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Seismic Surface-wave Analysis for Railway Platform Auscultation

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SUMMARY

The renewal of existent railways requires the characterisation of the mechanical properties of railway platforms (RP), thus raising the need to select appropriate maintenance actions. Conventional techniques (geotechnical soundings, coring) remain local, destructive, expensive and with low yields. Using non-destructive investigation techniques for local diagnosis and monitoring thus appears of great interest for enhancing RP control. Seismic surface-wave methods have been proposed to estimate in situ mechanical parameters of the superficial layers below railways. In this context, a joint geotechnical and seismic survey was carried out along the Northern Europe high-speed line (LGV) in order to precisely determine the origins of a phenomenon affecting the geometry of the track. Strong a priori knowledge of the RP structure allowed for inverting dispersion measurements for 1D VS models along the track. The results showed a contrast of VS in the loess lying below the RP, between areas where the phenomenon was observed and those it was not. This contrast was confirmed by Bender Elements measurements of VS performed on core drilling samples, and corresponded to the lateral variations observed along the track. These results encourage considering dispersion measurements as an appropriate tool of RP monitoring.

Introduction

The renewal of existent railway lines requires an accurate characterisation of the mechanical properties of the railway platforms (RP), thus raising the need to select appropriate maintenance actions, especially concerning local phenomena. The required data (bearing capacity, cone resistance etc.) depend mainly on the mechanical properties of the materials constituting these structures and the soil supporting the RP. But their accessibility is particularly difficult due to operational constraints. Furthermore, conventional techniques (geotechnical soundings, coring) remain local, destructive, expensive and with low yields. The use of non-destructive investigation techniques for local diagnosis and monitoring is of great interest for enhancing the control of RP. Ground penetrating radar is for instance used for the auscultation of the surface layers (Hugenschmidt et al., 2013) but does not assess the mechanical properties of RP. This technique, widely used in low attenuating medium, suffers from its great sensitivity to metal components and conductive media (*e.g.* clay), and from "three-dimensional" (3D) effects due to local geometry. Other geophysical techniques are used to characterise the RP such as micro-gravity to locate cavities and/or decompressed areas (Nebieridze and Leroux, 2012), but they also do not provide information about the mechanical properties of soils.

In such a context, seismic methods have been proposed to estimate *in situ* mechanical parameters of the superficial layers of the subsurface (compression and shear moduli) below railways, with sufficient resolution while maintaining high yields in terms of auscultated linear. For that purpose, seismic data sets can be acquired and interpreted in order to: (i) better define the variability of the mechanical properties of the involved materials; and (ii) better characterise the structure and mechanical behaviour of RP and soils on which they are grounded. Body wave (compression (P) and/or shear (S) wave) seismic refraction for instance allows for easily defining the geometry of the medium and the associated P- and S-wave propagation velocities (VP and VS, respectively). Although regarded as quick to implement and relatively simple to process, refraction seismic suffers from certain limitations that may complicate the interpretation of seismograms (*e.g.* presence of 3D structures or velocity inversion; difficulty in identifying the first arrivals in the presence of noise, especially in the case of S-wave studies). All these elements may limit the applicability of seismic refraction in the characterization of RP.

As an alternative to shear-wave refraction seismic, surface-wave methods are now classically suggested (*e.g.* Socco et al., 2010). Surface-wave prospecting, thanks to the guided character of these seismic events, appears to be less sensitive to the strong 3D character of the structures classically encountered in civil engineering (Karl et al., 2011). In addition, recent studies show an increasing interest for the implementation of surface-wave methods directly related to geotechnical issues (Heitor et al., 2012), even in railway context (Donohue et al., 2014; Hwang and Park, 2014).

