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Automated workflows for rapid understanding of ACT and RES imaging potential in an OSI context

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INTRODUCTION AND MAIN RESULTS

To enable rapid evaluation of the imaging potential of resonance seismometry (RES) and active seismic surveys (ACT) data acquired during an on-site inspection (OSI), semi-automated workflows have been developed. Both workflows were evaluated on OSI 2023 Field Test (UK, FT23) and OSI 2024 Build-Up Exercise (Hungary, BUE24) data. The ACT workflow follows a minimalistic processing approach leading to generation of a brute stack with coherent events likely originating from targeted tunnels observed. The RES workflow applies seismic interferometry in the form of auto- and cross-correlation, potentially turning concealed OSI-relevant subsurface features into secondary seismic sources. While some events are seen in cross-, auto-correlation results show diffractions collocated with known location of tunnels as seen in ACT data.

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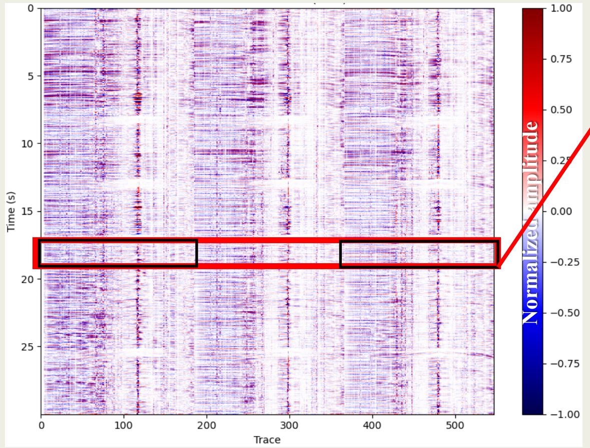
Introduction

On-site inspection (**OSI**) is the final verification measure of the **Comprehensive Nuclear Test Ban Treaty** (**CTBT**). Among other methods, **resonance seismometry** (**RES**) and **active seismic surveys** (**ACT**) can be used from the start of a continuation period of an OSI. Given the time-restricted nature of an OSI, automation is needed to quickly analyze these datasets. With this idea in mind, semi-automated workflows, compatible with the standardized data outputs of the current Preparatory Technical Secretariat (PTS) owned ACT equipment, have been developed for rapid analysis of data quality and imaging potential of both ACT and RES data.

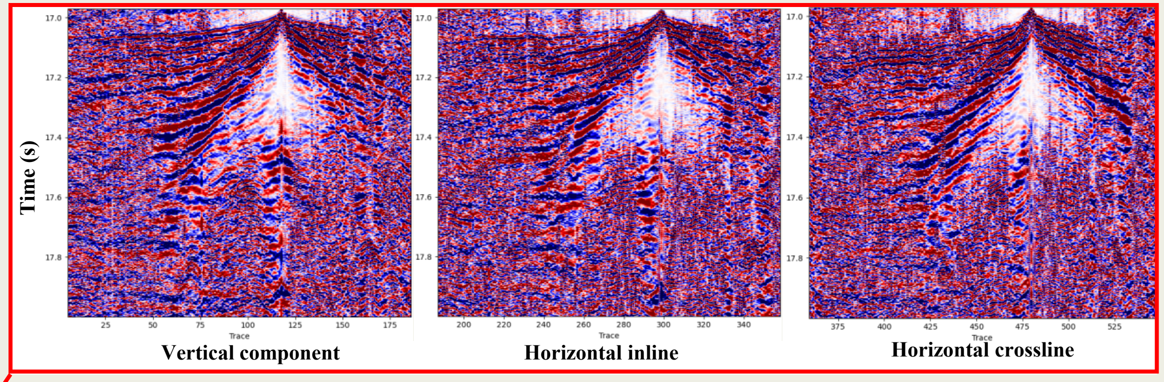
Methodology

The PTS currently owns **800 three-component (3C) seismic data recorders** – **GSB3 nodes** that are used together with **5 Hz 3C geophones**. The recorders can be used to continuously record **simultaneous RES** and **ACT data.** The semi-automated workflows rely on:

- **ACT** portion consisting of data segments specific to activation times of an active seismic source;
- **RES** data representing the continuous data segmented into smaller portions (30 s) for the ease of analysis.



Example of a 30 s long segment of ACT/RES data acquired using 181 GSB3 nodes.



