3rd EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING & SEISMOLOGY
BUCHAREST, ROMANIA, 2022

# Bedrock depth characterisation below public buildings with a geothermal interest using ambient seismic noise

**Koen Van Noten** – Royal Observatory of Belgium, Brussels, Belgium, e-mail: koen.vannoten@seismology.be

**Martin Zeckra** – Royal Observatory of Belgium, Brussels, Belgium, e-mail: martin.zeckra@seismology.be

**Abstract:** Below several public buildings in Brussels (Belgium), one aims to transform the main heating source away from hydrocarbons towards shallow geothermal energy. The GeoCamb project investigates the geothermal potential of the Brabant Massif bedrock below Brussels. For each potential project, however, prospecting drilling and hydrogeological surveys costs remain high. With the use of three-component seismic nodes, either mounted on tripods installed on sealed surfaces or classic spikes coupled to the ground, we use passive seismic ambient noise methods to characterize bedrock variation around the geothermal open wells below the buildings of interest. Bedrock depth variation is studied by converting resonance frequency ($f_0$), obtained from H/V spectral ratio analysis of ambient noise, to depth using a $f_0$-to-depth power law relation specifically developed for Brussels. With additional ongoing urban array measurements, we aim to understand which impedance contrast the H/V curve represents in this urban setting. We currently hypothesize that the main H/V peak below Brussels illuminates the sediment – weathered bedrock contrast, rather than the weathered – intact bedrock interface deeper within the Brabant Massif.

**Keywords:** H/V spectral ratio, resonance frequency, 3-component nodes, urban seismology

## 1. Introduction

In view of the transnational efforts and goals set by the European Commission in their European Green Deal, the overall energy transition and greenhouse gas emission reduction can only be achieved through consideration of the use of geothermal energy sources. It is anticipated to have 40% of the EUs energy mix coming from renewable sources and increase the use of renewable energy in heating and cooling by +1.1 percentage points each year, until 2030 (European Commission, 2019). The region of Brussels (capital of Belgium) is no exception and numerous public buildings holded by various administrative levels (e.g., communal town halls, hospitals, Universities, European parliament), as well as the private sector, aim to transform their main source for heating and cooling away from hydrocarbons. So far, geothermal projects were laid out solely for shallow-depths, low-efficient systems in the Cenozoic sedimentary cover due to the lack of investigations of the geothermal potential of the Cambrian bedrock below Brussels. The GeoCamb project (a Brain-be 2.0 project funded by the Federal Belgian Science Policy Office) aims for a comprehensive study to understand the return of energy efficiency of deeper and more expensive wells into the bedrock, jointly with federal research and industrial partners.

In the geophysical part of the GeoCamb project, non-invasive geophysical methods are key for the prospect of anticipated geothermal wells. Ambient seismic noise measurements require far less man-power and time to obtain sufficient data for first-order estimations of bedrock depths and rough subsurface characterization in comparison to highly expensive drilling. In return, drilling will outperform in terms of spatial sampling, in-situ ground truth and a variety of methods applied to estimate geothermal potential. However, we will show that the non-invasive character of three-component seismic sensors are highly beneficial in an urban environment. In dense urbanized areas such as Brussels, with largely sealed surfaces (e.g., sidewalks, parks, courtyards, parking lots), using modular seismic equipment allows arbitrary site selection and array geometries. In the first part of the project, we apply H/V Spectral Ratio (HVSR) analysis of ambient noise measurements at a large variety of sites all in Brussels where the subsurface is of geothermal interest. In a second part of the project, longer term temporary array installations are used to analyze the temporal variation in the HVSR analysis and interpretation.

