Railway near-surface passive seismic using trains as sources and fiber optic monitoring

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Summary

Rail tracks' deformation or collapse due to sinkhole formation beneath railway structure are natural hazards affecting train traffic regularity, causing extra maintenance costs and leading to crucial safety issues. Various geophysical methods have been used for decades to characterize the shallow near-surface, and more recently, the ability of Rayleigh surface waves to detect cavities has been proven. However, active seismic surveys remain too expensive and dramatically complex in railway environments. Recently, ambient noise and train signals have been used in combination with interferometry technology. Compared to ambient noise, train signals offer a much higher signal-to-noise ratio. Following this idea, we propose an imaging and monitoring system based on the deployment of a dense array along tracks and using trains as seismic sources. Using real case examples, we show that fiber optic with DAS technology can be used to monitor the near surface under railways on a variety of scales. All these studies show that DAS used in railway environment is efficient to image and monitor near-surface at different scale with a sufficient resolution and reliability.

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Introduction

The deformation or collapse of tracks due to sinkhole formation beneath railway platforms is a natural hazard that can affect train traffic regularity, cause extra maintenance costs, but also lead to crucial safety issues. Various geophysical methods have been used for decades to characterize the shallow near surface, and more recently, the ability of Rayleigh surface waves to detect cavities has been proven (Elawadi, 2010). However, active seismic surveys remain too expensive and too complex in railway environments.

Recently, train signals (Quiros et al., 2016) have been processed using interferometry technology to tackle this limitation. Compared to ambient noise, train signals offer a much higher signal-to-noise ratio. Following this idea, we propose an imaging and monitoring system based on the deployment of a dense array along tracks and using trains as seismic sources (Bardainne & Rondeleux, 2019; Tarnus et al., 2022). Contrary to ambient noise-based methods, we do not consider noise as isotropic but use trains as uncontrolled, but well-known, moving sources.

A dedicated process is performed for each train, allowing for accurate and repeatable surface wave passive imaging. This methodology has been developed and validated using densely spaced geophone or accelerometer arrays (0.5 m to 3 m) on several strategic areas of limited extension but characterized by high-level sinkhole risk.

Deployment and maintenance of electronic systems appears to be a limiting factor for very large target zones. Emerging alternative acquisition systems like fiber-optic cable using DAS (Distributed Acoustic Sensing) technology could permit increasing the scale of the investigated area (with either dedicated or telecom “dark” fiber already deployed). After describing the passive imaging methodology, we propose to compare DAS results at three different scales of observation: an experimental high-resolution acquisition for shallow cavity detection, a medium-scale imaging using dedicated fiber for accurate structural characterization, and a larger scale survey using dark fiber for geological imaging.

Method

Our method is based on the use of seismic interferometry (Campillo and Paul, 2003; Quiros, 2016; Dou et al., 2017). Traditionally, interferometry is based on seismic ambient noise, but it can also be performed using active sources with well-known locations. We propose a hybrid technique using trains as sources. Unlike conventional studies that consider railways as permanent sources of noise among a dataset, we consider trains as separated and well-localized moving sources (Figures 1a-b). The train’s location is tracked based on signal amplitude, only considering time periods when the train is aligned with a group of receivers. Only constructive waves are used in the cross-correlation process (Figure 1c). To enhance the signal, a summation is performed over all trains from a single day, accounting for several tens of trains. Even if train signatures vary, the result of each cross-correlation is equivalent for a given pair of receivers as it highlights only the propagation in the ground between receivers, allowing reconstruction of clear daily dispersion diagrams (Figure 1d).

