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AN EXPERIMENTAL STUDY OF EMBANKMENT CONDITIONS ON THE HIGH-SPEED RAILWAY GROUND VIBRATIONS

Georges Kouroussis[1], David Connolly[2], Mike Forde[2] and Olivier Verlinden[1]

1 *Université de Mons – UMONS, Faculty of Engineering, Department of Theoretical Mechanics, Dynamics and Vibrations, Place du Parc, 20 — 7000 Mons (BELGIUM)*
e-mail: georges.kouroussis@umons.ac.be
2 *University of Edinburgh, School of Engineering, Alexander Graham Bell Building — Edinburgh, EH9 3JF (SCOTLAND)*

High-speed rail infrastructure has been developed considerably in Europe, creating a dense rail network that links major capital cities. Although it has been the subject of continuous technological innovation (comfortable trains, ERTMS, embankment adaptation,. . .), high-speed rail causes elevated ground vibration levels, due to the large weight and speed of the moving load. This paper presents recent vibration measurements collected at Belgian sites during the passing of Thalys, Eurostar and French TGV Réseau high-speed trains. In common with other engineering disciplines, railway ground vibrations are increasingly studied using computer simulation. Despite this, experimental measurements are important for both investigating ground vibration phenomenon and for the validation of numerical models. The proposed study is in line with the development of high speed rail line in the United Kingdom, by focusing on the parameters and configurations that influence ground surface motion. A detailed analysis of the selected sites is performed in terms of soil dynamic parameters by using the MASW method. Three track configurations are investigated by comparing the effect of possible embankment (backfill or excavated) on the ground vibration level with respect to the distance from the source. It is found that the embankment case causes lower peak particle velocities than the cutting and at-grade cases which present comparable vibration levels. Particular attention is paid to the impact of the train and the soil configuration, as well as the direction of measurement, in both the near and far field.

1. Introduction

It is well admitted that the railway networks represent a promising modal transfer of road and airplane traffic for the short- and mid-distances. Since 1981 when the French railway operator SNCF opened the first high-speed line (HSL) between Paris and Lyon, the high-speed network never stopped to grow and became, at the present time, a large and valuable service network in the West of Europe (Figure 1). Nevertheless, some regions lag behind when it comes to high-speed train (HST) capacities and this is the case of the United Kingdom. In the last few years, several impact studies were launched to analyse the potential of HSL development on the country economy. One of the concerns is the environmental impact in terms of vibrations. One problematic issue is the so-called supercritical phenomenon that may appear when the vehicle speed is close to the Rayleigh ground wave speed, which is sufficiently small for soft soil configurations.

This phenomenon has been researched expensively. Theoretical and experimental studies of railway-induced ground-borne vibrations have multiplied in the last twenty years, ever since the rapid