Context and geotechnical results

A phenomenon affecting the geometry of the track on the Northern Europe high-speed line (LGV) was recently noticed. The origins of this phenomenon are possibly linked to large variations in the nature of the soils involved or to drainage aspects. In order to precisely determine its origins, a geological and geotechnical survey has been proposed (Dhemaied et al., 2014). During this survey, the lithological units observed under the railway were as follows: (i) an embankment formed with less than 1 m of backfilled loess mainly originating from the creation of the RP; (ii) loess characterised by beige silt "more or less" clayey; and (iii) Campanian chalk, whitish with low flint content, containing thin glauconitic intervals. As for the RP, it lies on the loess and presents the typical structure defined by the LGV standard, as shown schematically in Figure 1. The observed phenomenon is more pronounced track 2 (T2) side.

The geotechnical study carried out on the site consisted in eight core drilling reaching 3 and 12 m deep (numbered CD1 to CD8), and five dynamic penetrometer soundings reaching 12 m in depth performed along the rail track. These field tests were supplemented by laboratory measurements of water content, Atterberg limits, methylene blue test, density, grain size distribution curve and compressive strength on samples of core drilling. The interpretation of results (Dhemaied et al., 2014) reflects the typical structure of the RP. Under the ballast, the sub-ballast layer and subgrade appear more compact than loess, themselves being less compact than chalk present between 6 and 7 m deep under the side path of the rail track.

The water contents and densities values are similar in the loess layer for different core drilling samples at different depths. Geotechnical tests show no significant variability in the structure of the RP along T2, or from a track to another. This type of investigation was therefore not able to identify the origin of the observed phenomenon.

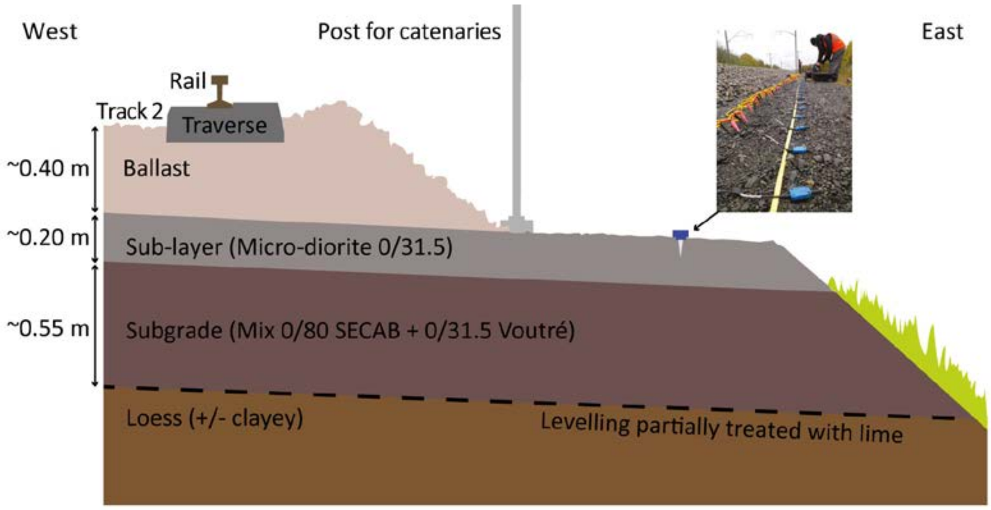

Figure 1 *Schematic section of the studied railway platform. The inset photo shows a typical seismic device used on the track.*

S-wave velocity measurements were also performed on core drilling samples using the Bender Elements (BE) technique (Lee and Santamarina, 2005). All samples were collected in the loess layer at one or more depths. The results, associated with water content and density measurements, have shown that the variation of VS (and therefore of the shear modulus) is correlated with the observed phenomenon along T2 (Dhemaied et al., 2014). For the same water content, the shear modulus turns out to be a good indicator of the quality of the loess layer from which originates the observed phenomenon, and bring out a variation in mechanical properties between the area presenting the phenomenon and the one not presenting it. Such a laboratory study is however not systematically possible to monitor tracks along great distances. These results thus justify the alternative for VS characterisation with seismic methods.