ACT workflow

The ACT workflow follows a minimalistic **common midpoint (CMP) reflection seismic processing approach** using standard OSI software (GLOBEClaritas), supplemented by internally written Python codes embedded in it, including:

- Vibroseis correlation and vertical summation (as applicable),
- Splitting the 3C data into individual components (**Vertical, Horizontal Inline and Crossline**),
- Amplitude balancing and frequency analysis in shot gather domain,
- CMP geometry binning and elevation statics estimation and
- Semi-automated first arrival picking where 10-20% of manual picks are used for training purposes of a **supervised neural-network based machine learning (ML) automatic picker**.

ACT - refraction

The picked first arrivals are used for **seismic refraction tomography** purposes.

ACT - reflection

The same tomographic solution provides also:

- Refraction static solution,
- Starting velocity model for stacking or depth conversion,

If this model is deemed insufficient, velocity analysis using common velocity stacks (CVS) and supergather method are implemented.

Final output is a brute stack enabling quick overview if any OSI relevant features might be present.

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RES workflow

The **RES workflow** assumes that the subsurface cavities, tunnels, rubble zones, etc., act as point scatters for distant wavefields (or secondary seismic sources).

Under these assumptions, **seismic interferometry in the form of auto- and cross-correlation** is applied. Both approaches are automated and involve:

- Loading portion (or complete) continuous RES data as 30 s segments and downsampling,
- Instrument response removal,
- Amplitude normalization,
- Spectrogram analysis of segmented data,
- Band-pass filtering and
- Spectral whitening.

Following this both auto- and cross-correlation are applied and the responses stacked to provide:

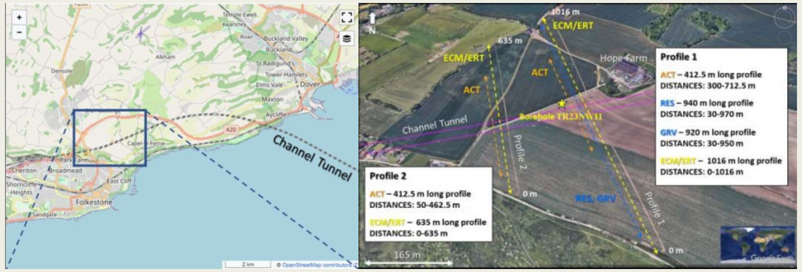
- Reflection response of the media underneath the entire receiver spread or
- Turn every ACT recorder into a virtual seismic source.

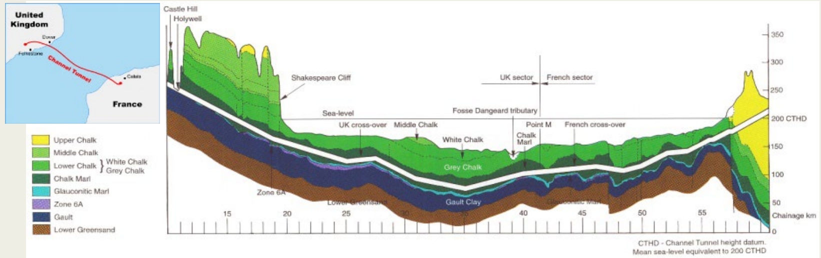
Both workflows have been tested on data from the OSI 2023 Field Test in the UK (FT23) and OSI 2024 Build-Up Exercise in Hungary (BUE24).

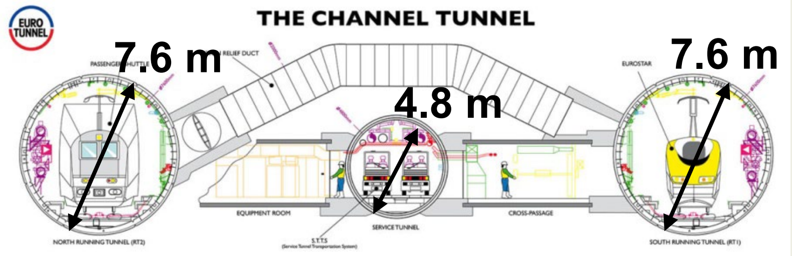
UK FT23 data

Field Test conducted in Folkestone, Kent, UK, 8-19 May above "The Channel Tunnel".

Goal: OSI ACT and Selected Geophysical Techniques for known tunnel detection (~ 90 m depth).







ACT: 276 GSB3 nodes, *P*- and *S*-wave seismic vibrator, two seismic profiles (Profile 1 and 2).

More details can be obtained from P3.3-556!

Hungary BUE24 data

An OSI Build-Up Exercise conducted in the area close to Gyöngyös, northern Hungary.

Exercise Scenario: ACT and RES surveys were conducted following the OSI search logic in a mountainous terrain densely forested with limited access roads and underground mining infrastructure at ~100-200 m depth.

