio and amplitude.

**RESULTS AND DISCUSSION**

Figure 8 shows typical AE recordings obtained at the site. The signals show a first arrival at R15. The first arrivals align with a clear slope for each receiver line. The time difference between the first arrivals of R09 and R15 is approximately 7 ms, which with a distance of 13.2 m between the receivers gives an apparent wave velocity of

1,885.7 m/s. This is close to the P wave velocity and therefore, the source location lies in the line R09..R15.

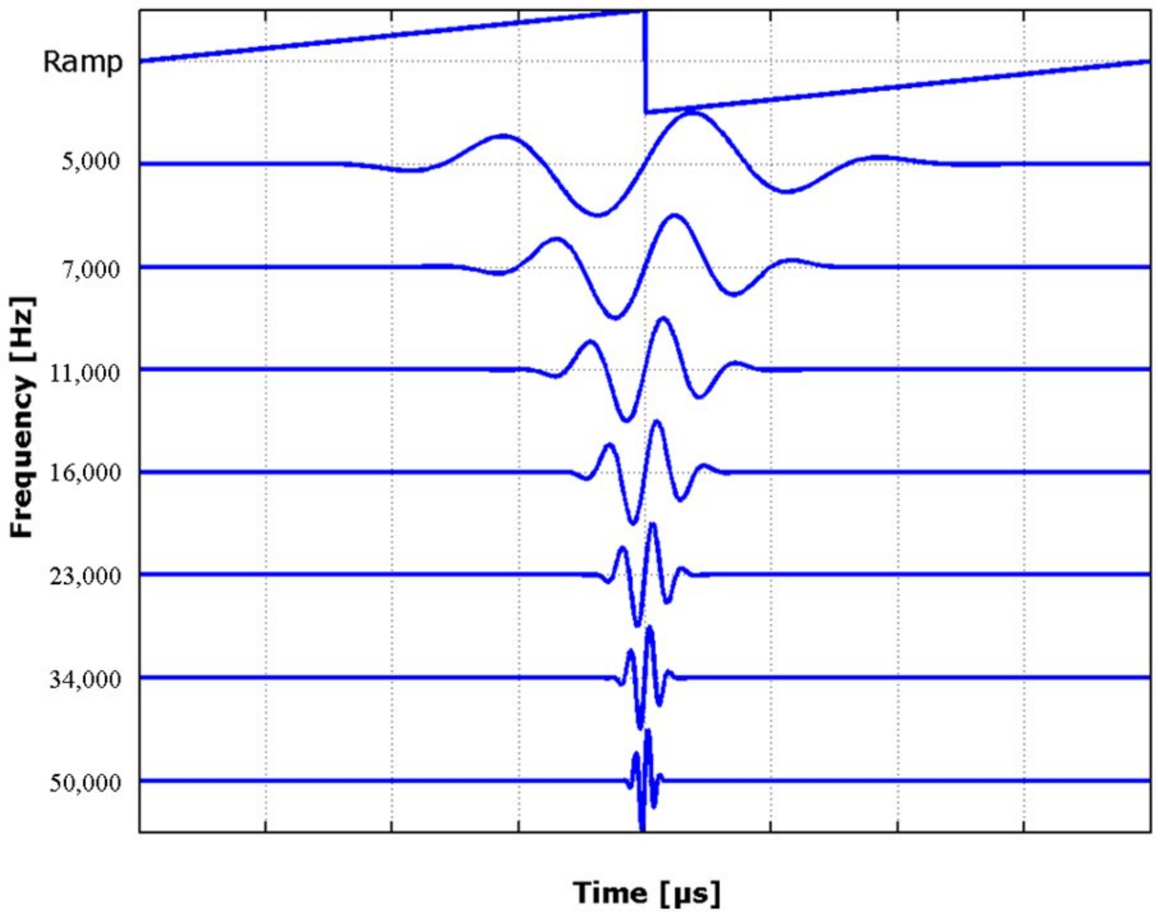


Fig 7. Shape of transmitted signals generated with the eight different frequencies.