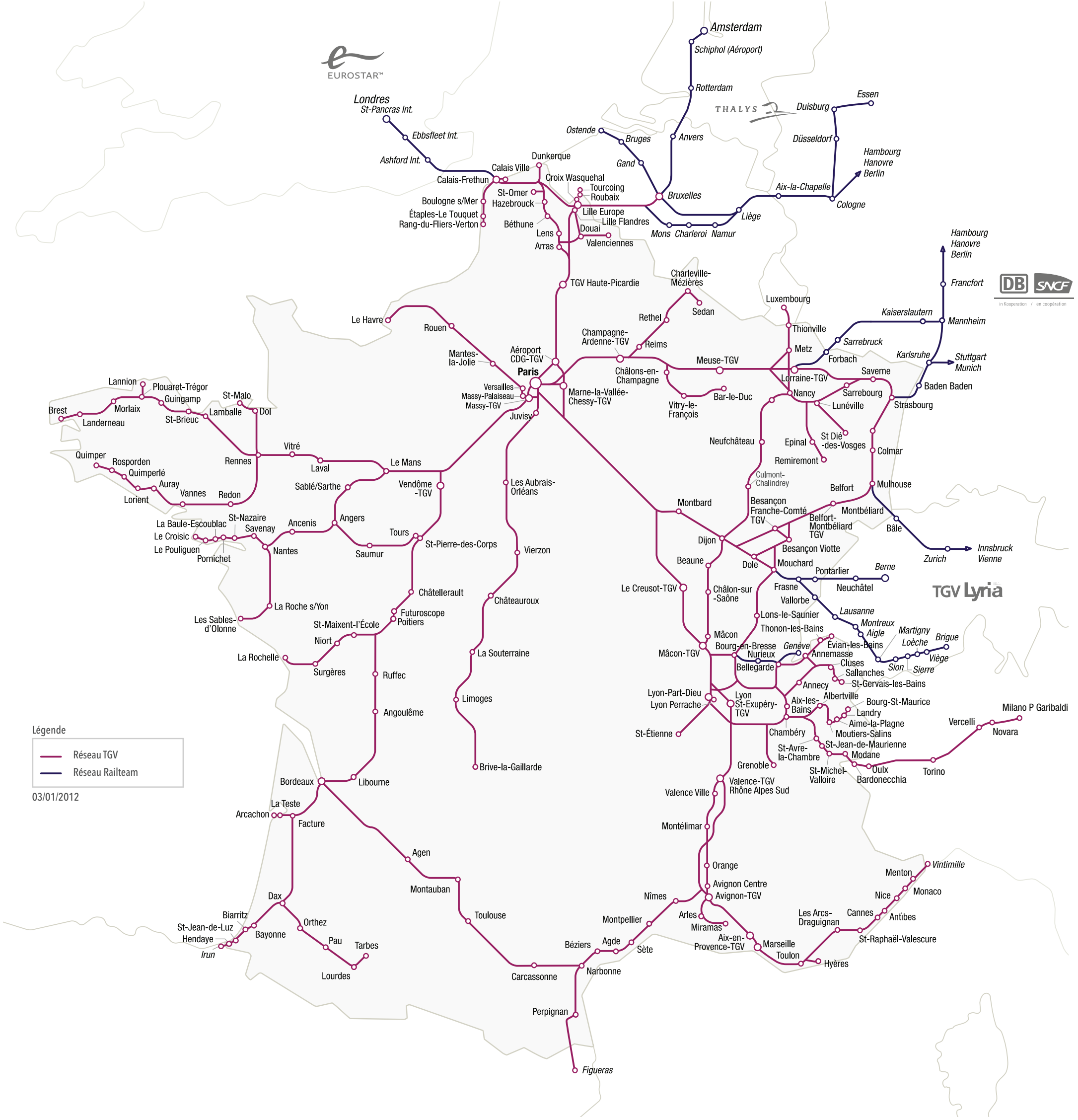


Figure 1. High-speed line in West of Europe (SNCF documentation)

development of HSL networks, especially in Europe. But the interest of scientific and technical communities was renewed when abnormal high vibration amplitudes were recently recorded in Sweden [1]. Other recorded data was presented afterwards. Let us mention the works of Degrande and Schillemans [2], P. Galvín and J. Domínguez [3], or Kouroussis et al. [4]. All these results were essentially presented in order to validate numerical models, with the assumption of simple soil geometry configurations. Particular geometries like embankments were voluntary omitted.

The present paper aims to be complementary to this aforementioned research by analysing the effect of embankment conditions on the ground vibrations. The purpose is also to collect experimental results of sufficient interest to validate recent prediction models based on a finite element approach and suitable for complex geometries [5, 6]. In situ tests were performed using the multichannel analysis of surface waves (MASW) method on three different sites, and several train passing were recorded. The role of embankments is finally studied.

2. Selected sites

The measurement location was around Leuze-en-Hainaut, near the French border, along the high-speed line LGV1 between Brussels and Paris/London. Three sites, in a stretch of 5 km, were selected according to their track geometrical configuration (Figures 2 and 3):

- with the track in embankment with a 30° slope and $5.5\,\mathrm{m}$ high (site 1),
- with the track at grade with respect to surrounding land (site 2),
- with the track in cutting with a angle of 25° and $7.2\,\mathrm{m}$ depth (site 3).

