Combining active and passive seismic methods for non-invasive site characterization of the Belgian seismic network.

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Abstract: With more than 120 years of continuous seismic recordings, Belgium is among the oldest seismological entities in Europe and the World. Currently, we are renewing several permanent sensors and opening their data stream to the community. Alongside, we perform a site-characterization study for all these stations. The main objective is to provide the most important site-characteristic parameters (e.g., f_0, vs_{30}, depth to bedrock) to the seismological community next to the publicly available waveforms. To do so, we perform ambient noise measurements with up to 24 3C SmartSolo nodes for seismic velocity inversion based on surface wave dispersion curves. Occasionally, we incorporate active source methods (e.g., hammer seismics, MASW) in order to increase the inversion robustness or if the available survey space is limited. Most of the stations are located in the southern part of Belgium very close or directly on the bedrock in areas of high relief, justifying the necessity of combining various active and passive methods.

Keywords: site-characterization, ambient noise, array seismology, active seismics

1. Introduction

The beginning of seismological monitoring in Belgium dates back to 1898 with the installation of a Rebeur-Ehlert three component seismograph in Uccle, Brussels as one of the first instruments in Europe. Since then the Royal Observatory of Belgium is providing one of the longest, continuous seismological monitoring in the world. Starting in the sixties of the last century, with the introduction of digital broadband seismometers, a seismic network across the Belgian territory has been introduced gradually. In its current status, the observatory maintains 27 seismic stations (three of them are located in Luxembourg) that are included in the routine earthquake monitoring (figure 1) with focus on the local seismic activity in the central European country and neighboring regions. The network currently undergoes a technical upgrade, in which former short-period sensors (sometimes single component only) are or will be replaced by modern broadband instruments. Contemporaneously, these stations are made publicly accessible in such a way that they will stream directly into the ORFEUS EIDA node, facilitating the access for the seismological community. In order to further assist the user in their interpretation of the obtained waveforms, the result of this EPOS-BE project also will provide the site characteristics of each of these stations.

For each permanent station site we are performing temporary and non-invasive seismic surveys with up to 24 lightweight, industrial, three component Geophones (SmartSolo IGU-16HR 3C). Instead of a full site-response investigation, we rather focus on specific parameters that are of primary interest to the seismological community (Cultrera et al., 2021), e.g., vs30, f_0, depth to bedrock. The results will be publicly available on the

ORFEUS StationBook instance that is providing a useful framework to store and distribute this kind of metadata as long as community standard file formats (e.g., siteXML) are still under development and not finally released. During the data processing intermediate results are stored alongside with processing parameters internally on a wiki server. This is highly beneficial for the reproducibility of the occasionally unambiguous results, i.e., the velocity inversion. In addition, it allows the storage of additional geoscientific data (e.g., hydrological and geological maps, structural profiles, potential noise sources) and supporting information regarding the field surveys as we combine diverse geophysical methods depending on each sites' conditions. After finalization of the site characterisation, this information will be made publically available.

