

# Identification and characterization of vibration sources for the Einstein Telescope in the Euregio Meuse-Rhine

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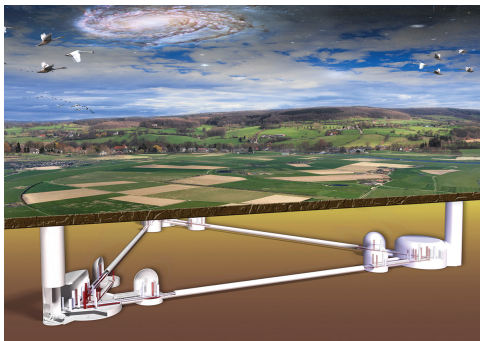
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# Introduction

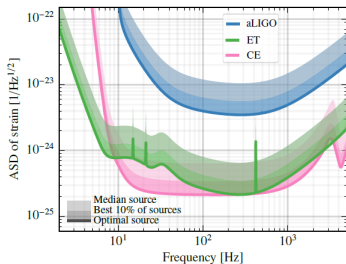
- Identification of vibration sources in the Euregio Meuse-Rhine.
- Identification of dynamic soil characteristics and site response analysis.
- Dynamic soil-structure interaction (SSI) analysis of tunnels, caverns, and shafts.



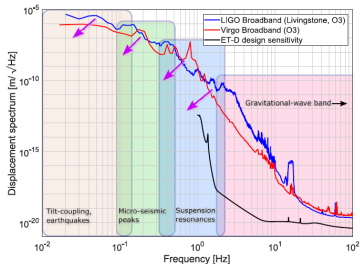
- Longer term: Structural Health Monitoring (SHM) of deep underground infrastructure with various sensors, construction of digital twins.

# Targets

- Design sensitivity for ET compared to (a) Cosmic Explorer (CE) and Advanced LIGO (aLIGO) and (b) LIGO and Virgo performance [ET Design Report 2020].



(a)



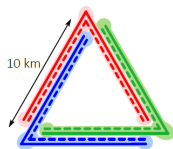
(b)

- Targets for ET (compared to existing Gravitational Wave detectors):

- Improve accuracy by one order of magnitude.
- Lower operating frequency to 3 Hz.

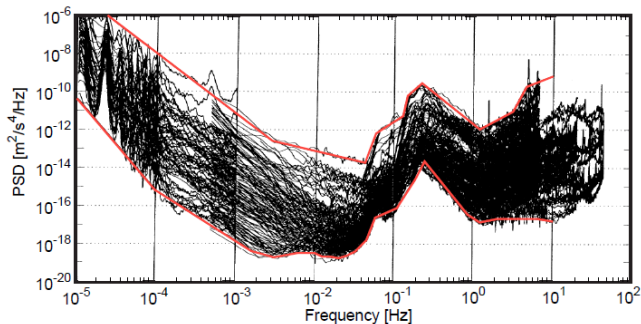
- Design choices to reach these targets:

- Triangular shape with 3 nested detectors.
- Increased tunnel length of 10 km.
- Underground construction at a depth of 250-300 m.



# Seismic noise

- Seismic noise spectra used in Peterson's background noise study (black) and low- and high-noise envelopes (red) [Peterson (1993)].



- $2.5 \times 10^{-5}$  Hz: tidal motion (gravitational attraction by the Moon and the Sun);
- 0.1 – 1 Hz: oceanic microseisms;
- 1 – 10 Hz: anthropogenic vibration sources.