Typical signals recorded for transmitter-generated waves in 2006 between transmitter T4 and receiver R3 appear in Figure 9. The figure shows the eight individual measurements corresponding to the transmission signals given in Figure 7. The first arrival signals shown on all traces are the crosstalk between the electrical transmitter signals and the electrical circuit of the receiver channels, which is a typical feature of this system.

The second arrivals shown are the P-wave signals. All transmission signals generate visible P waves even at the highest-frequency transmission signal of 50 kHz, which shows the weakest but still visible P-wave arrival.

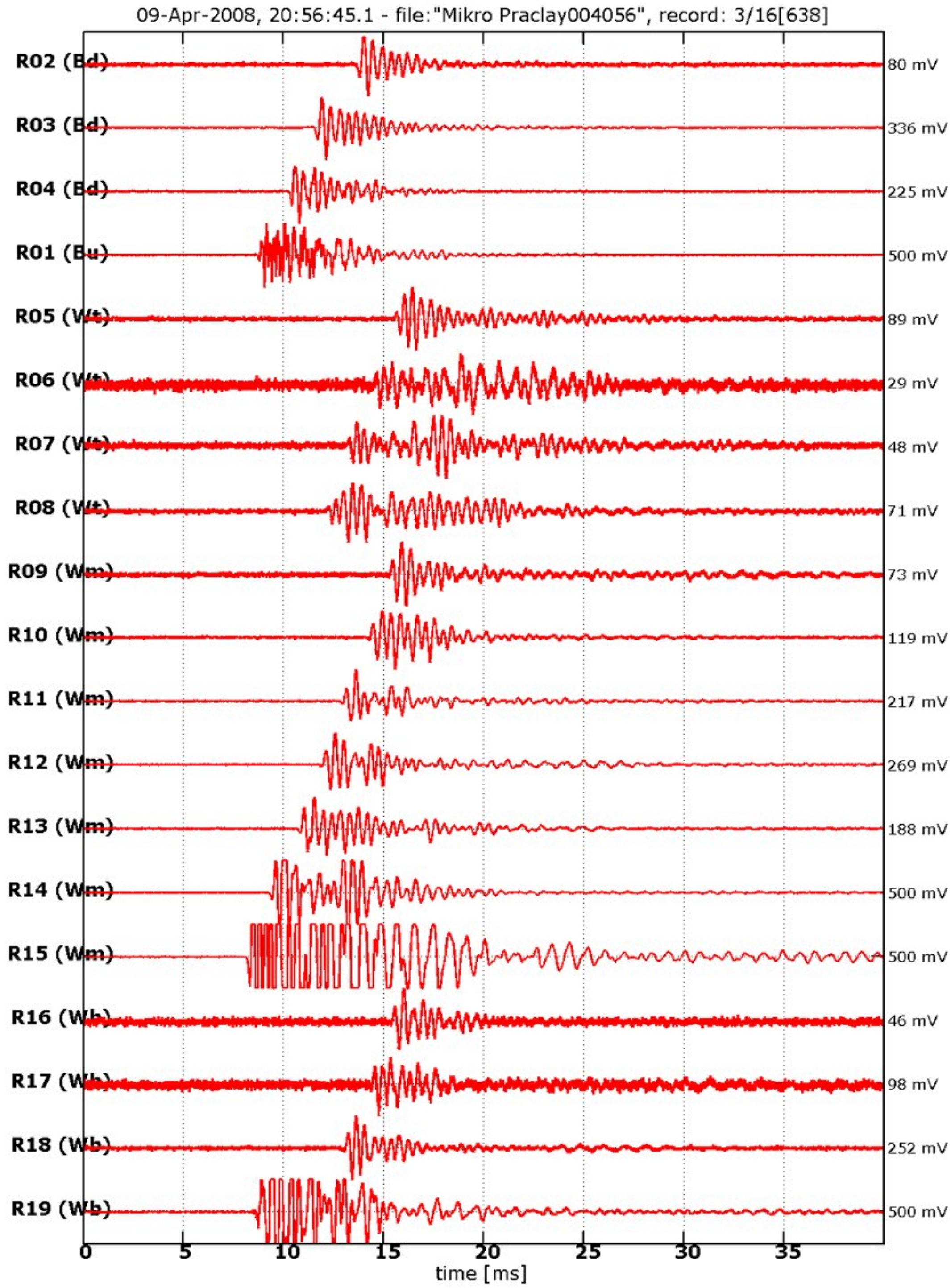


Fig 8. Sample of AE measurements showing first arrival at R15.

