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Permanent passive seismic monitoring of the near-surface ground beneath railways using trains as sources

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Abstract

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. In this paper, we present an innovative seismic monitoring method that uses train as seismic sources. Thanks to interferometric methods and the reconstruction of virtual seismic traces between pairs of receivers, we use the surface waves generated by trains and recorded on a seismic sensor network to image the near-surface. Combined to an adapted design, a robust acquisition system and a deported processing system, this innovative geophysical methodology allows a near-real-time permanent and continuous measurement of seismic attributes. Hence, some geophysical attributes – like surface (Rayleigh) wave phase velocity dispersion curves – can be computed continuously and inverted to produce periodically S-wave velocity volumes. The fully automated process can provide, on a daily basis, a high-resolution (~2 m) S-wave velocity 3D volume of the shallow near surface (from 0 to about 50 m in depth). Then, analysis of the variation of S-waves velocity along time can be directly interpreted to track the genesis and growth of cavities due to leakage and dissolution phenomena. In this study, we show the results obtained after one year of continuous monitoring obtained with a wired accelerometer system. This allowed to observe S-wave velocity variations related to complex phenomena of leakage and decompression. Alternative acquisition systems (fiber optic using DAS technology for instance), processing methods (analyzing body-waves or back-scattering in addition to surface waves), or even different targets (to further optimize preventive maintenance operations) are possible and should be benchmarked soon.

Keywords: sinkhole, monitoring, surface wave, passive seismic

1 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.

The sinkhole phenomenon, while being gradual and scarcely detectable in its initial phase – for instance, as gypsum layers progressively dissolve under the strain of rains or groundwater flow – can develop at an unpredictable rate.

As a result, emergency maintenance operations are triggered when its direct effects are observed. Hazardous areas are progressively identified, and followed-up with the integration of geological, geotechnical and geophysical surveys.

Different geophysical methods (such as High Resolution Seismic Reflection, Ground-Penetrating Radar, Microgravimetry…) have been used for decades to characterize the shallow near-surface [1] and more recently, the ability of surface Rayleigh waves to detect cavities has been proven [2]. Surface wave processing generally consists first in measuring the dispersion behaviour (propagation velocity as a function of frequency). High and low frequency contents are respectively related to shallow and deep parts of the near-surface (100Hz~1m, 10Hz~20m, 1Hz~300m). Dispersion curves are then inverted to obtain the near-surface structure, and S-waves velocity profiles as a function of depth.

Unfortunately, conventional geophysical and geotechnical “snapshot” surveys are not totally adapted to provide a responsive system able to alert – and prevent – sinkhole occurrences. Even if data are acquired at the origin or during the growth period of a sinkhole, interpretation of temporally sparse geophysical data can be complex.

Indeed, geophysical attributes can be strongly affected by external factors (such as temperature and water content), representing a “climatic” noise which, through intermittent surveys, would be difficult to separate from actual changes in ground density, as during the formation of sinkholes.

Therefore, a continuous alert system based on reliable and easy to interpret measurements would dramatically improve this monitoring, by allowing to characterize and follow the effect of external factors, while matching the hazard’s evolution rate.

In this paper, we propose a methodology of 4D monitoring based on the permanent and continuous recording of seismic data. Thanks to interferometric methods ([3][4]), we use the surface waves generated by trains, recorded on a seismic sensor network, to provide continuous geophysical monitoring. Hence, some geophysical attributes –

like surface (Rayleigh) waves phase velocity dispersion curves – can be computed continuously and inverted to produce S-waves velocity models, providing an accurate estimation of the evolution of near-surface properties.

2 Methods

The founding articles of interferometry ([3][4]) have established that seismic ambient noise can be used for underground imaging. The cross-correlation of a signal, recorded by a pair of receivers A and B, can produce a virtual source-receiver pair respectively from A to B. Surface waves are particularly well adapted to interferometry, but body waves can also be reconstructed. An important feature which controls the efficiency of interferometry is the alignment that must exist between the source of seismic waves and the pair of receivers.

Traditionally, interferometry is based on seismic ambient noise ([5][6]), by considering that the random distribution of noise sources will provide both constructive alignments and destructive misalignments. However, it can also be performed using active sources with well-known locations.