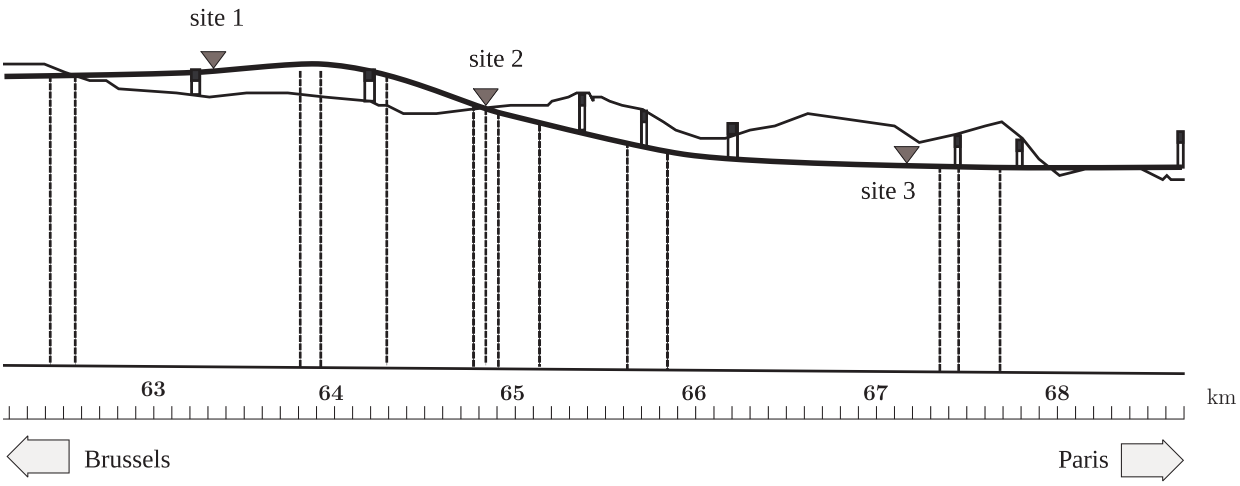


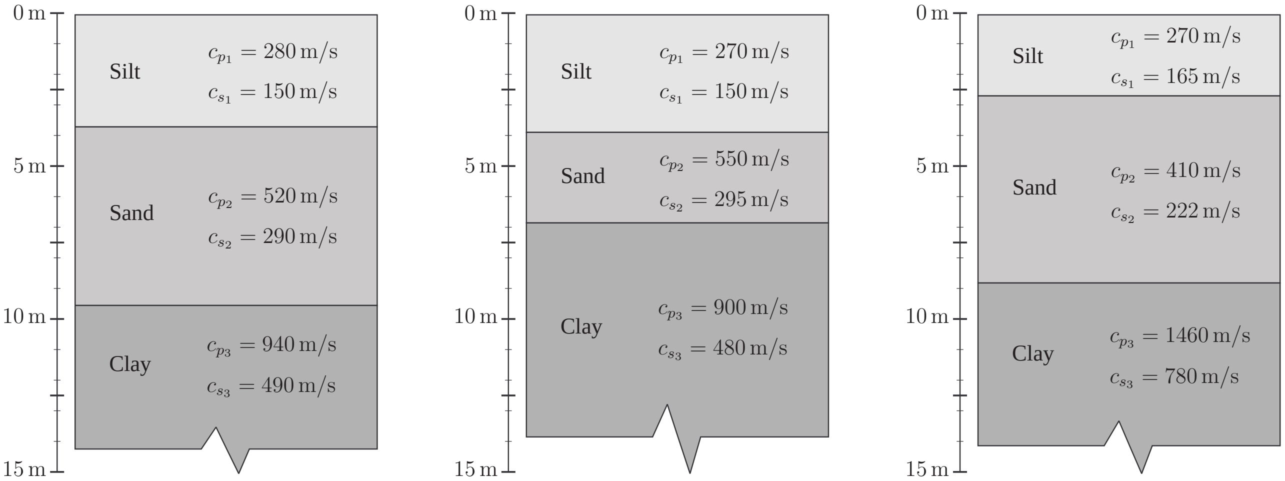
Figure 2. Location of the three selected sites