The uppermost trace (broadband step function) contains a third, low-frequency signal arrival corresponding to an S-wave. This trace contains frequency components below 5 kHz, while the measured S waves have frequencies mainly below 1 kHz. The other traces contain frequency contents above 5 kHz and do not show S-wave signals. In fact, with the current setup, only the broad-band step function allows the generation of both low-frequency (S) and high-frequency (P) waves.

Efforts are underway to optimise the detection of S waves for all of the transmission modes. In a first phase, signals were analysed after applying a low-pass filter of 3 kHz to the recorded traces. Figure 10 shows the results for waveforms recorded in September 2006 at receiver R3 from transmitters T3, T4, T5 and T6.

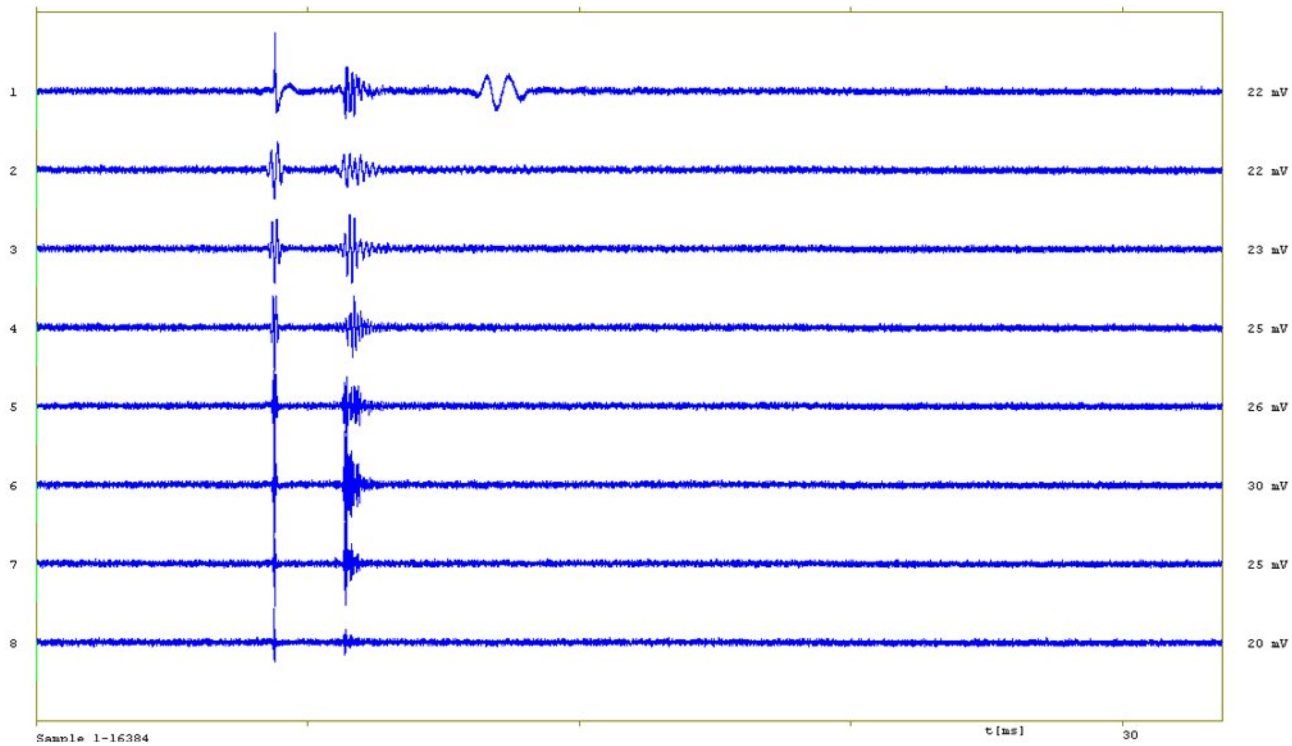


Fig 9. Transmission recordings made 15/11/2006 between T4 and R3. Uppermost signal from step function, below signals from 5 to 50 kHz.