# Methodology

## ■ Identification and characterization of vibration sources:

- External vibration sources:
  - ▶ road and railway traffic
  - ▶ wind turbines
  - ▶ mining
  - ▶ construction and industrial activities
  - ▶ earthquakes



- Internal vibration sources:
  - ▶ equipment (HVAC, pumps)
  - ▶ human induced vibration

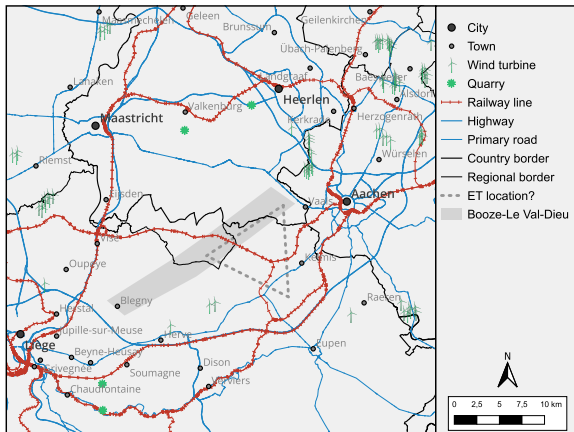
## ■ Supplement borehole measurements with numerical predictions, requiring knowledge about:

- soil layering and properties;
- vibration sources.

## ■ Recommendations for anthropogenic vibration sources (perimeters).

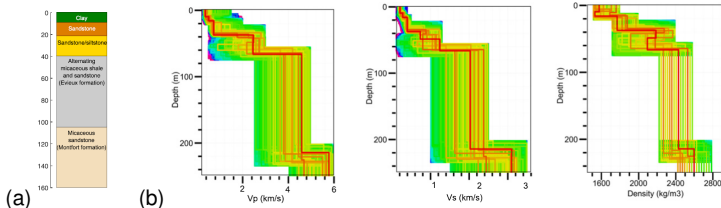
# Vibration sources

## ■ External vibration sources in the Euregio Meuse-Rhine.



# Soil layering and properties

- Experimental campaign in Terziet (The Netherlands) [Bader et al. (2022); Koley et al. (2022)]:
  - Borehole samples: lithology.
  - Resistivity, sonic and gamma-ray logging: lithology, density  $\rho$ , shear wave velocity  $C_s$  and dilatational wave velocity  $C_p$ .
  - Beamforming (two seismic arrays): shear wave velocity  $C_s$ .
  - Refraction tomography: dilatational wave velocity  $C_p$ .
- (a) Lithology and (b) P-wave, S-wave and density models [Koley et al. (2022)].



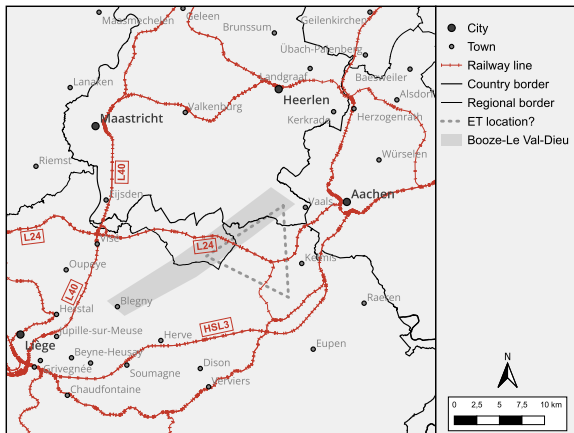
- Dynamic soil characteristics [Bader et al. (2022)].

Layer	Description	$h$ [m]	$C_s$ [m/s]	$C_p$ [m/s]	$\rho$ [kg/m <sup>3</sup> ]	$\beta_s$ [-]	$\beta_p$ [-]
1	Clay	5.7	165	385	1950	0.020	0.020
2	Sandstone/siltstone	10.2	270	445	2250	0.010	0.010
3	Sandstone/siltstone	18.9	335	685	2500	0.010	0.010
4	Quartzite/shales	58.2	1240	2810	2800	0.005	0.005
5	Silicified shales	$\infty$	2430	4050	2800	0.005	0.005

# Railway induced vibration

## Railway lines

Line	Traffic type	Speed limit
L24 Tongeren-Aachen	Freight	90 km/h
L40 Liège-Maastricht	Passenger	120 km/h
HSL3 Liège-Kelmis	Passenger	260 km/h





