Science of the Total Environment 557–558 (2016) 110–122

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Railway cuttings and embankments: Experimental and numerical studies of ground vibration

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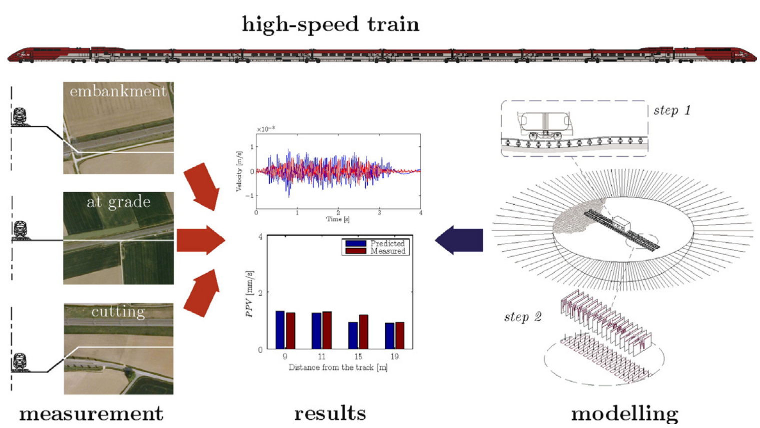
HIGHLIGHTS

- Field experiments undertaken on 3 high speed lines with different track profiles.
- A numerical prediction numerical model is is developed and validated for all the three cases.
- Predicted at-grade vibration levels are most accurately reproduced.
- Accuracy of predicted embankment vibration levels is shown to be acceptable.
- Predicted cutting vibration levels are most challenging to reproduce.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form 2 March 2016
Accepted 4 March 2016
Available online xxxx

Editor: D. Barcelo

Keywords:
Railway ground vibrations
Environmental impact assessment
Track embankment
Cutting-excavation
High speed rail
Earthworks

ABSTRACT

Railway track support conditions affect ground-borne vibration generation and propagation. Therefore this paper presents a combined experimental and numerical study into high speed rail vibrations for tracks on three types of support: a cutting, an embankment and an at grade section. Firstly, an experimental campaign is undertaken where vibrations and in-situ soil properties are measured at three Belgian rail sites. A finite element model is then developed to recreate the complex ground topology at each site. A validation is performed and it is found that although the at-grade and embankment cases show a correlation with the experimental results, the cutting case is more challenging to replicate. Despite this, each site is then analysed to determine the effect of earthworks profile on ground vibrations, with both the near and far fields being investigated. It is found that different earthwork profiles generate strongly differing ground-borne vibration characteristics, with the embankment profile generating lower vibration levels in comparison to the cutting and at-grade cases. Therefore it is concluded that it is important to consider earthwork profiles when undertaking vibration assessments.

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http://dx.doi.org/10.1016/j.scitotenv.2016.03.016
0048-9697/

1. Introduction

Although high-speed rail is a rapidly growing industry, it can cause ground vibration, due to the wheel-rail contact at high speed. Efforts have been made in order to reduce the vibrations generated by the vehicle itself while, at the same time, improving the passengers' comfort. However, ground-borne vibration is still a major environmental issue (Connolly et al., 2015b). Indeed, the propagation of railway vibrations generated in urban areas is complex, due to the different transmission paths in a medium fundamentally inhomogeneous and infinite in three directions (Connolly et al., 2015a). Specific calculation methods are required for dedicated applications, e.g. for metro (Vogiatzis, 2012; Hussein and Hunt, 2009; Parry et al., 2015) or freight lines (Waddington et al., 2015). High-speed lines present however other problems related to a vehicle speed greater than the nominal speeds for metros or for freight trains. A challenge in research, especially in numerical approaches, is to predict the forces generated in the ground and propagating in the free field or surrounding buildings, by simplifying as little as possible each component influencing the problem (Lopes et al., 2014). A further step focuses on the development and optimization of vibration mitigation solutions, not only for the vehicle which represents the source of railway induced vibrations (Kouroussis et al., 2014a), but also in the propagation path (e.g. wave impeding blocks (Coulier et al., 2013), trenches (Garinei et al., 2014; Barbosa et al., 2015), wave barriers (Connolly et al., 2013a), floating slabs (Vogiatzis, 2011a, 2011b) or subgrade stiffening (Alves Costa et al., 2012a)). The choice of a specific solution still represents an engineering challenge (Connolly et al., 2015b).