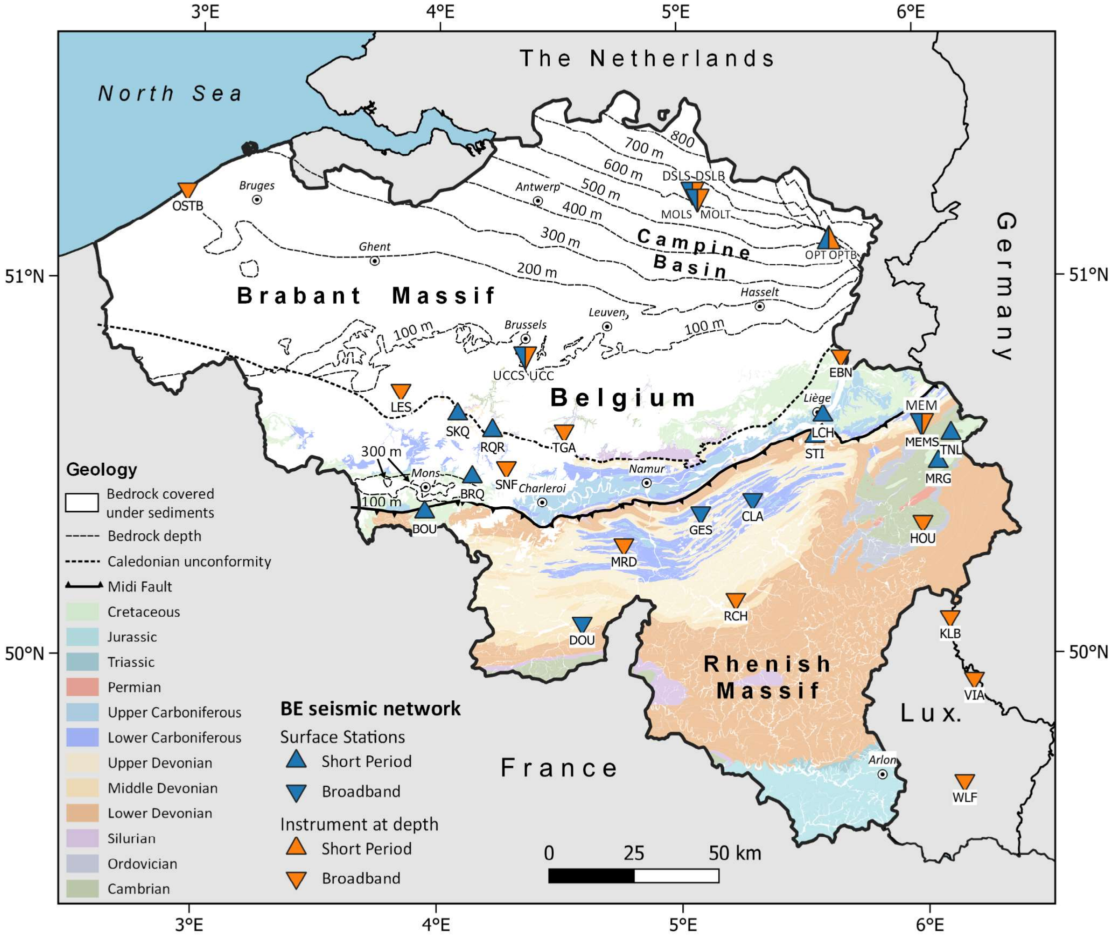

Fig. 1 - Overview map of Belgium with the seismological permanent station locations indicated by triangles (double colored stations host sensors in a borehole and at the surface). The background colors highlight the geology expressed at the surface for the south and isolines in the north, showing the depth to the underlying bedrock.

The geological conditions in the subsurface at each site in the Belgium territory are highly diverse (see figure 1). The northern third is dominated by flatlands that consists of thick sedimentary infill entailing low seismic velocities and strong attenuation. To the south in the central parts, the depth to bedrock decreases, and the topography and relief increases. The southern sector consists of high-grade and strongly deformed meta-sediments and limestones presenting very high seismic velocities. In combination with the high relief, this poses often difficulties to find adequate locations in which ambient noise arrays can be hosted.

For the processing we rely in most parts on the Geopsy software package (Wathelet *et al.*, 2020), that is widely used and includes method-wise standard applications of ambient noise measurement processing. In these cases where active point sources have been incorporated in the analysis, we developed partially our own data processing tools using jupyter-notebooks for python code development and the following processing. This allows us easier integration of machine-based processing and user-focused explanations of the non-standard methods applied here for later reuse and traceability.

2. Ambient noise methods

The use of ambient noise waveform recordings for the purpose of one dimensional subsurface site characterization has become in recent years a standard tool in seismological research. Various processing techniques focusing on surface-wave analysis have been developed (Foti *et al.*, 2011) and proven to be successful. Here, we rely on single station methods (H/V spectral ratio) as well as on array techniques (frequency-wavenumber - FK, Spatial Auto-Correlation - MSPAC) that will provide the input for the 1-D seismic velocity inversion.

Prior to the ambient noise survey, a rigorous planning of the array geometries is profitable for the processing of the ambient noise recordings. The aforementioned high diversity in subsurface geology and its architecture at depth with strong variations in the expected seismic velocities can quickly lead to over- or undersampling of the analyzed wavefield. Further, we could lose sensitivity for the depth range of interest; determining the average vs30 might need a different set-up as the estimation of depth to bedrock/engineering bedrock (H_{800}), which is for UCC surface station in Brussels at 114m. In this work, the use of the dispersion curve forward modeling module in Geopsy allows us to test arbitrary array configurations with respect to the number of available instruments, geometries and overall apertures, especially if availability of survey space is limited in terms of accessibility and topography.