## 2. Modular instrumentation for urban seismology

### 2.1. Lightweight industrial 3C geophones for ambient noise measurements

SmartSolo® node sensors have been introduced into the field of seismology recently and originally were developed for industrial purposes in active seismic experiments. The lightweight low-cost IGU-16 series comes either as one-component (1C, vertical) or three-component (3C) 5 Hz geophone sensors, with fully integrated 24-bit digitizer, GPS and battery in an autarkic casing. The reduced costs that allows purchasing large amounts of sensors comes alongside with user-friendly installation of the equipment, enabling the set-up of the increased number of instruments by the same number of operators. For short temporal installations, the standard battery pack further reduces the total weight and makes these sensors more feasible for the use in an urban environment, without relying on transport vehicles, i.e., several sites of interest in the GeoCamb project have been reached by bicycle (Fig. 1).

**Fig. 1 - A**: 3C lightweight sensors are transported for urban investigations with all means of transport. **B**: Set-up of lab-based instrument test, *top:* surface sensor of UCC seismic station, *blue:* Lennartz 3D/5s, four SmartSolo sensors with two sensors (*left*) with spikes in a sand-filled bucket and two sensors (*right*) on tripods. **C**: Ambient noise measurements on a paved footpath next to the abandoned Brasserie Wielemans in Forest (Brussels). Co-location of a 3C sensor installed on tripods and a Lennartz - Cityshark setup.

The standard 1C SmartSolo sensors are equipped with a long central spike and three smaller spikes. Many sites of interest in the densely populated city center of Brussels exhibit sealed surfaces without options to properly couple the sensors into the ground. To overcome this issue, we made use of the modular design of the IGU16 sensors and installed standard tripod-based batteries of the 1C instruments on the 3C nodes. Besides weight reduction, this setup deliberates the operator from finding suitable locations for temporal measurements in urban areas. Although we mostly rely on the Smartsolo 3C sensors, which are novel in the field of ambient noise studies, we also use high-performance Lennartz 3D-5s sensors in combination with CityShark digitizers. This instrumentation allows us to derive conclusions in the real-world application of both sensor types and identify potential misalignments in the interpretation of the processed waveform data.

## 2.2 Lab-based comparison with classical seismometers

To assure if the two different base set-ups of the SmartSolo nodes have no effect on the recorded noise field and to investigate the limits of the frequency bands of interest, we performed a lab-based comparison between sensors of different base set-ups and classical instruments under controlled conditions at the UCCS permanent surface station. We placed two nodes equipped with a tripod and two with the classical spike inside a sand-filled bucket (Fig. 1) next to a Lennartz 3D/5s with a cityshark digitizer and UCCS, that consists of a Güralp CMG-3ESP broadband seismometer. Test data was obtained over a period of 2 hours.

In the time domain, the recorded waveforms are self-consistent and coherent across sensors with respect to the particular transfer functions. The site of the UCC station is located inside the Belgium capital and thus shows an elevated level of anthropogenic noises for which all of the instruments were sensitive to, i.e., regular bypassing of cars and buses.

A more sophisticated insight of the recorded noise data is achieved in the frequency domain. The direct comparison of the power spectral densities (PSD) of the sensors with similar settings exhibit strong coherence for all components compared. By dividing the spectra from each other we observe stable results over a large frequency range, while above 10 Hz the spectral division has an increased variability with a mean around 1. In the cross-sensor comparison of using a tripod and a classical spike base, a large deviation of the spectra's can be observed above 25 Hz on all components. Especially the spectral division shows discrepancies from the expected value. In order to better compare the spectra in the higher frequency range, we applied a Konno-Ohmachi smoothing of 40% (Konno & Ohmachi, 1998). The smoothed spectra are highly coherent below 20 Hz for the vertical and below 10 Hz for the horizontal components (Fig. 2). This concludes that in Brussels, where bedrock depth ranges between 5 and 150 m, both types of instrument bases obtain identical data in the dominantly used frequency range and both sensors can be used co-locatively in combined field surveys. We tentatively suggest that the occurrence of high-frequency peaks in the horizontal components are related to limited coupling inside the sand-filled bucket and different heights of sensor masses above the ground tiles.

In the final step, we compared the spectra of the SmartSolo sensors with the standard Lennartz and Güralp instruments after restituting the waveforms of all sensors. Despite differences related to the gain factor, the smoothed spectra of the Lennartz and the node sensor on a tripod are coherent over a large frequency range from 30 Hz down to 10 s, way below the nodes' natural frequency. Deviations in longer periods might be rather introduced due to the temporary nature of the installation.