# Railway induced vibration

## Track unevenness

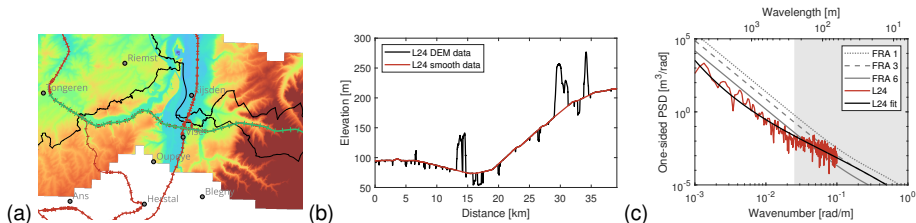
■ Ground borne vibration is due to track (and wheel) unevenness:

- track alignment;
- rail corrugation;
- rail joints.

■ Measurements:

- trolleys;
- track recording cars;
- digital elevation model (DEM).

■ (a) Line L24 on DEM, (b) elevation profile and (c) one-sided PSD indicating the relevant wavenumber range for excitation by freight trains between 0.1 and 10 Hz.

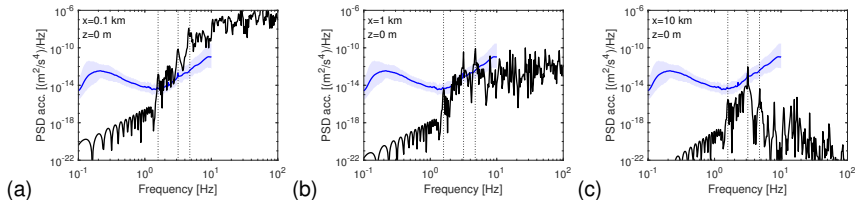


# Railway induced vibration

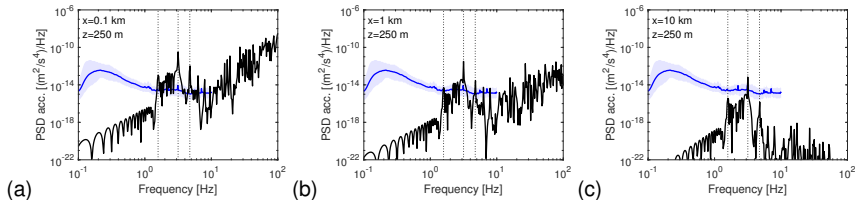
## Vibration levels

- Predicted one-sided PSD of the acceleration (black) due to a freight train running at 90 km/h; and measured seismic noise (blue) from surface and borehole seismometers in Terziet [Koley et al. (2022)].

- Receivers at free surface: (a) 0.1 km, (b) 1 km and (c) 10 km.



- Receivers in borehole: (a) 0.1 km, (b) 1 km and (c) 10 km.

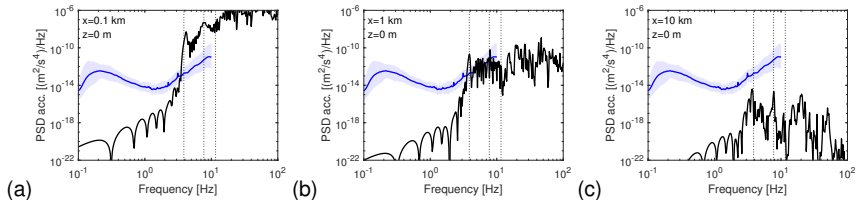


# Railway induced vibration

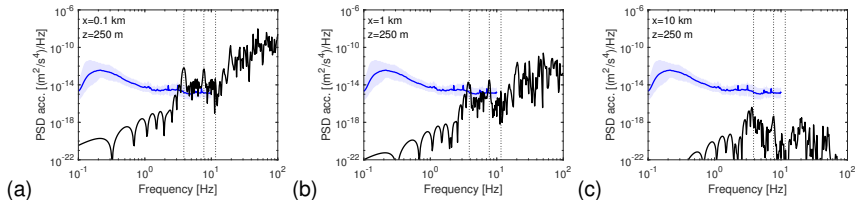
## Vibration levels

- Predicted one-sided PSD of the acceleration (black) due to a Thalys train running at 260 km/h; and measured seismic noise (blue) from surface and borehole seismometers in Terziet [Koley et al. (2022)].