For ambient seismic noise measurements (with the exception of MSPAC) it has been shown that irregular geometries are preferable to avoid spatial aliasing. But a perfectly irregular array geometry tends to be difficult to install, taking into account several operators installing simultaneously and limited accuracy of handheld/smartphone GPS locations, in addition to obstacles in the survey area. After testing various arrays and installation procedures, the most convenient practice was to take the inaccuracy of location into account during the survey. That means, we preplanned a regular grid that fits into the available area for the survey. For each location point, the operator has to locate himself roughly at that point and then deviate into a random direction for a fixed amount of steps to ensure irregularization of the geometry grid. Through this, we could create irregular arrays for an FK processing, while maintaining balanced intersensor distances for MSPAC processing and reducing the time for the array installation that would be necessary for accurate self-orientation.

2.1 single station noise surveys

The horizontal-to-vertical spectral ratio (HVSR) has been introduced from an engineering perspective in order to distinguish the seismic response at the ground surface to a reference bedrock site (Nakamura, 1989 & 2019). Later, it has turned out as a handy tool for first order estimation of the depth to bedrock based on various scaling relations derived from sites of known sediment infills of study sites (e.g., Van Noten *et al.*, 2021, Molnar et al., 2022). In short, the HVSR shows the fundamental resonance frequency (f_0) of a site at which - theoretically - multiple reflected SH-waves are trapped between bedrock and free surface, leading to superposition of ambient noise energy around f_0.

The data obtained during the temporary array installations is suitable for straightforward HVSR calculations providing manifold input for the site characterization of the permanent stations. First, f_0 and its H/V amplitude are the most requested parameters in site characterization by the seismological community (Cultrera *et al.*, 2021). Second, in the case of sites with shallow bedrock subsurface, we can immediately derive the *EC8 Ground type* as a parameter of interest in case of absence of clear HV peaks, as it is the case for the stations in southern Belgium: CLA, GES, SNF, SKQ. Lastly, the combination of f_0 with empirical scaling relations (Van Noten *et al.*, 2022) gives a first estimation for the expected bedrock depths that we forward into the velocity model inversion in order to limit the solution space for the sediment-bedrock transition at depth. So far, we only performed the site characterization for bedrock sites, preventing us from using the f_0 value as independent data input for the inversion.

The field surveys for site characterization are mainly performed as arrays. The processing of the HVSR for all sensors in these arrays then allows us to derive routinely more reliable results through cross sensor comparison. Through this we can identify and exclude outliers, noisy sensors and derive credible uncertainty measures. From the two dimensional expansion of sensors, the spatial distribution of fundamental frequencies also portrays potential divergences due to topologic fluctuation of the bedrock impedance contrast with respect to the surface topography.

2.2 array-based noise surveys

The main focus of data processing for the site characterization relies on the surface waves of ambient noise. We make use of the dispersive character of these types of waves that is controlled by the integrated shear wave velocity decomposed for the individual wavelengths that superimpose into the dominant characteristic surface wave field at this site. The frequency-wavenumber (FK) method is translating the frequency dependent spatiotemporal propagation of the wavefield into the phase velocity of the surface waves. By inverting the physical forward problem that constructs the frequency dependent phase velocity based on shear wave velocity variations with depths, we can derive a one dimensional shear wave velocity model.

To further constrain the inversion with an increased number of input parameters, we apply the Modified SPatial AutoCorrelation (MSPAC) method. This method uses a plane-wave approximation between all equidistant sensor pairs that can numerically be solved by a Bessel function. From the combination of all distance groups (so called rings of the co-array) we can also construct a dispersion curve that allows the estimation of a one-dimensional shear wave velocity model in the inverse process.

The Geopsy inversion tool allows the inversion of the velocity model using both array processing techniques simultaneously as input. However, the number of input data points stemming from FK and MSPAC differs strongly (one FK dispersion curve vs. a dozen rings in MSPAC) and we introduced a user-defined weighting scheme that put stronger weights on the FK processing. During the separate velocity inversion of the input data, it turned out that the MSPAC method provides high sensitivity for robust estimations of the velocity at intermediate but limited depth ranges; the overall depth range for velocity inversion depends on the overall aperture in general (see chapter 2. First paragraph). The use of FK dispersion curves seemed to appear more helpful in the estimation of depths of velocity variations. Thus, the use of the combination of both input datasets appears to be highly beneficial. As described before, we also integrate other information sources in order to limit the model space in the inversion that stems from geophysical methods (e.g., HVSR, active source experiments) as well as geological information (e.g., geological maps, profiles, outcrops).