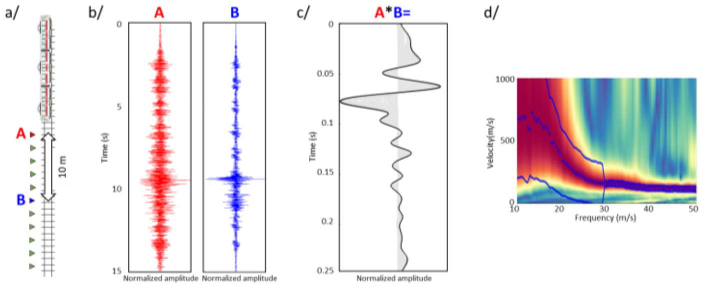

Figure 1 *Passive surface-wave processing workflow: a/ acquisition geometry example with a train and 2 m-spaced geophone line; b/ real signal recorded by 2 vertical geophones in positions A and B; c/ result of the cross-correlation of signals recorded on the 2 geophones, and d/ passive MASW phase*

velocity diagram computed using an antenna of 10 sensors (as in a/) and signals emitted by 32 trains. Blue crosses correspond to the picked Rayleigh wave velocity for each frequency.

Experimental DAS acquisition for artificial shallow cavity detection

The first experiment consisted of small-scale monitoring on a well-known experimental site characterized by an artificial cavity (2 m^3 empty tank) buried 2 m deep and located 15 m from an active railway (Figure 2). For benchmarking purposes, we deployed 3 lines of accelerometers and 3 interlaced (snake-like) lines of fiber-optic cable with the cavity located at the center of the acquisition system.

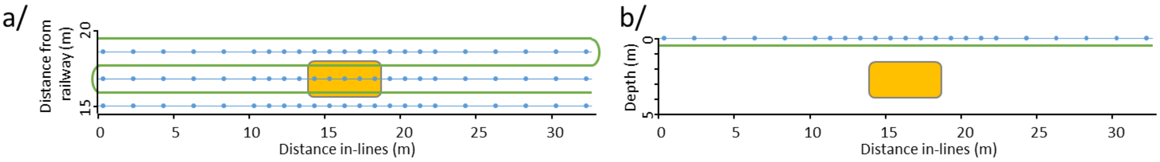

***Figure 2** Artificial cavity and acquisition system : a/ map and b/ cross-section views: acquisition system consisting of 3 lines of accelerometers (blue) and 3 (snake-)lines of fiber optic (green) buried at 30 cm depth. An artificial cavity (orange) has been buried at 2 m depth in the center of the acquisition system.*

Our processing was then applied using the signal of 8 trains on both datasets (accelerometers in Figure 3a and DAS in Figure 3b). It has allowed reconstructing Rayleigh wave phase velocity profiles between 10 and 40 Hz. Using the accelerometers, an accurate profile consistent with local geology and clearly localizing the cavity could be reconstructed. As for the DAS, despite poor resolution at this frequency range due to a large gauge length (~5 m), the cavity is still clearly visible and easy to localize (Figure 3b).

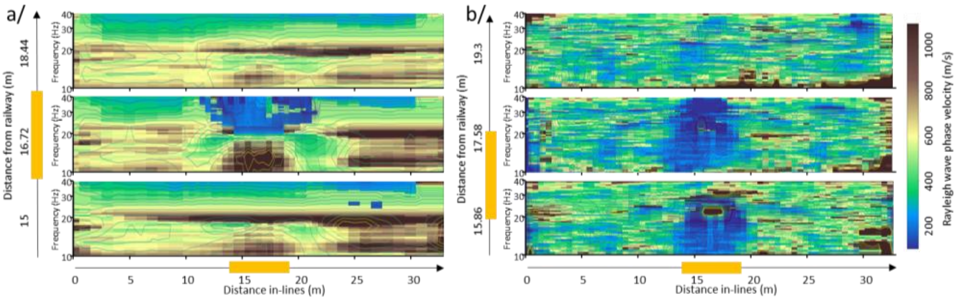

***Figure 3** Passive MASW profiles above artificial cavity using a/ 3 accelerometers and b/ DAS. Cavity position is reported with orange markers. Only the central line of accelerometer is deployed directly above cavity, against two lines of optical fiber for the DAS (on the 2 lower sections of b/).*

Dedicated fiber for middle-scale imaging

This middle-scale DAS investigation using dedicated optical fibers was performed on a site known to be exposed to subsidence hazards. Two different types of fibers were buried in a trench along the railway: a classic straight fiber and a helically wounded cable (HWC). The trench was 350 m long and located about 4 m apart away from the tracks. 300 accelerometers were also deployed along the trench with a 1 m spacing, enabling a comparison with DAS data results in a similar context. The DAS interrogator gauge length was set to 5 m.