In the end, we show that the novel, industrial purpose SmartSolo seismometers are similarly suitable for ambient noise measurements, while they outperform classical instrumentation in overall size, weight and especially costs.

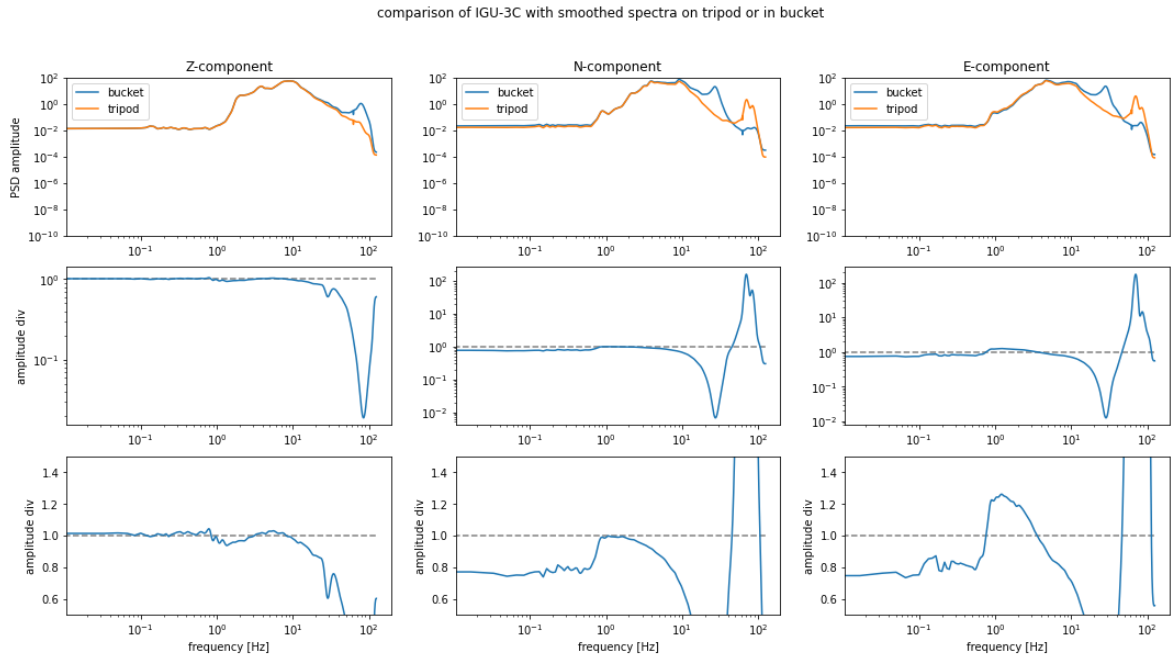

**Fig. 2 -** Comparison of the smoothed spectra of 3C SmartSolo sensors with a tripod base (orange) and a spike-base installed in a sand-filled bucket (blue). Each column represents one of the three components. *Upper row*: smoothed spectra; *Middle row*: division of smoothed spectra of both sensors; *Lower row*: division of smoothed spectra, but with a linear amplitude ratio scale limited around the expected value 1±0.5.

## 2.3 Real-world performance

At two potential geothermal sites of the GeoCamb project, we performed ambient noise measurements for bedrock depth estimations with all three types of sensors (node with spike, node on tripod, Lennartz) under actual conditions. The chosen sites in the commune Forest (i.e., Wiels cultural center and the abandoned Brasserie Wielemans; Fig. 1C) are characterized by high anthropogenic noise induced by a four-lane road, tramlines and public buses. For these noise sources, the Smartsolo sensor has a more pronounced signal-to-noise ratio. That is related to the applied transfer function that suppresses microseism and other noise sources < 1 Hz stronger than the Lennartz instrument does with the natural frequencies of 5 Hz and 5s, respectively.

