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A case study for railway underground imaging using trains as seismic signal for sinkhole and subsidence phenomena prevention

R. Tarnus, T. Bardainne, L. Michel, N. Deladerrière, C. Cai

Sercel SAS, Carquefou, France

Abstract

Railway tracks are particularly exposed to the danger represented by sinkholes, a type of naturally forming underground cavity. Preventing the potentially severe outcomes through early detection represents a challenge for underground imaging techniques. We present here a method derived from seismic interferometry combined with a Multichannel Analysis of Surface Waves (MASW) approach. Technical aspects include using the energy from regular train traffic as a powerful and broadband signal source, recorded using a linear network of autonomous sensor nodes. In addition to lightweight deployment, this allows for more reliable and stable results due to the high energy transmitted into the ground by passing trains. Final results are provided in the form of surface waves velocity cross-sections of the ground, where decompressed terrains associated with cavities are identified as low-velocity anomalies. To illustrate the potential of this technique, a case study is presented here from a survey conducted on a railway section having experienced a severe collapsing phenomenon, due to a sinkhole cavity.

Keywords: sinkhole, seismic, imaging, masw.

1 Introduction

Railway tracks, as weakly embedded structures required to cross all types of terrains, are structurally exposed to the danger represented by sinkholes, a type of naturally forming underground cavity which occurs in terrains prone to dissolution phenomena linked to rainwater infiltrations. They can evolve slowly, causing moderate but troublesome subsidence phenomena, or silently until reaching ground surface, provoking sudden collapse. Outcomes can then be very severe, while the associated risk assessment and prevention remains complicated.

Through the last decades, a wide range of geophysical investigation methods, in particular seismic methods, have been applied along railways to help detecting and characterizing these sinkholes before they reach the surface.

Seismic methods are based on the recording and analysis of seismic waves using a network of sensors deployed along a grid or, as in the case of railways, along linear profiles on the ground surface. Among the available seismic imaging techniques, the active MASW method (for Multichannel Analysis of Surface Waves) has become very popular, providing, for near-surface applications, more practical results than reflection techniques which are disadvantaged by complex data processing, and the high heterogeneity of shallow layers. In more, the sensitivity of Rayleigh surface waves toward underground cavities has been proven [1, 2]. However, restrictions when operating on railway tracks usually limits seismic acquisition to low-energy sources, such as impact hammers. Moreover, these portable active sources require the continuous presence of dedicated personnel, who will have to comply with restrictive access schedules.

The method we propose here is derived from seismic interferometric methods [3, 4, 5] combined with a MASW approach. Technical aspects include using the energy from regular train traffic as a powerful and broadband signal source, recorded using a linear network of autonomous sensor nodes.

This lightweight approach allows for more reliable and stable results due to the high energy transmitted into the ground by passing trains, while requiring access to tracks only for nodes deployment and recovery. Processing also requires minor parametric adjustments, before final results are provided in the form of surface waves velocity cross-sections of the ground, where cavities and their usually associated decompressed terrains are identified as low-velocity anomalies.

To illustrate the potential of this technique, a case study is presented here from a survey conducted on a railway section having experienced a severe collapsing phenomenon, due to a sinkhole cavity.

2 Methods

The present method can be classified as “hybrid” between passive and active seismic: while in place, the sensors’ network is permanently recording, but trains being automatically detected thanks to their high signal-to-noise ratio, only relevant periods of signal are processed.

Interferometry consists in cross-correlating two signals recorded on couples of sensors, revealing similarities that will be retained as a delay in propagation time, here for surface waves. Cross-correlating records from a large combination of sensors allows reconstructing an analyzable "virtual" waves packet encompassing the whole linear profile of sensors parallel to the railway (figure 1a).