ACT: 181 GSB3 nodes, *P*-wave sledgehammer seismic source, single profile.

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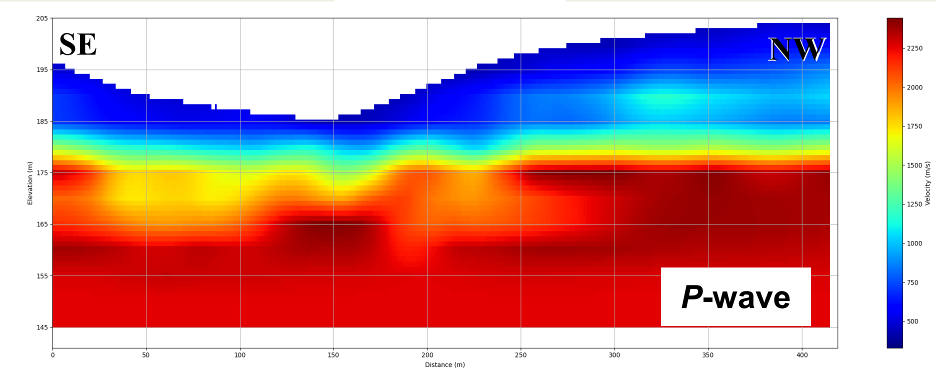
UK FT23 ACT refraction result – Profile 1

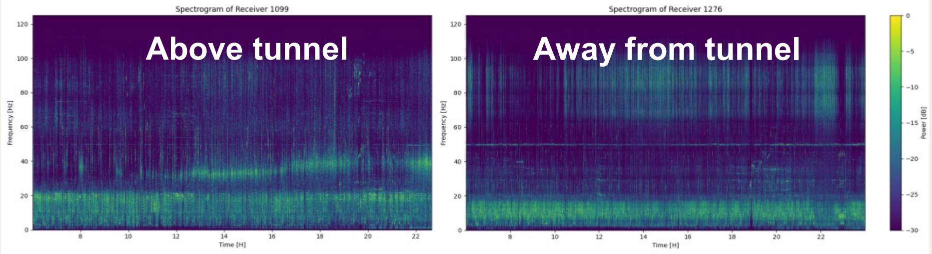
Manually picked first arrivals (20% portion) were used for supervised neural-network based **ML** picking and picks as inputs for traveltime tomography.



FT23 *P*-wave first arrival **traveltime tomography** result. Although the rays do not reach tunnel depth, near-surface is well resolved.

UK FT23 RES data

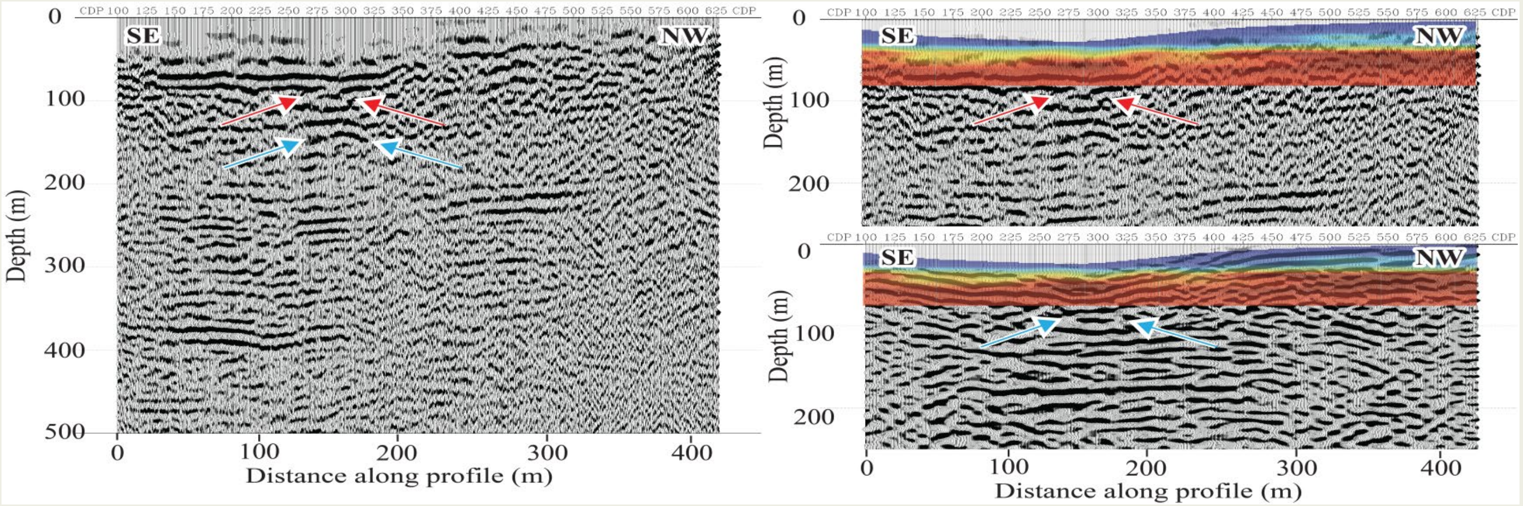
FT23 RES data properties are dependent both on proximity to the tunnel and traffic inside it.