In terms of the overall project goal of estimation of bedrock depths, both sensors' outcomes lead to the exact same results. For the routine HVSR processing, we work with the open software package Geopsy (Wathelet *et al.*, 2020). As expected from the lab-based analysis in the previous section, the results are highly coherent for the SmartSolo sensor on a tripod and the Lennartz-cityshark setup. Not only that the $f_0$ value and the H/V amplitude are the same, the full spectral ratio curves are congruent between 0.5 and 30 Hz.

Based on the obtained HVSR and waveforms in general, we state that the use of the Smartsolo sensors in various sites in Brussels and other urban sites of interest lead to the same outcome as classical instrument set-ups that are in use for decades. Further with an increasing number of sites, the nodes are more profitable as one single operator can set-up one Lennartz and Cityshark, while the second can install four sensors at the same time.

## 3. Characterizing Brussels' subsurface using H/V Spectral Ratio

Brussels is characterized by a tabular Cenozoic sedimentary geology overlying the strongly deformed Lower Paleozoic Brabant Massif (Fig. 3, inset figure). Borehole data indicate that the bedrock of the Brabant Massif varies between a few meters depth, south of Brussels, up to 150 m depth along its northern border. These values correspond to resonance frequencies of 9 Hz and 0.68 Hz, respectively (Fig. 3). The cover is composed of well-known sandy and silty soft sediment formations. The basement rock consists of alternating pelitic and quartzitic beds, giving rise to a variable bedrock paleotopography due to differential erosion. Up to recently, this variability was only known from outcrops south of Brussels or from aeromagnetic and Bouguer anomaly data, and was only drilled sporadically by few boreholes in Brussels. Recently, Van Noten *et al.* (2022) showed that urban, high density HVSR campaigns allow studying this variability and the paleotopography, which can strongly complement studies on the bedrock's geothermal potential.