In this paper we propose a hybrid technique using trains as sources. Differing from conventional studies that consider trains as permanent sources of noise among a dataset [7], we consider trains as separated and well-localized moving sources. The trains' locations are continuously tracked based on signal amplitude, using this information to maximize the cross-correlation's product. More precisely, for each pair of receivers and each detected train, a time interval corresponding to an alignment between the source (train) and each pair of receivers is selected. Thanks to this technique, only constructive waves are used in the cross-correlation process, delivering virtual traces characterized by strong signal-to-noise ratios, with as much virtual traces provided as pairs of receivers.

In order to improve the signal-to-noise ratio, a stack (summation) is performed among a given period of records (typically one day, several tenth trains). Even if train signatures are different (length, velocity, etc…), the result of each cross-correlation is equivalent for a given pair of receivers as it highlights only the propagation between receivers. Hence, each product of the day are summed, allowing to improve to signal-to-noise ratio by $\sqrt{N}$ where N is the number of trains.

Surface waves information is then inverted to produce a S-waves velocity volume thanks to a tomography process and a surface wave inversion process, as proposed in [8].

3 Results

A continuous monitoring system has been deployed on a site geologically known to be prone to sinkhole formations due to gypsum dissolution. Five lines of 42 accelerometers, spaced every 3 meters were installed between and around two railway tracks (Figure 1a-b).

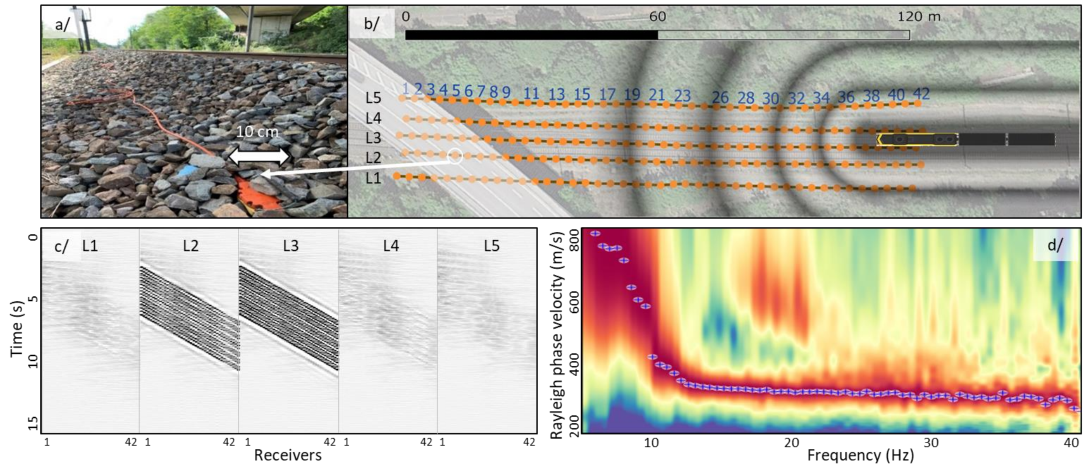

Figure 1: Acquisition system: a/ wired accelerometer buried in ballast; b/ acquisition design (5 lines of 42 accelerometers); c/raw seismic data recorded on the 210 receivers during passing train; d/ example of surface waves dispersion diagram obtained after a stacking of one full day (~40 trains).

Every day, trains are detected (Figure 1c) and processed (Figure 1d) to provide dispersion curves between 5 and 40 Hz for all ray paths of interest, i.e. all pairs or groups of receivers spaced by less than 15 m. This dataset is then introduced into a tomographic process to produce a surface wave 3D volume x(m), y(m), f(Hz).

Finally, a Rayleigh waves velocity volume is inverted using a non-linear inversion process [8] to access body-waves velocity in depth, providing a 3D volume x(m), y(m), z(m) of the S-waves velocity of the near surface below the monitoring zone (125m x 30m x 35m) (Figure 2).