- Receivers at free surface: (a) 0.1 km, (b) 1 km and (c) 10 km.



- Receivers in borehole: (a) 0.1 km, (b) 1 km and (c) 10 km.

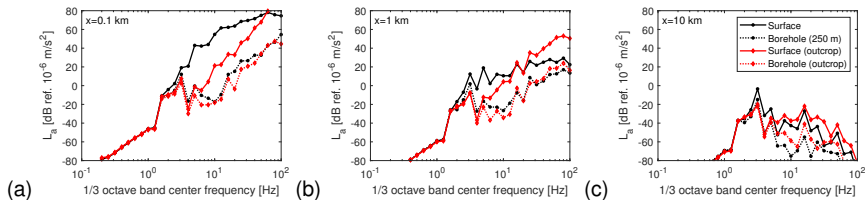


# Railway induced vibration

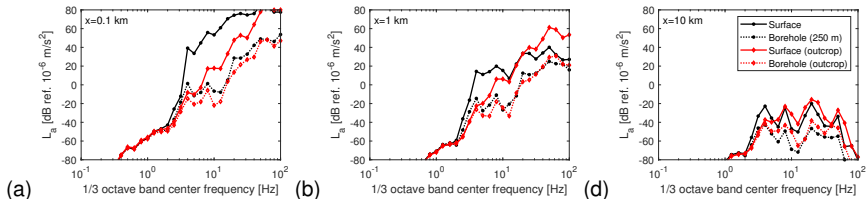
## Vibration levels

- Predicted acceleration level [dB ref.  $10^{-6}$  m/s<sup>2</sup>] at the free surface (solid) and at 250 m depth (dotted) at (a) 0.1 km, (b) 1 km, and (c) 10 km for the Terziet soil (black) and for outcrop (red).

- Freight train running at 90 km/h.



- Thalys train running at 260 km/h.

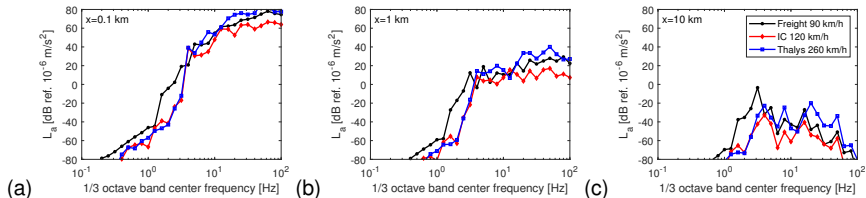


# Railway induced vibration

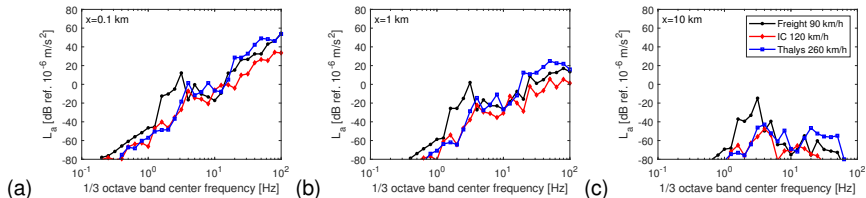
## Vibration levels

- Predicted acceleration level [dB ref.  $10^{-6} \text{ m/s}^2$ ] at the free surface at (a) 0.1 km, (b) 1 km, and (c) 10 km during the passage of a freight train at 90 km/h (black), an IC-train at 120 km/h (red), and a Thalys train at 260 km/h (blue).