The vertical axis gives the distance between receiver R3 and the various signal transmitters noted on the right hand side of the graph. Traces T3, T4 and T5 show visible S waves, which confirm the characteristically low frequency content of shear-wave signals. The results give velocities of 2,200 m/s for the P waves and between 600 and 800 m/s for the S waves. Further research is on-going to improve the generation of S waves at HADES, including the development of a new S-wave source to generate high energy, directional S waves. This work will be carried out as part of the EC MoDeRn project [1].

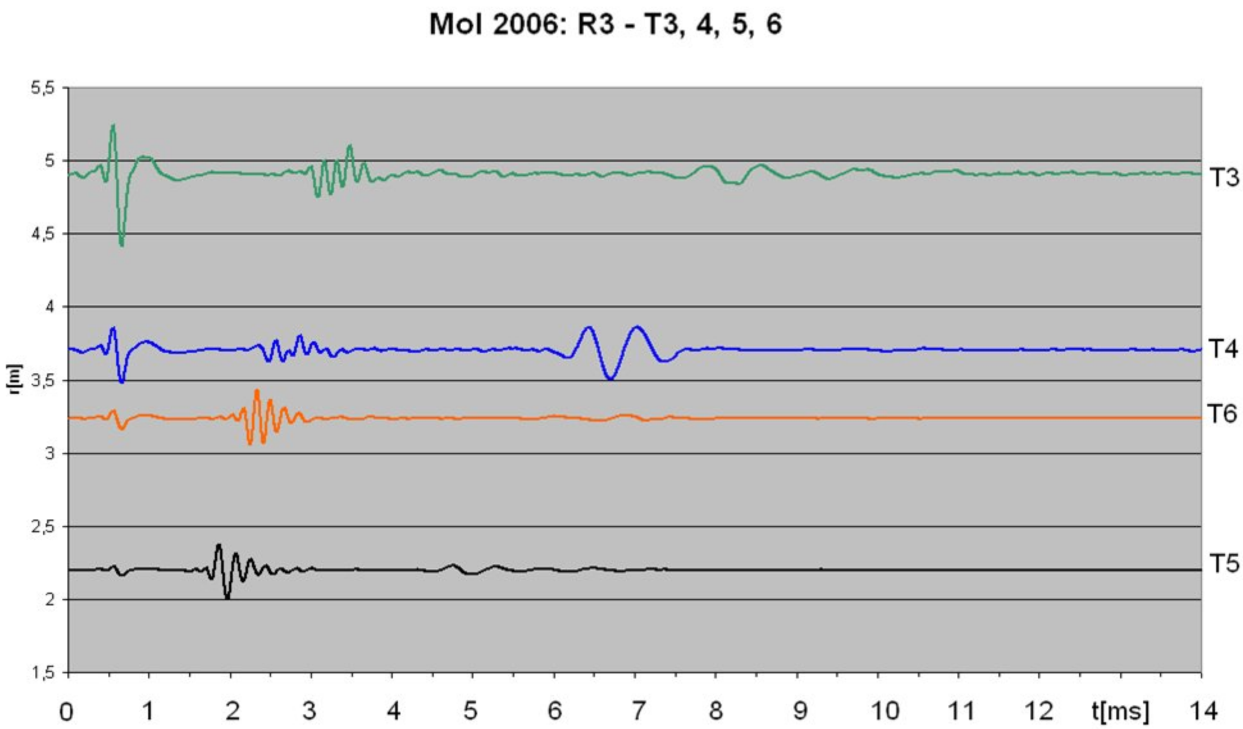


Fig 10. Received signals generated September 2006 analysed after 3 kHz low-pass filtering. Measurements from R3 and T3, T4, T5 and T6.

To improve the signal-to-noise ratio of S-waves it is necessary to apply a strong low-pass filter that matches the S-wave frequency content. Since the frequency range of P waves is much broader than that of S waves, it is not advisable to apply the same low-pass filter to both P and S waves. Doing this would remove most of the signal energy in the P waves. The alternative is to treat P and S waves separately.