Spectrograms (**18 h**) of a receiver close to the tunnel (left) and away from it (right).

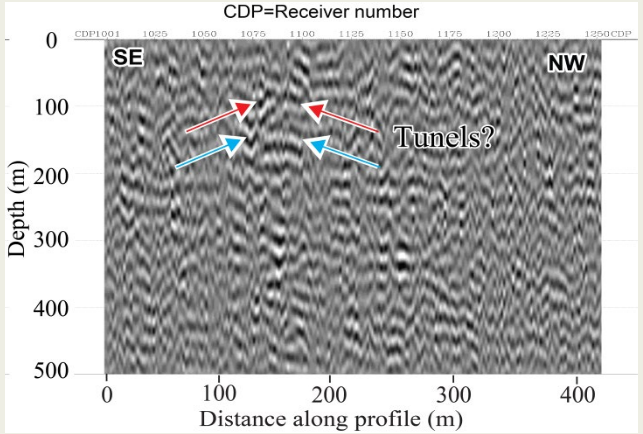
UK FT23 ACT reflection result – Profile 1, *P*- & *S*-wave

Smoothed, scaled and depth extended tomography model was further used for stacking and time-to-depth conversion, along with the shot and receiver statics obtained from the tomographic solution.



***P*-wave unmigrated stacked seismic section** without (left) and with *P*-wave tomography result (right, top), along with ***S*-wave unmigrated section** with the tomography (right, bottom). Red arrows show *P*- and blue *S*-wave **tunnel diffractions**.

UK FT23 RES Auto-correlation result - Profile 1



Vertical component auto-correlation result obtained using **18 h of RES data**, plotted as variable density. Red arrows show at possible *P*- and blue *S*-wave **tunnel diffractions**. The diffractions are collocated with ACT reflection results. Both ACT and RES results show reflectivity likely related to a known geological reflector (200-250 m).

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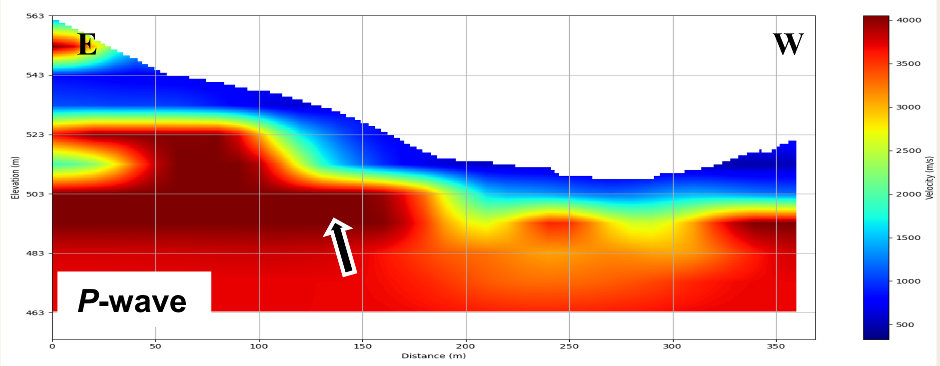
Hungary BUE24 ACT refraction result

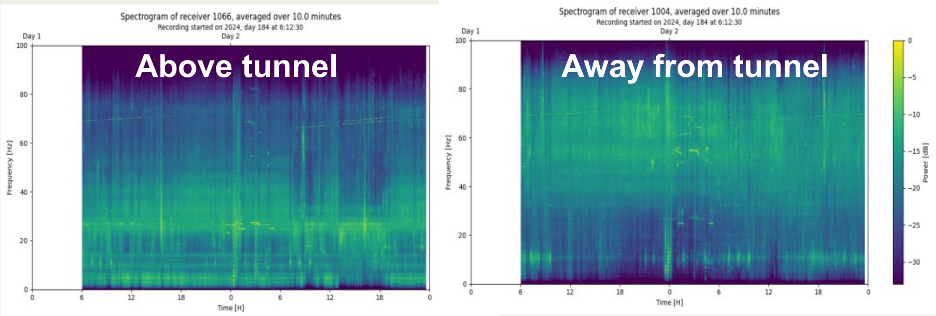
For this dataset, 10% of the data was manually picked and used for **ML** picking and picks as inputs for traveltime tomography.