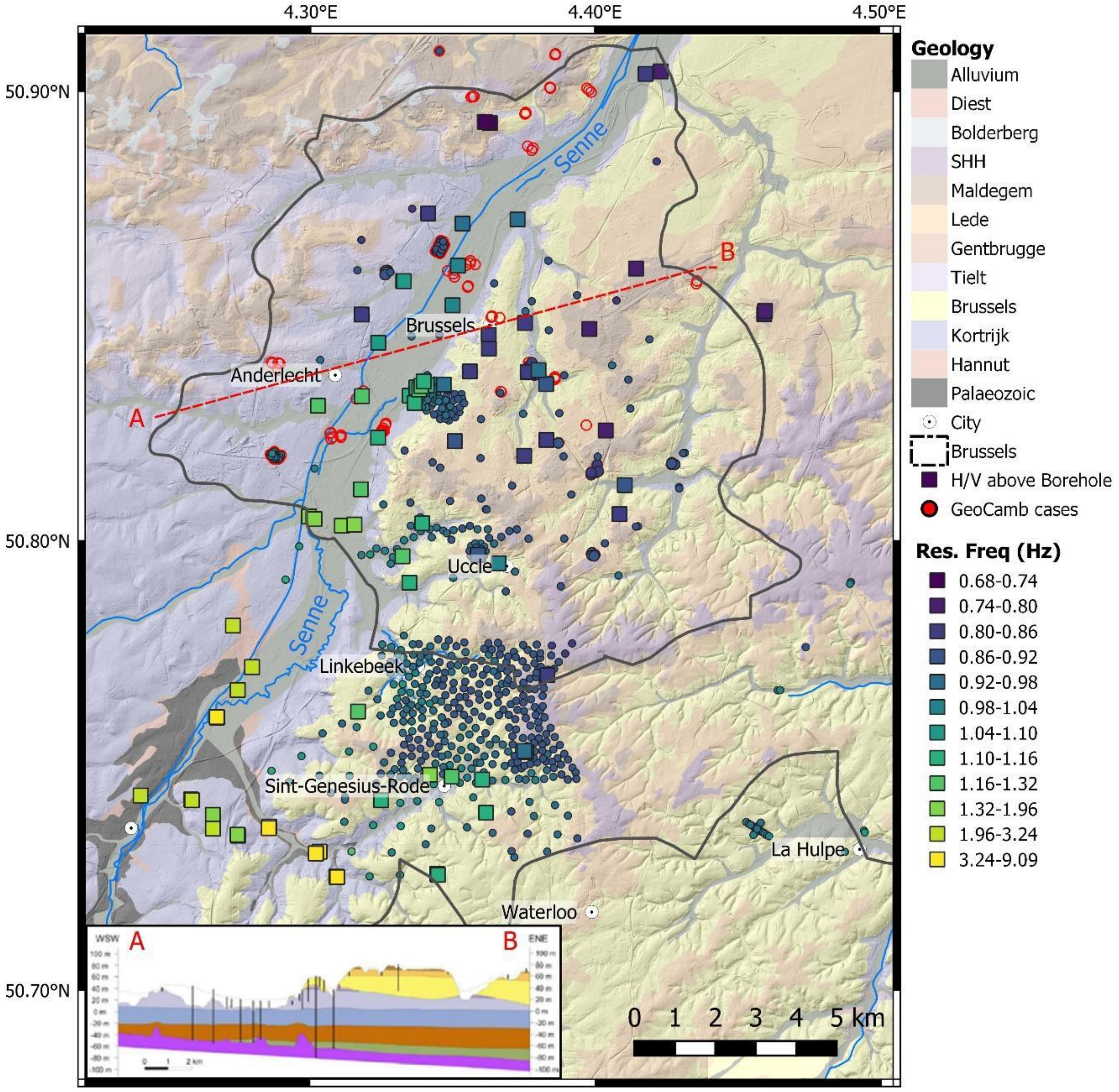

**Fig. 3 -** Geological map of Brussels' subsurface geology. Squares present resonance frequency obtained from ambient noise measurements above boreholes (Van Noten *et al.*, 2022). Small circles represent the HVSR database of Belgium (Scherps & Van Noten, 2021). Points in red indicate the GeoCamb case studies of interest. Inset shows the tabular geology below Brussels with the purple layer indicating the BM bedrock.

The determination of the resonance frequency ($f_0$), using HVSR, and an empirical resonance-to-depth power law scaling relation (Van Noten *et al.*, 2022) already provides a cost-efficient approach to estimate bedrock depth prior to geothermal drilling. In the GeoCamb project, at the time of writing, 116 HVSR analyses (red dots in Fig. 3) have already been completed below sites of interest, complementing the Belgian HVSR database (Scherps and Van Noten, 2021). The depth estimations correspond well to depths obtained from co-located wells drilled for geothermal interest, with depth uncertainties below 10 m. This justifies using Brussels' power law relation for extrapolating the bedrock orientation and paleotopography around the geothermal wells. We also convert each HVSR curve to a virtual borehole (Fig. 4) as this visual information is valuable for other GeoCamb partners that focus on the hydrogeology within the Brabant Massif, measured flow rates and heat transfer.