Regarding the study of topography effects, a large amount of research has been performed in the field of seismic wave propagation. Bouckovalas and Papadimitriou (2005) used a numerical model to analyse the effect of a step-like slope topography and pointed out the intense amplification or de-amplification at neighbouring area of the slope. Nguyen and Gatmiri (2007) showed that local geometric conditions play an important role in the modification of seismic ground motion. In addition to these topography effects, dynamic wave propagation may also be affected by two-dimensional (or three-dimensional) valley effects, localized near the edges (Gelagoti et al., 2010). Numerical investigations showed that two-dimensional modelling can be an efficient tool for investigating the seismic response of an elongated deep embanked valley (Frischknecht and Wagner, 2004). In the case of railway excitation, similar studies are limited. Numerical models, using finite element (FE) models (Wang and Zeng, 2004) or boundary element (BE) models (Sheng et al., 2006; Coulier et al., 2013; Alves Costa et al., 2015), included embankment configurations in the soil geometry without analysing their effect on the ground wave propagation. A challenge of numerical approaches is the assumptions of embankment conditions (material, geometry) used in methods. For example, Ditzel and Herman (2004) modelled an embankment with some restrictions; the embankment is embedded inside the soil and with perfectly vertical sides. For numerical models, FE and BE approaches also present some specific features. For example, BE in the frequency domain is usually restricted to deal with problems with simple geometries. This limitation comes from the use of the Green's functions, essential to resolve the associated dynamic problems. As for the time domain FE approach, it is not often used to simulate ground vibrations induced by the rail traffic due to its computational cost but some models have been recently developed and validated. With the evolution of computational facilities, some FE studies emerged and presented potential possibilities offered by this approach. For example, Ju (2009), as well as Gardien and Stuit (2003), proposed interesting approaches using finite elements, with variation of the mesh of solid elements and force-time signal convolution method, respectively. Alternatively, Kouroussis et al. (2014b) demonstrated that it is possible to alleviate the modelling restrictions in time domain simulation, with the aim of reducing the domain size and de facto the computational burden. Andersen and Nielsen (2005) investigated the response of the ground surface for the case of vertical and horizontal loads using a coupled FE-BE model and concluded that using trenches provides a better vibration reduction than achieved by a local soil stiffening within an embankment. Galvín et al. (2010) compared two alternative FE-BE models for a ballasted track on an embankment and showed that a simplified embankment model provides low quality results at high frequencies. Recently, Connolly et al. (2013b) showed numerically that soft embankments exhibit large deflections and may act as a wave guide for vibrations.

The problem of soil dynamics does not depend only on these general considerations. Railway problems are moving load problems and some elegant solutions in FE have been proposed. For example, Auersch (2012) proposed the study of transfer functions in order to show the influence of the train speed on the amplitude of the ground vibrations. Ekevid et al. (2006) also described in detail the mesh size effect in the case of high-speed train (HST) applications, with successful validations. A train in motion has a tendency to induce large vibrations for speeds around the Rayleigh wave velocity of the upper soil layer, defined as the soil critical speed. This phenomenon is generally observable for soft soils. Various research activities, such as those carried out by Kaynia et al. (2000), Takemiya and Bian (2005), Costa et al. (2010) or Kouroussis et al. (2012), have been conducted to simulate this phenomenon.

Despite the abundance of prediction tools, a lot of questions remain unanswered as presented in the beginning of this introduction. In actual fact, the soil is rarely considered as a half-space and human activities have locally modified its composition due to local construction. In railways, embankments are built using mixed soil materials, usually excavated from adjacent cuts. Due to their proximity of vibration sources and their geometry, these earthworks (cuttings and embankments) could affect the transmission of vibration and its environmental effect. The focus of this study is to analyse the effect of high-speed track earthworks conditions on railway-induced ground vibrations, by presenting two complementary approaches based on:

- an experimental investigation of the passing of several trains on three different sites, and
- a numerical analysis of these three sites with additional findings offered by the prediction scheme.

Next, a preliminary validation of the proposed model is presented before focusing on the effect of track earthworks. Then, an analysis is presented, based on the HST case, by comparing the results obtained by the present approach with experimental records and results provided in a previous work methodology (Connolly et al., 2014). Last, the paper ends up with some concluding remarks.

2. Experimental investigation and analysis

2.1. Selected sites

The measurement sites were located around Leuze-en-Hainaut in Belgium, near the French border, along the high-speed line LGV1 linking Brussels and Paris/London. Three sites were selected according to their track geometrical configurations (Figs. 1 and 2):

- embankment with a 30° slope and 5.5 m height (site 1),
- at grade with respect to the surrounding land (site 2),
- cutting with a 25° slope and 7.2 m depth (site 3).

The choice of these sites was initially motivated by their geographic proximity (located in a stretch of 5 km), to increase the probability of soil profiles being comparable. Furthermore, the line LGV1 is used by different train types (Thalys for connections between France and Belgium, Eurostar for services between Britain and France, and some TGV circulating in the north of France), thus allowing for more detailed