Compared to the straight fiber, the HWC fiber is sensitive to signals polarized in all directions, while the straight fiber is only sensitive to strains collinear to the fiber. Moreover, the spatial sampling and gauge length for the HWC fiber are half that of the straight fiber.

Our processing was applied using one day of data, corresponding to the signal of approximately 50 trains, on both accelerometer and DAS datasets. The processing of the surface waves allowed to reconstruct Rayleigh waves phase velocity profiles between 2 and 20 Hz for DAS data and between 2 and 40 Hz for accelerometer data. We could then reconstruct S-wave velocity depth cross-sections after surface-wave inversion (Figure 4).

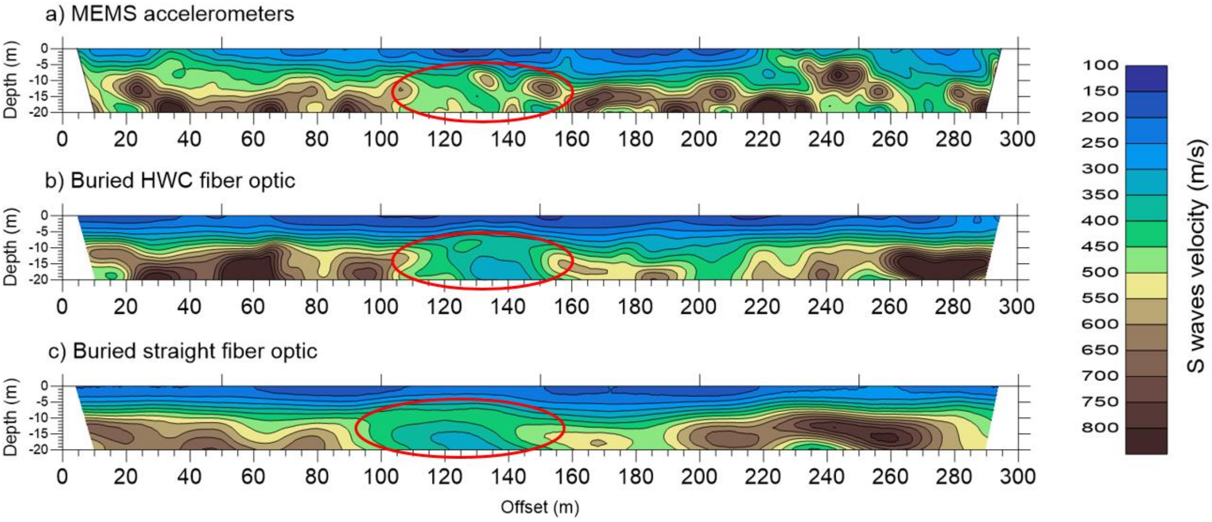

Figure 4 *S-wave velocity cross-sections; a/ with accelerometers; b/ with buried HWC fiber; c/ with buried straight fiber.*

For DAS data, the high-frequency recording is constrained by the gauge length (5 m), which acts as a high-cut filter. Therefore, shallow resolution is poorer for DAS than for accelerometers. Additionally, the HWC has better resolution than the straight fiber, as its gauge length is two times shorter.

Velocity profiles obtained with accelerometers and DAS data are consistent, with S-wave velocities ranging from 200 m/s just below the surface to 800 m/s at 20 m in depth in the terrain identified as the bedrock. The outline of the bedrock's top, represented by high velocities in brown dominant color (above 500 m/s), remains coherent between the different profiles.

A large low-velocity area can be highlighted in the middle of the section, between 100-150 m along the profile (delineated by the red ellipses on the figure), and between 10 and 20 m in depth. Within this area, S-wave velocities decrease down to 300 m/s at bedrock depths, designating it as the largest potentially decompressed area over the survey.