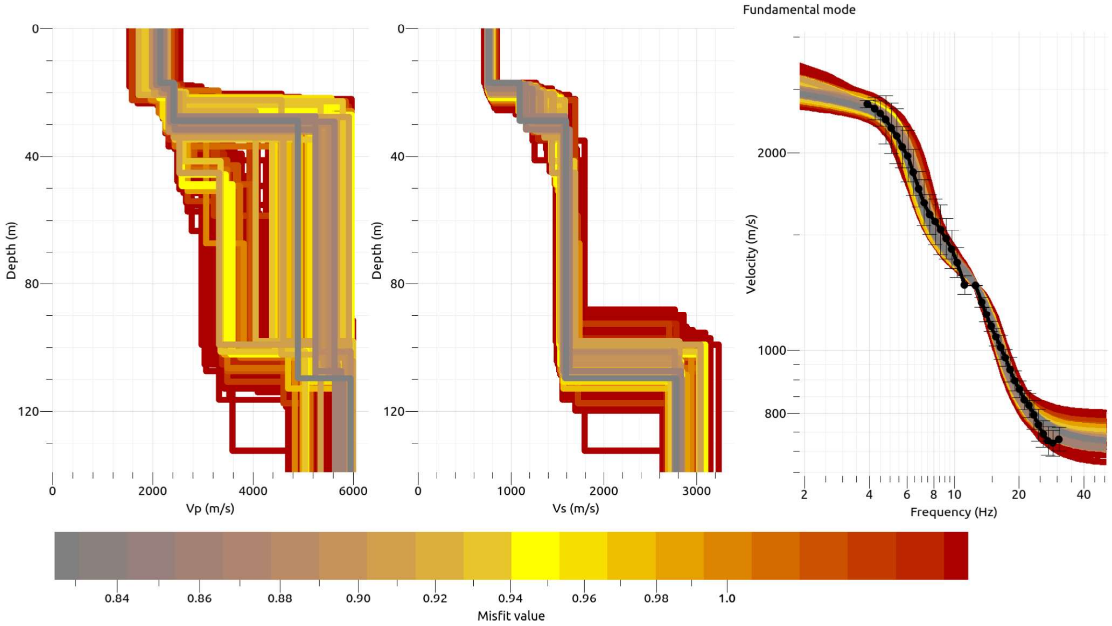

Fig. 2 - Final shallow subsurface 1D velocity model for GES station (p-velocity left, s-wave velocity right). Here, we estimated a 4 layer model that shows a comparable misfit value as a 3 layer model but better represents the uppermost few meters below the temporary array, which are absent for the permanent sensor. This figure also illustrates the intrinsic ambiguity of the inversion in combination with the limited ability to constrain the p-wave velocity profile with the ambient noise methods.

So far, we could perform the site-characterisation by using the passive ambient noise methods for four stations of the permanent network (CLA, GES, SKQ and UCC). Further, we already acquired the necessary data for two permanent stations (MEM, RQR) that are currently in processing. Except for the station in Uccle at the Royal Observatory, all stations are situated on or within 1m of the bedrock that consists of very stiff metamorphic rocks and thus lead to comparably high vs_{30} values above 700 m/s. Hydrological parameters were estimated through data of the Geological service, but they show no direct impact on the velocity model inversion. For some stations (e.g., CLA) we rather suggest to the users to take into account the local relief around the stations in order to prevent data misinterpretation due to topographic effects that have stronger impact than the hydrological parameters, but are not specified in the ORFEUS Stationbook.