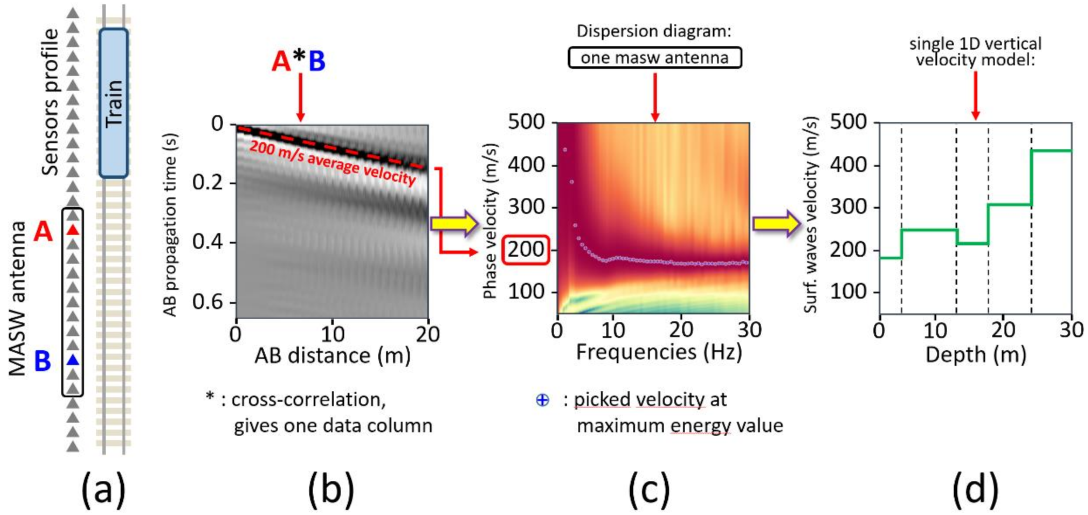

Figure 1: (a) sensor profile; (b) reconstructed surface waves packet; (c) dispersion diagram; (d) 1D S-waves layered depth velocity model.

The cross-correlations of all sources are summed to enhance the output virtual wave's contrast: even if each train's signal is unique, the result of each cross-correlation remains equivalent, as it depends on the intrinsic ground propagation velocity between a given pair of receivers.

Let's consider that surface waves generated by a train propagate in the near-surface of interest - here down to a few tens of meters, at velocities dependent with the ground's density. The wave packet is composed of many monochromatic waves, and if the ground shows density variations, the packet will "disperse", as the propagation velocity v (in m), each frequency f (in Hz) and its associated wavelength L (m) are interdependent through the relationship $L = v / f$. This separation of the waves in depth and velocity allows MASW processing [6].

Once collected and labelled in terms of source-receiver distance (figure 1b), the virtual seismic data are processed as regular MASW, where traces selected among contiguous groups of sensors designated as "antennas" are integrated into the calculation of "dispersion diagrams" (figure 1c), which allow highlighting, at maximal energy values, the velocity at which each frequency of the surface waves propagates.

Maximum values extracted from the dispersion diagrams provide raw 1D MASW dispersion curves, which are converted to vertical "soundings" of S-waves velocities in function of depth, through an inversion process using industry-standard software (figure 1d). Each sounding's surface location is positioned at its antenna's center.

Finally, the combination of multiple 1D inversions allows producing a continuous vertical cross-section of the ground along the profile, where structural aspects and low-velocity anomalies (as in the presence of cavities) can directly be identified in depth and extension.

3 Results

The results presented here come from a survey conducted on a railway section exposed to a severe subsidence phenomena, due to the collapse of an untracked sinkhole. Consequences included a maximal elevation loss of about 1,7 m in the immediate vicinity of the railway, and up to several tenths of centimeters in various places directly below the rails, along a section longer than 10 m. The site has been remediated before the survey with filling materials.

The sensor profile was implanted with 450 autonomous nodes, aligned with 1 m separation, at a distance of 5 m from the closest rail. The system recorded for a full day at a sampling of 2 milliseconds, cross-correlating the signal of 40 trains, and processing the virtual output using a 15 m sliding MASW antenna.

Figure 2a represents the raw MASW cross-section in terms of phase velocity vs frequency. At this stage, a major anomalous area of low-velocities (In blue, below 180 m/s) is already identifiable, between 200 and 310 m. The higher velocity values area between 245 and 260 m could be related to the denser filling materials, as it is very well correlated with the actual zone of subsidence.

1D depth-inversions are then realized on each MASW frequency sounding (each data column from the frequency cross-section), allowing to produce a 2D vertical, surface waves velocity section, represented in real depths on figure 2b.