So, even if the global spatial resolution of the results does not reach what can be obtained from accelerometers, the entrenched optical fiber has the required sensitivity for sinkhole detection in railway environments, allowing for a relatively fast deployment for middle-scale imaging.

Dark fiber for large-scale imaging

The last example deals with the first attempt at applying our processing workflow on dark fiber. In this case, a telecom fiber is already deployed – now standardly – in cement gutters along train tracks.

For this, we were provided with a single day of already acquired DAS data on a large section of rail track, from which 2.5 km were selected for processing. At this scale, the workflow is adapted to process data by overlapping sections of 600 m, which are reassembled at the end.

The processed data consisted of a single day of recording, where about 50 trains were detected. The gauge length was 10 m with a 2.5 m spatial sampling. The fundamental mode for surface-wave dispersion could be automatically picked between 2 and 12 Hz and then inverted. The resulting S-wave velocity depth cross-section is presented in Figure 5. The white section corresponds to an un-processed area where the fiber is running through an aerial channel, and therefore not coupled at all with the ground. S-wave velocities range from 120 to 500 m/s, and the image shows clear spatial and geological coherency in terms of how velocities are distributed (lower near the surface with more altered or loose materials and higher at depth with compaction and the presence of denser terrains).

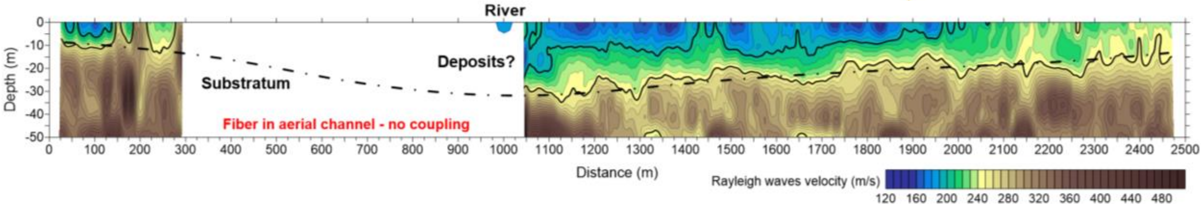

Figure 5 *Depth-inverted cross-section for dark fiber processing. Black iso-value lines outline from top to bottom the base of the lower-velocity sedimentary layers (in blue below 200 m/s), and the top of the underlying denser substratum (in brown, above 250 m/s). The dotted line extrapolates the latter interface through the data-less area resulting from the aerial channeling of the fiber.*

Without any *a priori* information other than the presence of a crossing river, the section can be divided into two main entities. The first being a deeper, denser, and slightly inhomogeneous substratum with higher velocities, represented in Figure 5 in brown dominant color (velocities above 250 m/s). The top of this substratum (outlined in black), extrapolated laterally in the white area (as a dotted line), shows a dip with a maximum depth of about 30 m at 1000 m along the profile, which corresponds to the localization of the river. It is then topped with a second entity consisting of layers of sediments. In particular, the lower velocity, most superficial layer (with blue dominant color, bottom outlined in black on the figure) corresponding to the more recent deposits, extends roughly from 0 to 2000 m, with a center matching the river's location. In summary, except for aerial fiber sections with no coupling at all, dark fiber allows us to build a reliable geological image at a sufficient resolution to detect large anomalies or characterize bedrock depth.

Conclusions

We developed a system based on the combination of a robust acquisition and processing system with an innovative geophysical methodology that is able to provide permanent and reliable measurements of surface-wave velocities in the near surface below railway tracks, using trains as seismic sources.
The system was developed using accelerometer technology, but we have shown that it is possible to reach a greater acquisition scale by extending it to fiber-optic cable DAS monitoring. We have shown on real case examples that geological near-surface monitoring is reliable and accurate enough using DAS and that, despite a loss of high-frequency content due to DAS gauge length filtering, it is possible to detect very shallow disorders like cavities very close to the surface, as well as deeper ones.

Acknowledgements

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