3. Velocity estimation including active source surveys

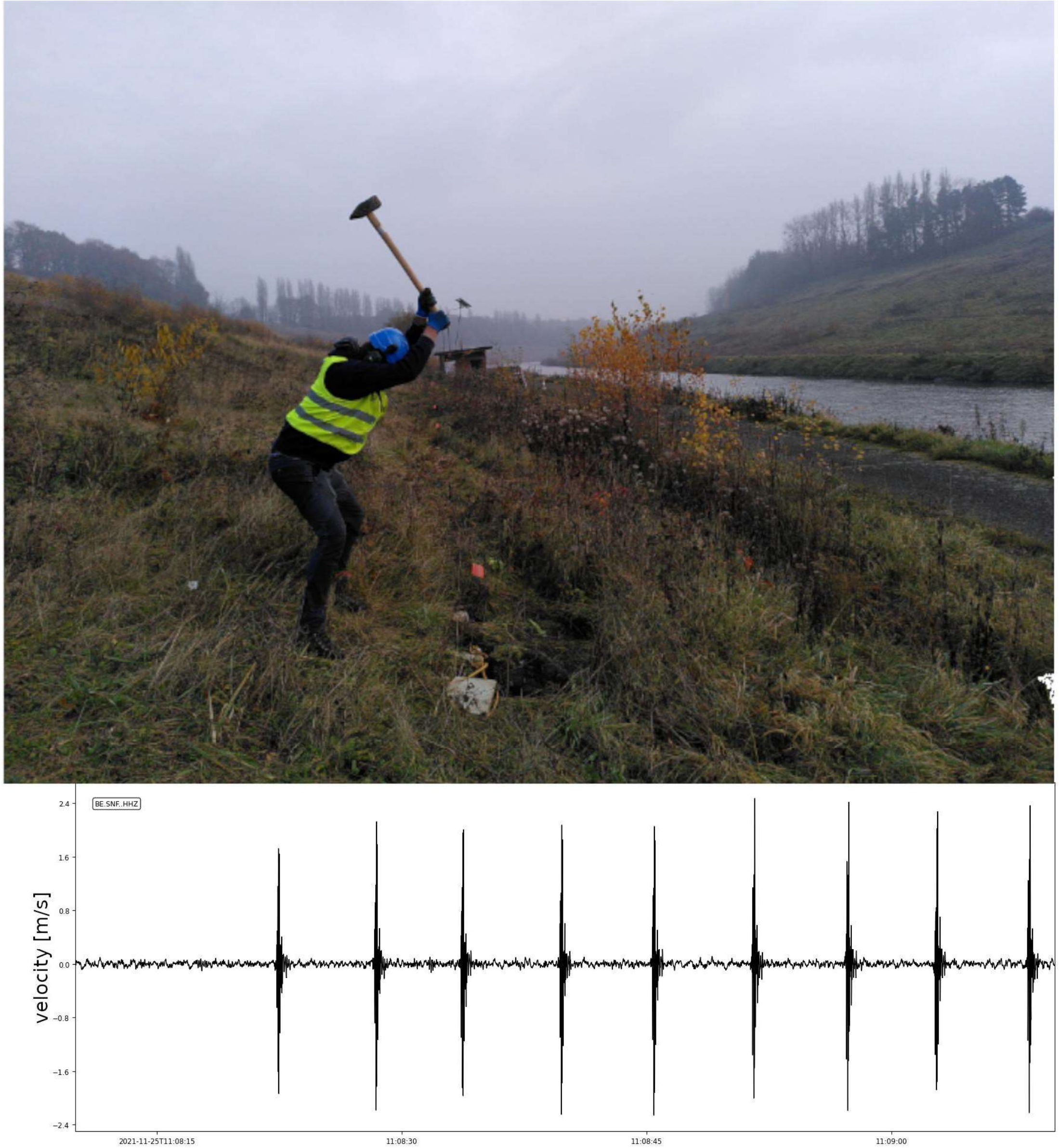

Fig. 3 - *Upper*: Active seismic experiment at the SNF station (hut in the background) with a line array along the Brussels-Charleroi Channel. *Lower:* The corresponding waveform recordings of the renewed permanent broadband instrument in a 12.6m borehole (highpass filtered at 1 Hz).

The aforementioned high relief in the southern sector of Belgium sometimes hinders the execution of ambient noise measurements with classical arrays, as the array apertures would exceed available spaces with homogeneous site conditions. Thus, we included active source experiments to increase the robustness of the velocity inversion at first. For specific sites we even ruled out the use of ambient noise arrays at all, i.e., the SNF station is located in the valley of the Brussels-Charleroi Channel 40m below the surrounding terrain (figure 3).