Figure 11 presents typical time and amplitude series of transmission measurements recorded at the PRACLAY gallery in HADES between 2006 and 2009.The P-wave plots shown are for transmitter T9 and receiver R2. They contain the complete raw signal, which has not been filtered. The sharp drop in amplitude corresponds to the construction period of the PRACLAY gallery. As expected, the time-series trace shows no evidence of the presence of S waves.

Figure 12 shows the evolution of the S-wave trace between transmitter T5 and receiver R3, for the period of 2006 to 2009, using a low-pass filter of 5 kHz. It is obvious from the time-series trace that the low-pass filter of 5 kHz clearly improves the signal-to-noise ratio of the S wave while allowing part of the P-wave content.

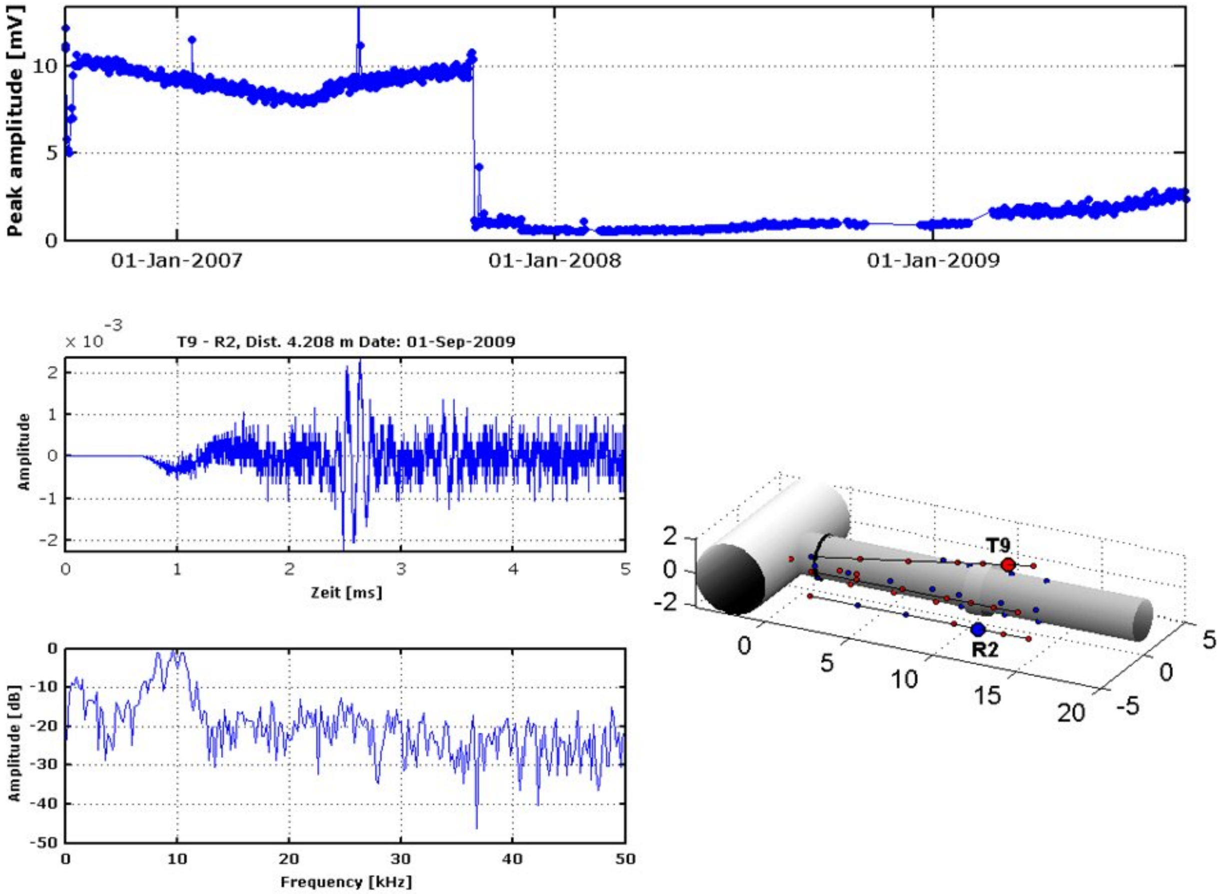


Fig 11. Evolution of P-wave signals between T9 and R2 from 2006 to 2009, no filtering.