Seismic acquisition and results

The seismic survey consisted in seven identical seismic acquisition setups carried out along T2, using vertical component geophones. The profiles were implanted on the side path to ensure good geophone coupling with the medium and overcome specific acquisition conditions on ballast (Hwang and Park, 2014). For each profile, we performed shots every 24 geophones and on both sides of the profile, one half receiver spacing away from the first and last geophones, using an aluminium plate hit vertically by a small hammer. The plate was hit several times at each position to increase signal-to-noise ratio. Profile P1 was carried out at the base of CD5 in the area where the phenomenon was initially observed, while the profile P2 was centred on CD8 in an area which never showed the phenomenon. Five other profiles (P3 to P7) helped to complete the survey between these two profiles and slightly south of the maintenance area where the phenomenon was spotted during the campaign (Figure 2).

For each profile, surface-wave dispersion images were extracted from both direct and reverse shots. To obtain these images, the wavefield was transformed, after correction for geometrical spreading, to the frequency-phase velocity (*f-c*) domain in which maxima should correspond to Rayleigh-wave propagation modes (Mokhtar et al., 1988). The comparison of both single dispersion images presented only slight differences (considering measurement errors). These images were then stacked in order to increase the signal-to-noise ratio. The stacked dispersion data present a strong “effective character”, with a large number of propagation modes hardly distinguishable. On each dispersion image, two distinct propagation modes were finally identified as fundamental (0) and first (1) higher modes, and extracted with an estimated standard error in phase velocity.

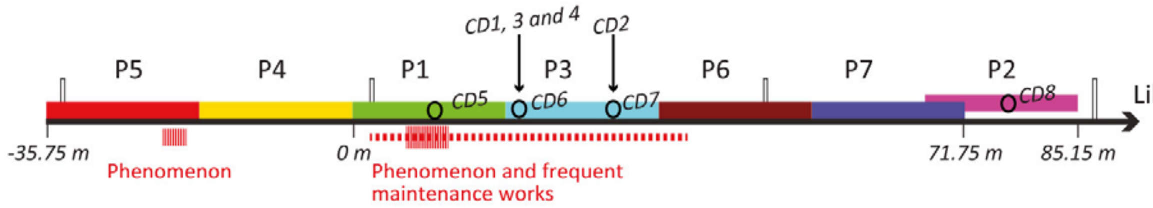

Figure 2 *Schematic layout of the seismic profiles. The approximate positions of core drilling (CD#) are given for information.*

Assuming a 1D tabular medium below each spread, we performed 1D inversion of dispersion data for each profile. We used the Neighbourhood Algorithm (NA) implemented for near-surface applications by Wathelet et al. (2004), which performs a stochastic search of a pre-defined parameter space (namely VP, VS, density and thickness of each layer). Based on our geological and geotechnical *a priori*, we used a parameterisation with a stack of three layers overlaying the half-space. The half-space depth (HSD), of great importance since it depends on the poorly known depth of investigation of the method, was fixed to 50 % of the maximum observed wavelength (*i.e.* 9 m). The valid parameter ranges for sampling velocity models was 10 to 750 m/s for VS in the three top layers and 10 to 1500 m/s in the half-space. The depths of the two top layers were allowed to vary between 0.1 and 1 m, while the depth of the third layer could range between 1 and 7 m. With such a parameterisation, the algorithm has strong *a priori* concerning the RP (number of layers in particular), but remains free to explore a wide range of models far from these *a priori*.

For each profile, dispersion data were inverted generating a total of 100500 models. The results are shown for P1 and P2 in Figure 3. Each model is represented with a colour depending on the difference (misfit value) between the data and the calculated dispersion. Despite the freedom offered by the parameterisation, the models included in the error bars for P1 (Figure 3a) and P2 (Figure 3c) present two first layers at a depth of less than 1 m in average, but do not present any interface for the chalk. Between these first layers and the half-space, the "best models" present a third layer of at least 4 m with constant VS. A representation of the misfit in function of the thickness of this layer (HVS3) and the associated velocity (VS3) is given Figure 3. It confirms the impossibility of defining the depth of the chalk. However, this representation of the parameter space allows quantifying VS in loess (*i.e.* around 190 m/s for P1, Figure 3b; and 300 m/s for P2, Figure 3d). The resulting contrast corresponds to the lateral variations observed along T2 and confirmed by the BE measurements.