(a) Site 1 (backfill embankment)
(b) Site 2 (in grade)
(c) Site 3 (excavated embankment)

Figure 3. Configuration of the selected sites and location of the vibration sensors

3. In situ soil tests

First introduced by Park et al. [7], the MASW method is one of the seismic survey methods used in evaluating the ground stiffness for geotechnical engineering purposes. It can be seen as an extension of the SASW (spectral analysis of surface waves) method since it uses the spectral analysis of ground roll recorded by more than a pair of receivers, and tries to overcome the weaknesses of the SASW method. MASW is based on surface waves generated from various types of seismic sources, more particularly impacts generated by sledge hammer. It analyses the propagation velocities of those surface waves and deduces shear-wave velocity c_S variations below the surveyed area. After a relatively simple procedure inverting a calculated dispersion curve (a plot of phase velocity versus frequency), final c_S information is provided in 1D, 2D or 3D formats as a function of the depth. A multichannel shot gather decomposed into a swept–frequency format allows the fast generation of an accurate dispersion curve. Figure 4 displays the estimated elastic conditions for the studied sites using GeoPsy software. It gives an accurate representation of the soil configuration by defining several layers of constant dynamic parameters. It clearly appears that the three sites approximately present a similar configuration in terms of layer geometry and soil dynamic parameters (sites 1 and 2 are quite similar but site 3 is slightly different for the second and third layer dynamic properties).



(a) Site 1 (b) Site 2 (c) Site 3

Figure 4. Stiffness map of the selected sites based on the primary and secondary wave velocities c_P and c_S

4. Passages of high-speed trains

Several passages of HST were recorded during three days in August 2012, including the passing of Thalys (Figure 5), Eurostar (Figure 6) and the French TGV (Figure 7). To reduce any uncertainty on the parameters used for simulation, soil identification tests and train passing measurements were performed on the same day, for each site. The three high-speed vehicles studied in this work stem from the same generation, with a geometrical difference for the Eurostar, which has two side carriages in the centre for safety reasons inherent to the Channel tunnel configuration.

The same uniaxial and triaxial geophone sensors (Sensor SM-6 low frequency) were used as for the site testing, at distances y_R from 9 to $35\,\mathrm{m}$ from the edge of closest rail (up to around $80\,\mathrm{m}$ for the vertical direction only). They were placed along (x-direction), perpendicularly (y-direction), and vertically (z-direction) to the track. The advantage of velocity sensors over seismic accelerometers is that numerical integration, coupled with a low-pass filter to avoid drifting, is not necessary. Moreover they do not need an amplifier and their cost is low, for the same precision. Measurements were stored using a 24-channels Geode seismic recorder equipped with a 24 bit A/D converter. The sampling rate was fixed to $f_s = 1000\,\mathrm{Hz}$, coupled to an anti-aliasing filter.