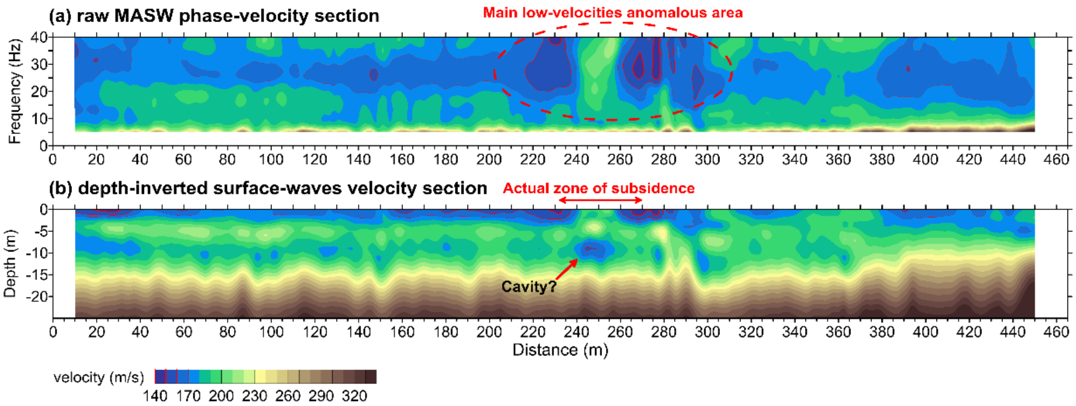

Figure 2: (a) profile raw vertical cross-section, representing phase velocity in function of frequency; (b) depth-inverted cross-section, converted to surface waves velocities in function of real depths.

The more visible effect of inversion is the near-surface flattening of the apparently large layer of low phase velocity values (from 25 to 40 Hz), and a simultaneous elevation of the deeper velocities which indicate a more compact ground. The anomalous, large low-velocity pockets from the pseudo cross-section are still present but now confined to the first 3 meters, while directly below the superficial filling's higher velocities, an area of low velocities (between 6 and 12 m in depth) that can be related to the persisting presence of decompressed materials – cavity? – is clearly highlighted.

A provisional but important conclusion could be that the problem might not have been completely remediated by the filling process, and that other areas of minor anomalies at similar depths should be considered for investigation and tracking (before 40 m; at 125 and 300 m).

4 Conclusions and Contributions

A seismic survey based on autonomous nodes has been performed on a section of railway track recently subject to a major hazardous subsidence phenomena, due to the presence of an untracked sinkhole - a naturally forming underground cavity.

While based on passive seismic interferometry, the method presented here uses the passing train signal from normal traffic as strong and broadband seismic signal sources.

The setup consisted in 450 sensor nodes deployed as a linear profile along the concerned railway section, separated each other by a 1 m interval.

Using this network to record and cross-correlate the signals of about 40 trains (corresponding to a full day of acquisition), allowed to produce virtual signals subsequently processed similarly to classical MASW (Multichannel Analysis of Surface-Waves).

The workflow's final output consists in depth-inverted vertical cross-sections of the ground, representing variations of Rayleigh surface waves propagation velocities in depth and extension. Through interpretation, low-velocity anomalous areas can then be associated to lower-density, potentially decompressed materials where subsidence problems are more likely to occur.

Results showed that, before depth conversion, the subsidence area can already be clearly identified in lateral extension from raw MASW cross-sections. The depth-inversion process allowed to characterize more accurately in real depth the persistent presence of decompressed materials – possibly a remaining cavity – between 6 and 12 m under the superficial layer of more compact materials used for filling as remediation to the collapse. In more, it also highlighted other potential areas which would deserve preventive investigations.

These results confirm that this lightweight approach is well-fitted to assess the sinkhole problem in railway context, providing crucial information on where to focus investigation, or to track the effect of remediation processes in known sensitive areas.

References

[1] E.A. Elawadi "Cavity Detection Using Geophysical Methods", VDM Verlag, 2010.

[2] Y. Wang, T.K. Tran D. Horhota, "Road sinkhole detection with 2D ambient noise tomography", Geophysics, Vol. 86 No. 6, 123-135, 2021.

[3] M. Campillo, A. Paul, "Long-range correlations in the diffuse seismic coda", Science, Vol. 299 (5606), 547-549, 2003.

[4] D.A. Quiros, L.D. Brown, D. Kim, "Seismic interferometry of railroad induced ground motions: body and surface wave imaging", Geophysical Journal International, Volume 205, Issue 1, 301–313, 2016.

[5] S. Dou, N. Lindsey, A.M. Wagner et al., 'Distributed Acoustic Sensing for Seismic Monitoring of The Near Surface: A Traffic-Noise Interferometry Case Study', Nature, Sci Rep 7, 11620, 2017.

[6] B.P. Choon, R.D. Miller, J. Xia, "Multichannel Analysis of Surface Waves", Geophysics, Vol. 64, No.3, 800-808, 1999.