The sudden drop in peak amplitude with time of both P and S waves shown in Figures 11 and 12, respectively clearly highlight the construction activities of the PRACLAY gallery. The results also show a progressive recovery of P and S-wave velocities after construction of the gallery suggesting that the EDZ recovers after the construction activities.

Modelling analysis further confirm the recovery of the EDZ indicated earlier. The results are shown in Figure 13 giving the variation in crack density obtained from the inversion of the modelled P-wave transmission velocities. They have been calculated using a modelling technique that allows the derivation of anisotropy and splitting of elastic waves from modelled crack density, aspect ratio and fabric orientation [2]. The main observation from the model is the decreasing trend in crack density with time after construction activities, confirming recovery and self-sealing of the Boom Clay after excavation. This also suggests that the permeability properties of the clay recover after excavation but further analysis is necessary to confirm this.

Fig 12. Evolution of S-wave signals between T5 and R3 from 2006 to 2009, low-pass filter 5 kHz.

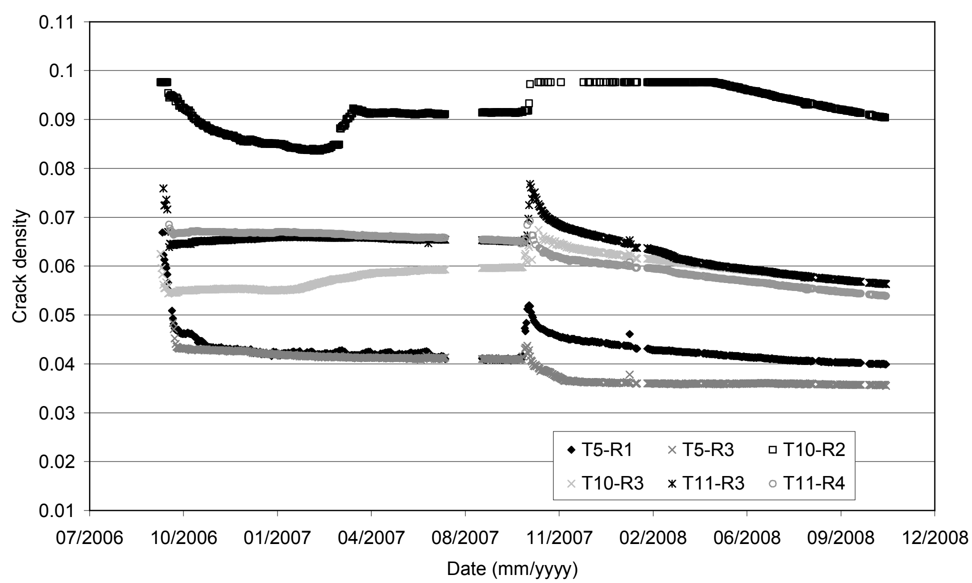


Fig 13. Crack density inverted from modelled P-wave velocities around the PRACLAY gallery [1].

## CONCLUSIONS

The seismic installation at HADES continues to provide useful information on the changing properties of the Boom Clay in the near and far field around the PRACLAY gallery since its start of operation in 2006. In the future, the system will also monitor the PRACLAY heater experiment that will start in 2012 and go on for 10 years.

So far, the results of long term seismic monitoring show that S waves contain frequencies mainly below 1 kHz. The P waves are detectable at all of the eight transmitted frequencies but show optimum resolution in the range of 7 to 23 kHz. To improve the signal-to-noise ratio and detection of S waves at HADES it is, therefore, necessary to apply a strong low-pass filter that matches the S-wave frequency content. Due to the different frequency ranges observed for the P and S waves, it is recommended to treat them separately.

The evolution of both P and S wave velocities in the EDZ around the PRACLAY gallery show continued recovery since its construction in 2007. Modelling results of the variation in crack density obtained from the inversion of the modelled P-wave transmission velocities further confirm the recovery of the EDZ and the self-healing properties of the Boom Clay.

## REFERENCES

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