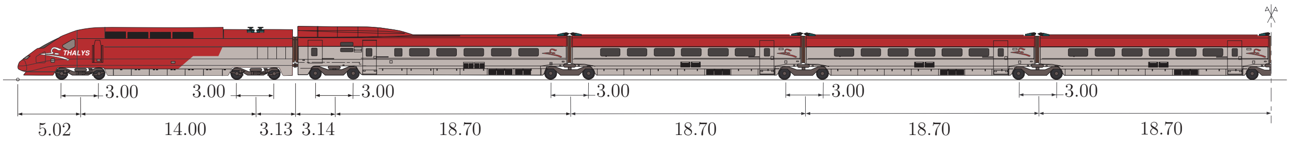


Figure 5. Thalys HST dimensions

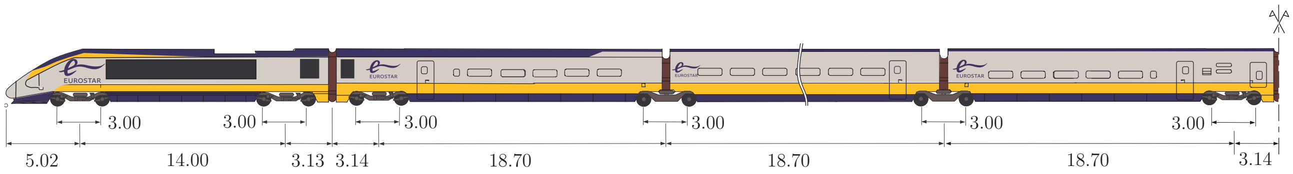


Figure 6. Eurostar HST dimensions

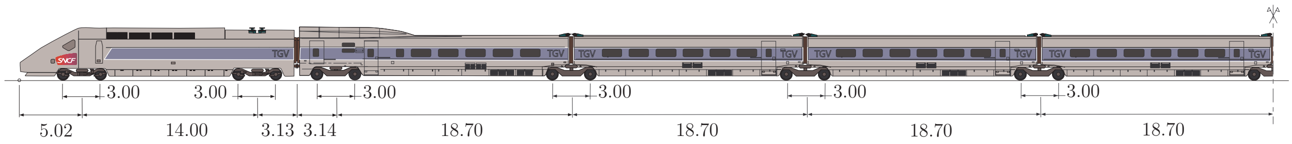
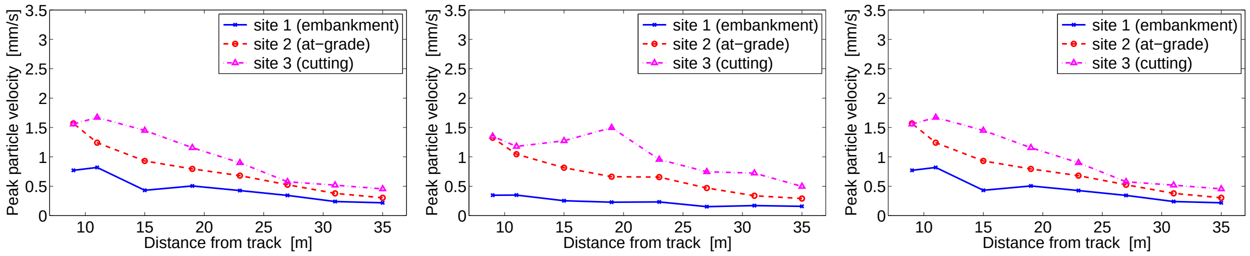


Figure 7. French TGV dimensions

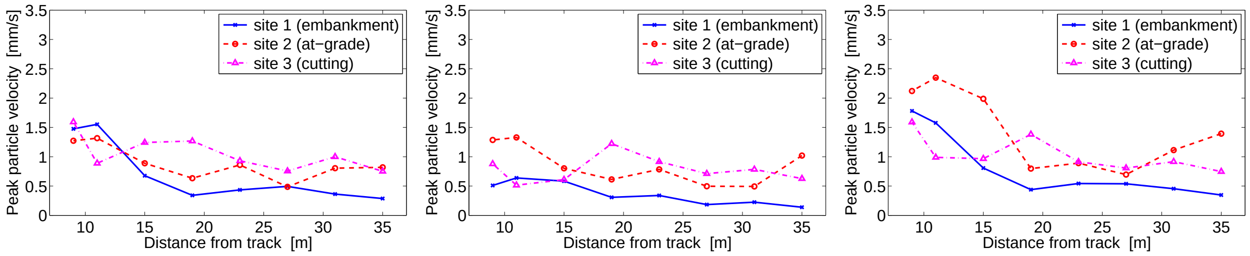
Experimental data are also of invaluable help in validating prediction railway-induced ground vibrations models. The determination of vehicle speed is performed using a procedure based on the dominant frequency method induced by train loads [8].