- At the free surface.



- At a depth of 250 m.

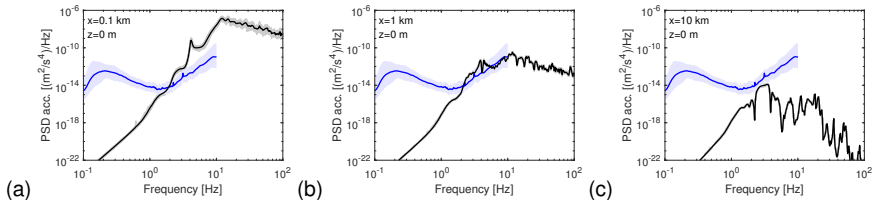


# Road induced vibration

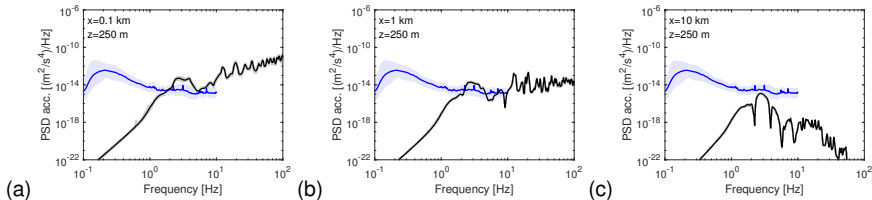
## Vibration levels

- Predicted one-sided PSD of the acceleration (black) due to road traffic at 120 km/h on an uneven road (ISO A); and measured seismic noise (blue) from surface and borehole seismometers in Terziet [Koley et al. (2022)].

- Receivers at free surface: (a) 0.1 km, (b) 1 km and (c) 10 km.



- Receivers in borehole: (a) 0.1 km, (b) 1 km and (c) 10 km.

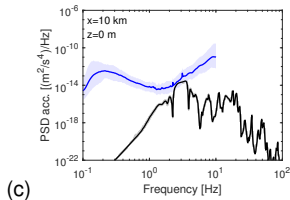
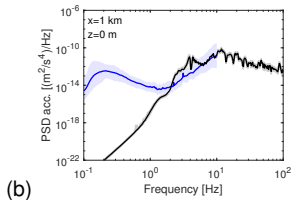
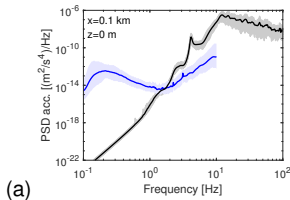


# Road induced vibration

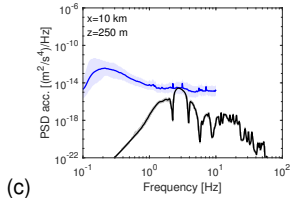
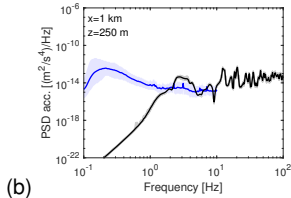
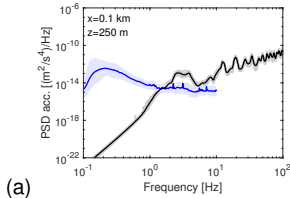
## Vibration levels

- Predicted one-sided PSD of the acceleration (black) due to road traffic at 50 km/h on an uneven road (ISO C); and measured seismic noise (blue) from surface and borehole seismometers in Terziet [Koley et al. (2022)].

- Receivers at free surface: (a) 0.1 km, (b) 1 km and (c) 10 km.



- Receivers in borehole: (a) 0.1 km, (b) 1 km and (c) 10 km.