In the case of active source surveys only, we used the 3C node instruments in two equidistant line array geometries with two different intersensor distances. Through this we broaden the depth ranges for which we are sensitive to. During the processing, it allows us to apply simple velocity estimation based on refracted waves in the shallow subsurface and extend the robustness by applying the MASW (multichannel analysis of surface waves) method. The use of these two methods combines the nature of two different wave types (body waves and surface waves) and further enhances the robustness in v_P estimation in comparison to dispersion curve based processing only. In addition, this setup gives us the advantage of having a better understanding of the subsurface impedance contrasts geometry in two dimensions.

In the case of ambient noise arrays with smaller aperture (< 100m) we now routinely apply localized active hammer shots. Even without a linear geometry of the sensors, velocity estimations of refracted body waves in the shallower layers can still be resolved. The manual arrival picking and following linear regression allows the narrowing of the velocity inversion model space for the uppermost meters, which might have a reduced sensitivity with larger apertures; the shallowest meters are also not of primary interest as many sensors are placed in boreholes or basements of few meters of depths. Also, explosions in nearby (up to 50 km) stone quarries allowed a first order estimation of the deepest section of the local 1D velocity estimations. The shallow source location of such events excites strong amplitude surface waves, which can be tracked propagating through the temporary arrays by simple cross correlation. After narrowly filtering the surface-wave signal, the dispersion curve is reconstructed between 0.25 and 2.5 Hz for the apparent phase velocity, based on the cross-correlation time residuals and the raypath based on a planar wavefront assumption. Through this method, we can increase the velocity inversion robustness by limiting the model space for the deepest section and extending the frequency range to longer periods.

4. Conclusion

In this article we present the combined use of active seismic and passive ambient noise measurements for conducting site-characterization of the permanent stations of the Belgian seismological network. So far, we could finish the analysis of four stations in the southern part of Belgium and have the necessary data obtained for three stations. In this part of the country, we observe shallow depths to bedrock, with high velocities and poor site amplification. From this we conclude high quality station sites for seismological observation, that allows the recording of seismic waveforms and ambient noises over a large frequency bandwidth.

Acknowledgements

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The TURNkey European Testbeds for Consistent Real-time Monitoring of Seismic Ground Motion and Other Geophysical Markers

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Abstract: A total of 132 TURNkey Raspberry Shake 4D accelerometric and seismic sensor units and 26 TURNkey GNSS units have been deployed in six European Testbeds (TBs): TB1: Bucharest, Romania; TB2: Pyrenees, France; TB3: Towns of Hveragerði and Húsavík (Iceland); TB4: City of Patras and Aegion, Greece; TB5: Port of Gioia Tauro, Italy; and TB6: Groningen, the Netherlands. The deployments served the purpose of partially addressing weaknesses in existing sensor networks, and to secure and demonstrate the near real-time streaming of multidisciplinary data (e.g., seismic, deformation, structural response, etc.) in European seismic regions that range in their tectonic setting, levels and types of earthquake hazard, population densities, types of vulnerable infrastructure, and spatial extents. This TURNkey approach to real-time data streaming adheres to a common and consistent data format, even though multiple geophysical and structural measurements are involved. This data, in addition to earthquake impact reports from worldwide affected seismic regions (TB7), and transient data from TURNkey's EEW mobile system for aftershock (TB8), forms the basis of the development of the TURNkey FWCR platform in the project.

Keywords: Earthquake, Seismic, Structural, EEW, OEF, SeisComP

1 Introduction

The overall objective of the TURNkey project is to contribute to earthquake risk reduction and to mitigate the direct and indirect consequences of earthquakes in Europe (Meslem et al., 2021). For that purpose, TURNkey develops the TURNkey FWCR (Forecasting, Early Warning, Consequence Prediction, Response) platform, a multi-sensor-based earthquake information cloud-based system. The TURNkey platform is demonstrated and developed in six European earthquake prone Testbeds (TBs) that range in their tectonic setting, levels and types of earthquake hazard, population densities, types of vulnerable infrastructure, and spatial extents. They are TB1, Bucharest, Romania; TB2, Pyrenees, France; TB3, Towns of Hveragerði and Húsavík, Iceland; TB4: City of Patras and Aegion town, Greece; TB5, Port of Gioia Tauro, Italy; and TB6, Groningen, the Netherlands (Halldorsson & et., 2020). We present how a total of 132 new TURNkey RS4D accelerometric and seismic sensor units and 26 TURNkey GNSS units have been strategically deployed in the TBs to address particular weaknesses in existing sensor networks and that demonstrate and secure the real-time streaming of multidisciplinary data (e.g., seismic, deformation, structural response,