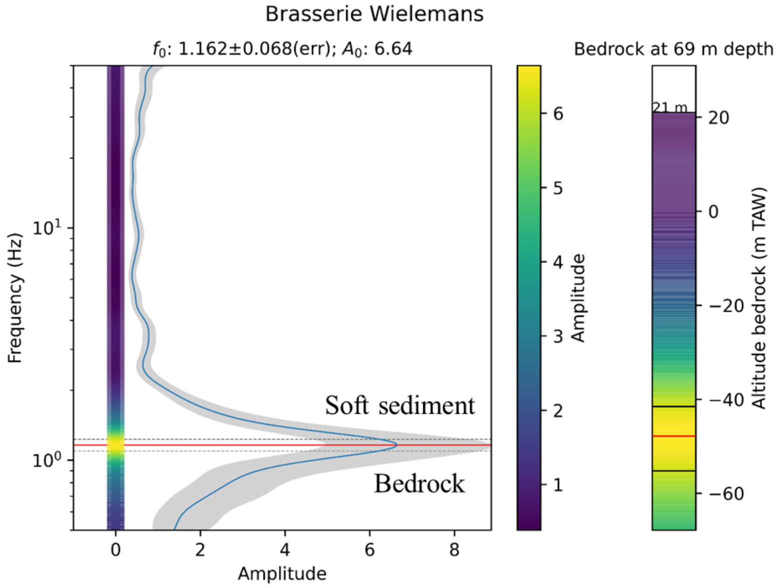

**Fig. 4** – HVSR analysis of ambient noise recording with a SmartSolo seismic node (Fig. 1C) next to the Brasserie Wielemans (Forest, Brussels, Belgium). **Left:** Amplitude-frequency diagram showing the resonance frequency peak illustrating the acoustic impedance contrast between soft sediment and the BM bedrock. **Right:** Virtual borehole coloured with amplitude values. Code to generate these virtual boreholes can be found in Van Noten et al. (2020).

In Brussels and the majority of Flanders as the surrounding region, the transition between the soft Cenozoic sediment layer and the metamorphic Lower Paleozoic bedrock is marked by a strong velocity contrast that is sharp along its erosional surface. Wells into the Cambrian bedrock revealed that the thickness of the weathered top of the Brabant Massif bedrock can reach up to several tens of meters, making this weathered layer of particular interest for geothermal purposes because of its higher hydraulic conductivity. Along-side well-logging, the bedrock’s erosional surface is currently being investigated by HVSR and array seismology. However, correlating resonance frequency and well data shows that the H/V reflector corresponds to the interface between sediment and top weathered layer, rather than to the base of the weathered layer and the intact bedrock. Reason for this observation is that the strongly fractured weathered layer has a much higher density than the overlying sediments, causing the clear impedance contrast seen by HVSR. This conclusion complicates the interpretation of the thickness of the weathered layer from geophysical data alone. Our current efforts focus on array seismology to create velocity profiles at those places where the geothermal test wells indicate a thick weathered layer to strengthen our single point H/V observations.

## 4. Conclusions

Preliminary results of the geophysical part of the GeoCamb project show that the nodal setup (tripod and spike) can be easily combined with more classical standard field equipment (Lennartz) for gathering ambient noise data. This is beneficial for urban seismological needs and is promising for array seismology in otherwise difficult accessible urban areas. With the use of lightweight SmartSolo® nodes we pursue efficient surveys in time and weight and can identify the depth to bedrock under the Cenozoic sediments in Brussels with high accuracy.

## Acknowledgements

The authors sincerely thank the Belgian Federal Science Policy Office for funding the Brain-be 2.0 GeoCamb project (B2/191/P1/GEOCAMB).

## References

Journal Article:

- Konno K, Ohmachi T (1998). Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. *Bulletin of the Seismological Society of America* 88: 228-241. https://doi.org/10.1785/BSSA0880010228
- Scherps E, Van Noten K (2021) Developing a HVSR database for Belgium. Internship at the Seismology-Gravimetry section of the Royal Observatory of Belgium. Unpublished internship report. Katholieke Universiteit Leuven, MSc Geography.
- Van Noten K, Lecocq T, Goffin C, Meyvis B, Molron J, Debacker TN, Devleeschouwer X (2022). Brussels' bedrock paleorelief from borehole-controlled power laws linking polarised H/V resonance frequencies and sediment thickness. *Journal of Seismology* 26: 35-55. https://doi.org/10.1007/s10950-021-10039-8
- Wathelet M, Chatelain JL, Cornou C, Di Giulio G, Guillier B, Ohrnberger M, Savvaidis A (2020). Geopsy: A user-friendly open-source tool set for ambient vibration processing. *Seismological Research Letters* 91: 1878–1889 https://doi.org/10.1785/0220190360

Codes:

- Van Noten K, Lecocq T, Power B (2020) HVSR to virtual borehole (Version 1.0). Zenodo. https://doi.org/10.5281/zenodo.4276310

Website:

- European Commission. (2019). Delivering the European Green Deal. (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)