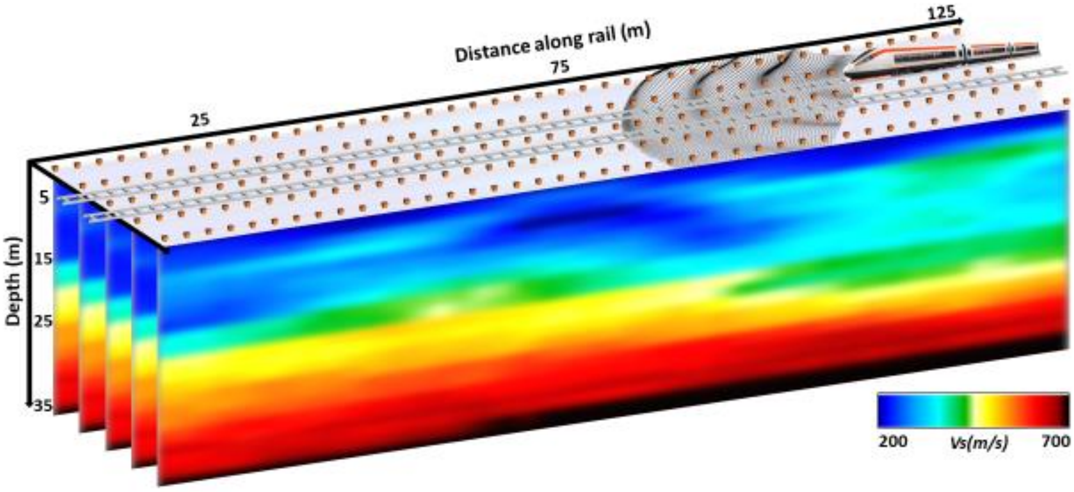

Figure 2: Vertical section of a daily 3D volume of S-waves velocity (first day of acquisition).

Absolute velocity models can be directly interpreted for geological purposes. The Gypsum layer correspond to the light blue/green 5 meters-thick layer (~ 350-400 m/s) at around 15 m in depth, confirmed by borehole survey. This layer is on top of a basement layer (500 m/s and more, yellow/red). The dissolution of gypsum can induce the decompression of overburden layers, interpretable as very low velocity layers (dark blue).

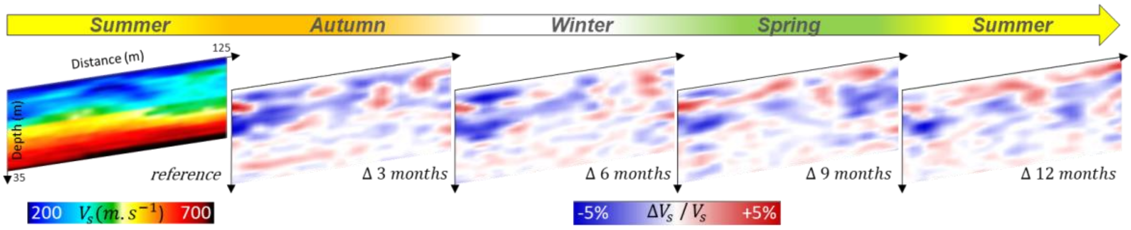

Figure 3: Reference and relative cross-section view of the s-waves velocity field during one year.

Such daily information can be analysed along time to assess the apparition and growth of cavities. Figure 3 shows the reference absolute velocity section on line 5 (north) and the relative variations of velocity after 3, 6, 9 and 12 months. This analysis highlights an important relationship between climatic variations and waves velocity. It also allows detecting an heterogeneous decrease of waves velocity showing a process of leakage and decompression, particularly in the western zone, where the anomaly (dark blue) persists over time and doesn't revert back to balance (its original state at the start of measurements) after one year.

4 Conclusions and Contributions

We have developed a system based on the combination of a robust acquisition and processing system with an innovative geophysical methodology, able to provide permanent and reliable measurements of the surface waves velocity in the near-surface below railway platforms.

We have proven that trains can be used as seismic sources to compute virtual seismic traces by means of interferometry, and that the area of interest can be covered accurately using the adapted design of receivers.

Thanks to the system's permanent recording of the seismic signal, a S-waves velocity volume of the near-surface underground (from 0 to about 50 m in depth) can be produced every day. These daily results can be directly interpreted to track the genesis and growth of cavities due to leakage and dissolution phenomena

As a whole, the system is able to alert railway maintenance managers, allowing to provide preventive and accurately targeted maintenance operations; and to avoid accidents.

In more, other attributes can be extracted from the virtual traces, and the extraction of transmitted and reflected body-waves and back-scattering could help improving interpretation in order to propose a "traffic light" geotechnical alert system. In the same way, a lot of additional data by-products can be extracted from such a permanent recording system, with the potential to further optimize preventive maintenance operations.

While the methodology remains globally the same, different instrumental techniques can be applied in order to accommodate variations in sites and train track geometries: dense accelerometer arrays for high resolution measurements, optical fiber layouts using DAS technology for long range and lower-resolution monitoring – or a combination of both.

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