5. The influence of soil embankment

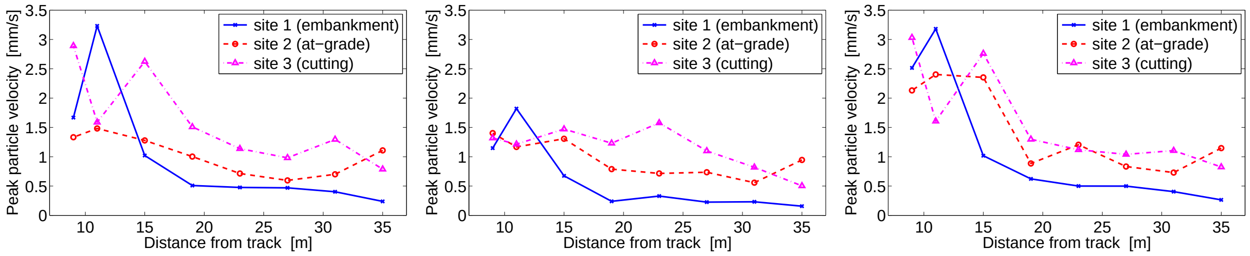
Figures 8 to 10 present the complete results for the passage of the Thalys HST, the Eurostar HST and the French TGV at similar speeds (around $290\,\mathrm{km/h}$). In order to have an overall view,



(a) Thalys HST — x direction (b) Eurostar HST — x direction (c) French TGV — x direction

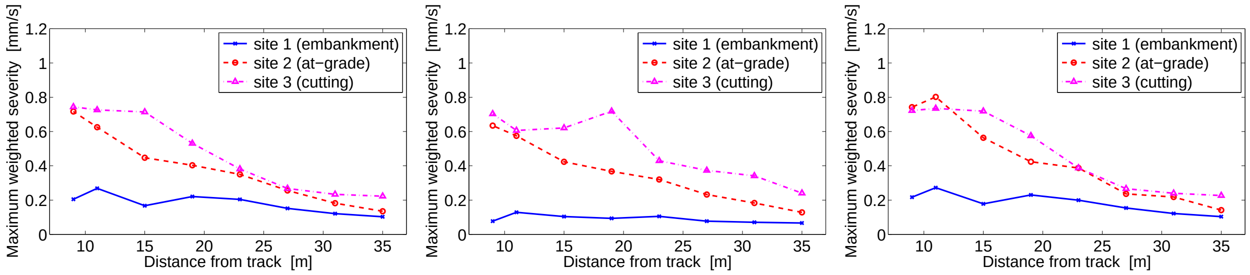


(d) Thalys HST — y direction (e) Eurostar HST — y direction (f) French TGV — y direction

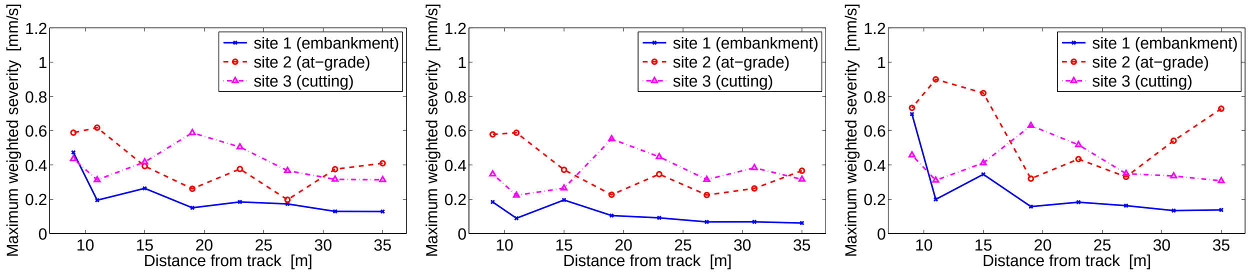


(g) Thalys HST — z direction (h) Eurostar HST — z direction (i) French TGV — z direction