BUE24 ***P*-wave** first arrival **traveltime tomography** result. Tunnels are located around distance ~130 m where velocities abruptly change, as indicated by black arrow.

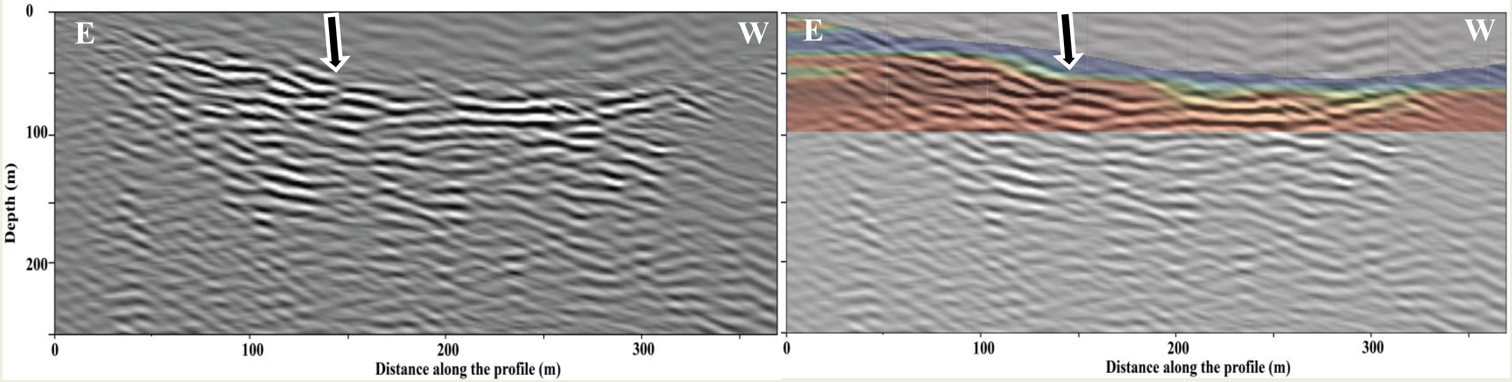
Hungary BUE24 RES data

BUE24 RES data are more quiet compared to FT23. Receiver above the tunnel shows certain frequency differences as, along with more anthropogenic activities in tunnels after midnight.



Hungary BUE24 ACT reflection result

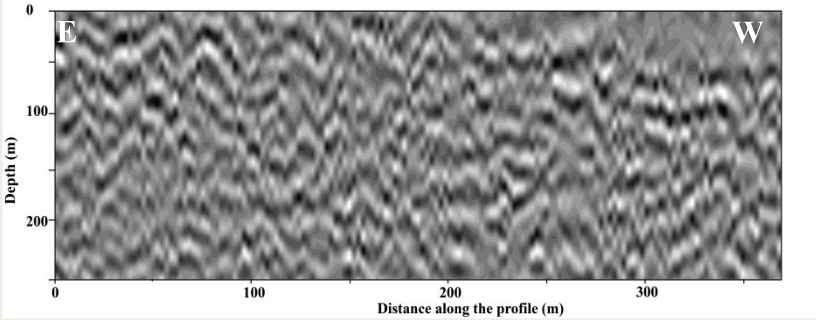
Smoothed and depth extended tomography model was used for stacking, while 2000 m/s was used for time-to-depth conversion, along with the shot and receiver statics obtained from the tomographic solution.



BUE24 ***P*-wave unmigrated** stacked seismic section without (left) and with tomography results (right). Tunnels are located around distance ~130 m where velocities abruptly change and reflection looses continuity, as indicated by black arrow.

Hungary BUE24 RES Auto-correlation result

Vertical component auto-correlation result of **42 h RES data** (depth converted with 2000 m/s and with ACT elevation correction). Some coherent events are observed in W portion, but no clear tunnel signature.



Conclusions

For the UK case, both workflows produce coherent reflectivity from known geological boundaries and visible diffractions originating from known train tunnels.

The topography and complex geology of the BUE2024 site make interpretation more ambiguous, however, the results still provide relevant information about the velocity and spectral properties of signals of interests.

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