Conclusions

Dhemaied et al. (2014) showed with geotechnical testing and in particular thanks to BE tests that VS was a good indicator of the quality of soils constituting the RP. Unlike conventional geotechnical approaches (*e.g.* field or laboratory tests), the VS obtained with BE tests showed a correlation between the phenomenon affecting the geometry of the tracks and the mechanical state of the RP. Surface-wave methods were proposed to characterise VS in the soils constituting the RP. Strong *a priori* knowledge of the RP structure on this site then allowed for inverting dispersion measurements for 1D VS models along the track. A representation of the misfit in function of the thickness of the third layer (HVS3) and the associated speed (VS3) allowed quantifying VS in the loess along the side path and showed a contrast between the area where the phenomenon could be observed and in those it could not. This contrast corresponds to the lateral variations observed along T2 and confirmed by the BE measurements on core drilling samples. The proposed inversions were able to produce relevant results only thanks to strong available *a priori*. These results show that the measured dispersion can be considered as a control criterion of the RP state. They obviously need to be demonstrated in the context of other lines (LGV and classic ones) before being generalised. New tests are required to optimise this approach, its implementation (particularly concerning the inclusion of ballast) and processing (particularly concerning the inclusion of higher modes).

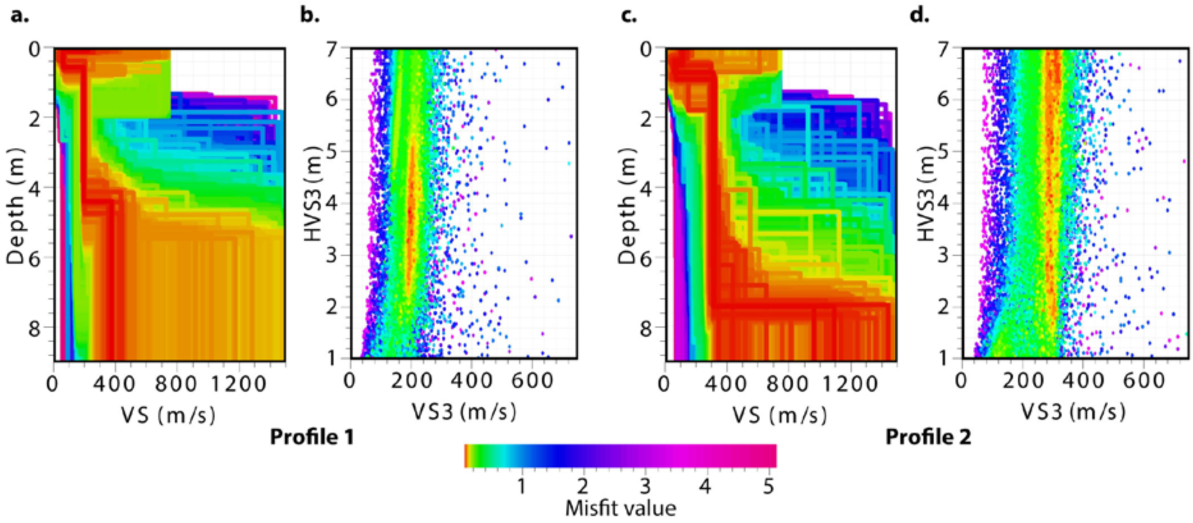

Figure 3 *VS models obtained from surface-wave dispersion inversion for P1 (a) and P2 (c). Each generated model is represented with a colour depending of the difference (misfit value) between the data and the calculated dispersion. Representation of the misfit in function of the thickness in the third layer (HVS3) and the associated velocity (VS3) for P1 (b) and P2 (d).*

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