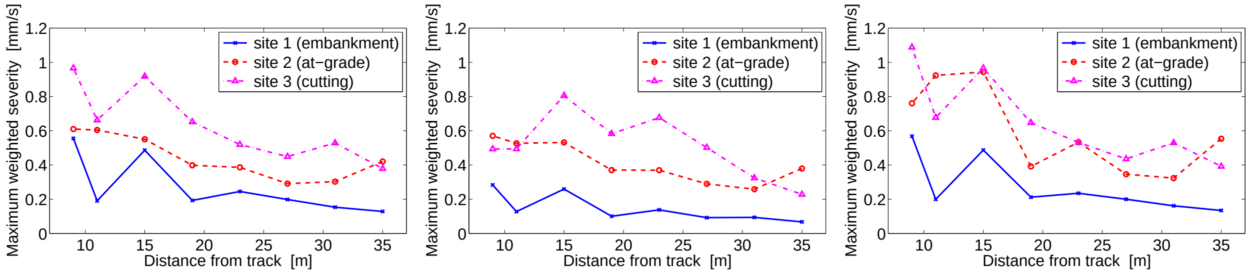
Figure 8. Peak particle velocity calculated for each vehicle passing and each direction of measurement, as a function of the site configuration



(a) Thalys HST — x direction (b) Eurostar HST — x direction (c) French TGV — x direction



(d) Thalys HST — y direction (e) Eurostar HST — y direction (f) French TGV — y direction



(g) Thalys HST — z direction (h) Eurostar HST — z direction (i) French TGV — z direction

Figure 9. Maximum weighted severity calculated for each vehicle passing and each direction of measurement, as a function of the site configuration

three indicators were calculated:

- the peak particle velocity

$$PPV = \max|v(t)| \ , \tag{1}$$

  defined as the maximum instantaneous positive or negative peak of the vibration signal $v(t)$ and used in evaluating the potential of building damage (DIN 4150 part 3 and SN 640312a standards),

- the maximum weighted severity, according to the DIN 4150 part 2 standards, for evaluating human response,

$$KB_F(t) = \sqrt{\frac{1}{\tau}\int_0^t KB^2(\xi)\, e^{-\frac{t-\xi}{\tau}}\, \mathrm{d}\xi} \qquad (\tau = 0.125\,\mathrm{s}) \tag{2}$$

  ans based on the weighted velocity signal $KB(t)$ defined by

$$H_{KB}(f) = \frac{1}{\sqrt{1+(5.6/f)^2}} \ , \tag{3}$$

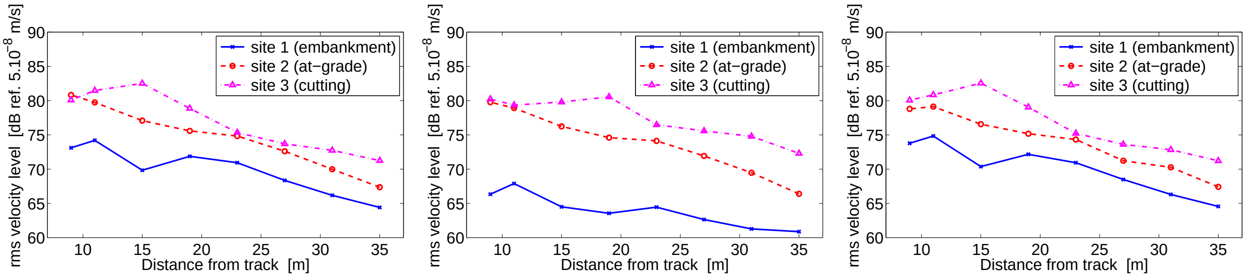
- the vibration velocity level, used by the U.S. Department of Transportation and defined as:

$$V_{dB} = 20\log_{10}\frac{v_{rms}}{v_0} \tag{4}$$

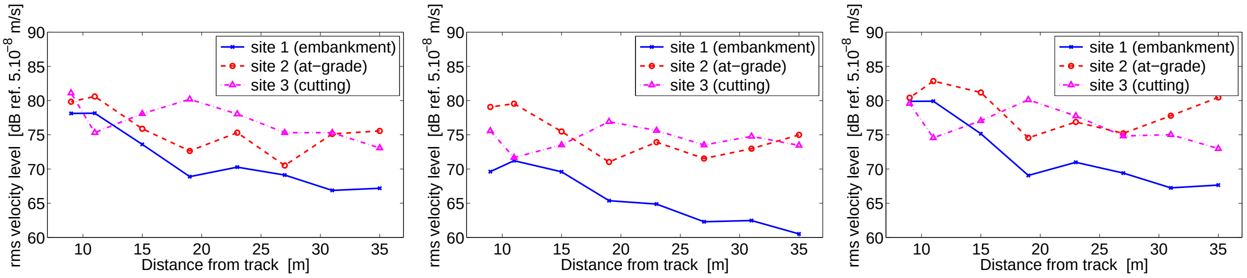
where v_{rms} is the root mean square amplitude and v_0 the reference quantity for a vibration velocity equal to $510^{-8}\,\mathrm{m/s}$. This vibration level is used to describe the smoothed vibration amplitude by supposing that the human body responds to an average vibration amplitude.

The three directions are analysed for each site configuration, as a function of the distance from the track (these results correspond to the train passing on the near track).

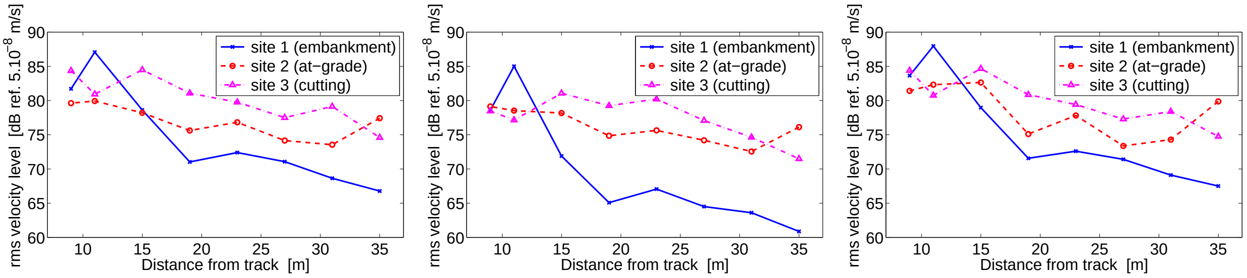
It appears clearly that the three motion components have the same order of magnitude and the vertical vibrations are not sufficient for a comprehensive evaluation. Similar results are obtained for the French TGV and the Thalys HST with levels comparable to previous studies [4]. Ground vibration levels generated by the Eurostar are the smallest, for the three directions of measurement. It is interesting to note that, for vertical vibration, the embankment case causes the least vibration and the cutting one causes the greatest vibration. For the horizontal directions, vibrations vary much more. This situation can be explained by the nature of embankments, consisting of compacted silt and clay, originating from neighbourhing soil. The dynamic properties are a mix of those obtained from the MASW test and, with the effect of compaction, the embankment formed from a stiffer material than the underlying first layer reduces the far field vibrations, as theoretically explained in [6].



(a) Thalys HST — x direction (b) Eurostar HST — x direction (c) French TGV — x direction



(d) Thalys HST — y direction (e) Eurostar HST — y direction (f) French TGV — y direction



(g) Thalys HST — z direction (h) Eurostar HST — z direction (i) French TGV — z direction

Figure 10. Maximum rms velocity calculated for each vehicle passing and each direction of measurement, as a function of the site configuration

6. Conclusion

The two purposes of this paper are to evaluate the effect of embankment conditions on the ground surface motion and to have a large database to validate prediction schemes of railway–induced ground vibrations. This was successfully achieved by obtaining experimental time histories of passing Thalys HST, Eurostar HST and French TGV and by analysing the vibration level through key indicators like peak particle velocity, maximum weighted severity and maximum root mean square velocity, often used by international standards. MASW tests provide useful results about the soil configuration. The effect of embankment geometry is then compared between the three sites and for the various analysed vehicles. The presence of embankment reduces the vibration level compared to the cutting and at-grade cases which present comparable vibration levels. This is linked to the fact that the embankment may act as a waveguide which traps energy within it.

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