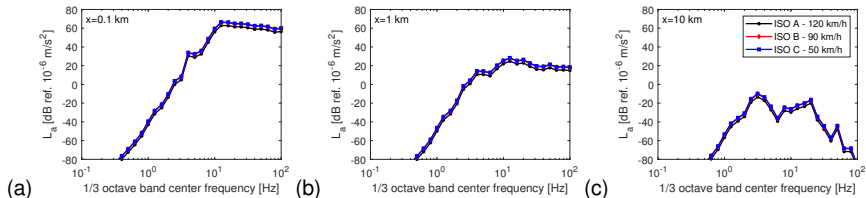


# Road induced vibration

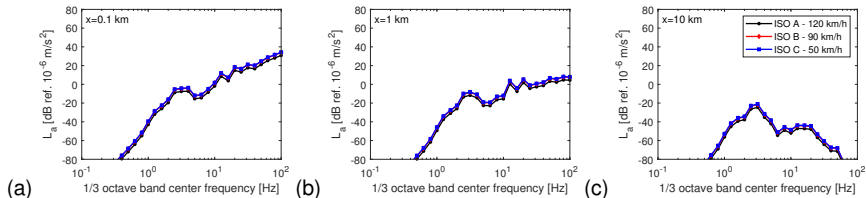
## Vibration levels

- Predicted acceleration level [dB ref.  $10^{-6} \text{ m/s}^2$ ] at the free surface at (a) 0.1 km, (b) 1 km, and (c) 10 km for road traffic at 120 km/h (ISO A) (black), 90 km/h (ISO B) (red) and 50 km/h (ISO C) (blue).

- At the free surface.



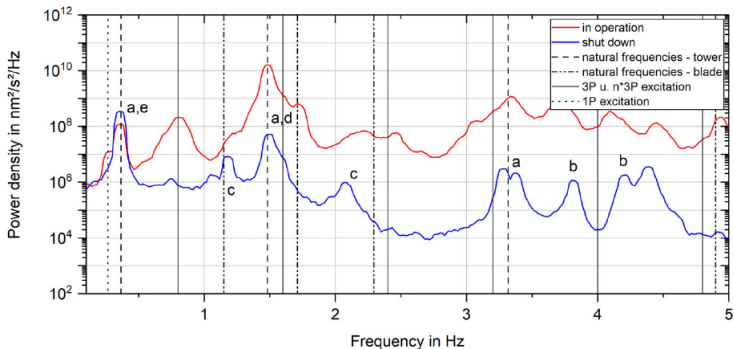
- At a depth of 250 m.





# Wind turbines

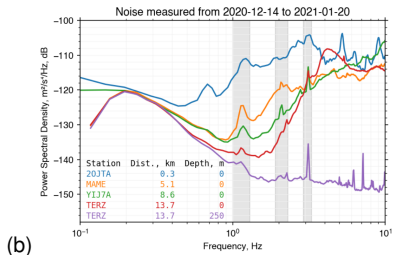
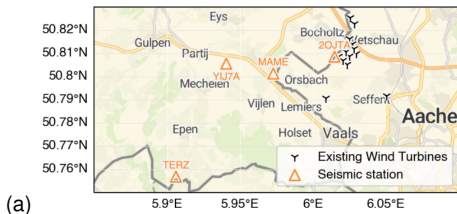
- Power spectral density of the ground velocity near the foundation of a wind turbine (figure taken from [Nagel et al. (2021)]).



- peaks related to rotor speed (1P and 3P excitation);
- eigenfrequencies of tower and blades.

# Wind turbines

- (a) Location of surface and borehole seismometers in South-Limburg and the Aachen wind park and (b) PSD of the measured acceleration [Shani-Kadmiel (2022)].



# Outlook

- Link vibration fields to Newtonian noise.
- Need for reliable soil data: layering and properties (including material damping).
- Need for additional borehole measurements.
- Various sources of vibration:
  - wind turbines
  - railway traffic
  - road traffic
  - mining
  - industry
  - earthquakes
- Develop vibration maps with perimeters depending on source type.