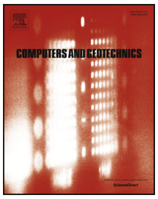
Computers and Geotechnics 100 (2018) 188–202

Contents lists available at ScienceDirect

Computers and Geotechnics

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



Research Paper

Adaptive meshing scheme for prediction of high-speed moving loads induced ground vibrations

Reda Mezeh[a,b], Marwan Sadek[a,b,*], Fadi Hage Chehade[b], Hussein Mroueh[a]

[a] *Laboratory of Civil Engineering and geo-Environment, University of Lille 1, Sciences and Technologies, Polytech'Lille, Villeneuve d'Ascq, France*
[b] *Lebanese University, Doctoral School of Science and Technology, Beirut, Lebanon*

ARTICLE INFO

Keywords:
Track/soil interaction
Moving loads
Adaptive meshing
Finite difference method

ABSTRACT

This article proposes an advanced modeling of the vibrations induced by high speed time-variant moving loads. The model considers the complex mutual dynamic coupling between the track components and the subgrade layer, thus a high realistic simulation of force transmission from rail interface to soil is involved. An adaptive meshing scheme is proposed to simulate the moving loads effect. The spatiotemporal mesh parameters are investigated within the frame of adaptive meshing. Numerical experiments carried out in the sub-Rayleigh and super-Rayleigh velocity ranges show an important capacity of the proposed scheme to model the impact of moving loads on ground response.

1. Introduction

In recent years, the rapid development of High Speed Lines (HSL) leads to large crossing zones with urban areas; therefore, they are increasingly representing one of the most important sources of nuisance for residents living in the vicinity of condensed traffic. The International Organization for Standardization ISO [1] specify the limit for human perception of vibration as 0.2 mm/s. Physically this threshold can be easily exceeded, hence the importance of studying the emission problem of noise and vibration in areas with railway traffic.

By focusing on structure borne sound and vibration from rail traffic, Heckl et al. [2] have categorized the rail excitation mechanisms; they cited firstly the quasi-static contribution due to load kinetic energy, then the dynamic contribution comprising the parametric, transient, wheel/rail roughness and track unevenness excitation mechanisms. In this context, Sheng et al. [3] found that the quasi-static excitation is dominant when the train speed is close to a critical phase velocity of the coupled track/soil system in which it is found to be close to the minimum velocity of the Rayleigh waves in the subsoil. However, the contribution of the other components of load is significant for other values of train speed.

To highlight the impact of trains speed when approaches that of waves in the ground, rail deflection measurements were carried out at a railway track south of Peterborough over Stilton Fen in UK. The subgrade consists of a relatively soft material made of peat with some clay to a depth of about 7 m. Results showed that when the speed increased from 130 to 185 km/h, the vertical rail deflections were increased from about 6 mm to 12 mm [4]. A more critical case was observed in 1998, at a location with very soft soil at Ledsgard, Sweden [5,6] during the passage of an X-2000 passenger train at 200 km/h. The recorded level of track vibration has reached 20 mm which exceeded the limit for safety and stability.

For railway engineering, numerical tools are required to predict the pattern and to assess the amplitude of the train-induced ground vibrations in order to avoid any malfunction of the system that could lead to catastrophic damage. Numerical procedures have been presented by several authors. Paolucci et al. [7] proposed a comprehensive model to simulate the ground vibrations at the Ledsgaard site through a spectral element discretization. In their study, the track motion is reproduced in the frequency range up to about 10 Hz. The soil transmissibility for vibrations induced by moving trains was studied by Yang et al. [8] in which the moving loads were calculated using the deflection curve of an infinitely elastically supported beam and were directly applied on the soil stratum. Subsequently the soil complex response function was computed using the finite/infinite element approach in the frequency domain. Alves Costa et al. [9] proposed an iterative two-and-a-half-dimensional (2.5D) procedure based on an equivalent linear elastic scheme in order to evaluate the relevance of the non-linear behavior of the soil on the track response. The fact that the condition of geo-material symmetry in the load-moving direction is necessary to apply the 2.5D methodology; they assumed an equivalent continuous medium to model the discrete supports of the rail.

According to Hall [10], the three-dimensional (3D) analyses are necessary to achieve a better simulation of the train-induced ground

---

* Corresponding author at: Lebanese University, Doctoral School of Science and Technology, Beirut, Lebanon.
E-mail addresses: Marwan.Sadek@polytech-lille.fr, marwansadek00@gmail.com (M. Sadek).

https://doi.org/10.1016/j.compgeo.2018.03.014
Received 10 September 2017; Received in revised form 14 February 2018; Accepted 29 March 2018

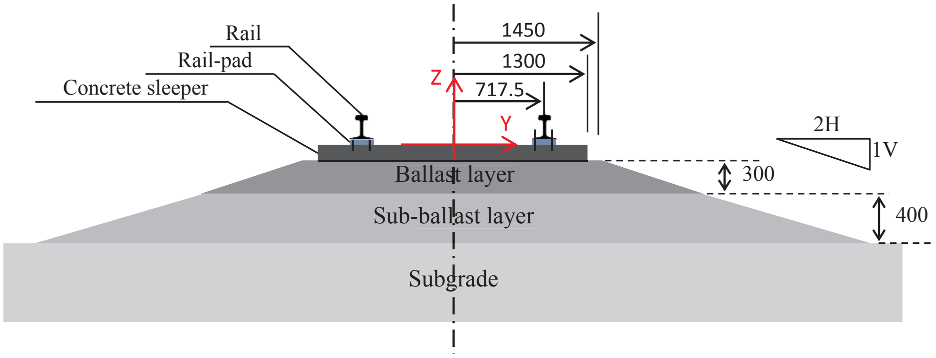


Fig. 1. Cross section of the studied railway track (dimensions are in mm).

vibrations. Galvin et al. [11,12] developed a fully 3D multi-body-finite element (FE)-boundary element (BE) model to study vibrations due to train passage on ballast and non-ballast tracks and then to analyze the dynamic behavior of a transition zone. They found that the soil behavior changes significantly with track system. Connolly et al. [13] investigated the effect of embankment constituent material on ground borne vibration levels using a 3D FE-multi-body model. They noticed that embankments formed from stiff material reduce vibrations in the near and far fields. Subsequently, this model was used to develop an assessment prediction tool for HSL induced vibrations based upon synthetic records for a wide range of soil types [14]. Relationships between soil conditions, train speed and vibration levels were found using a machine learning approach. They demonstrated that, for typical soil properties, the Young's modulus has a much greater influence on vibration levels that density or Poisson's ratio.

As presented in the previous studies, the present-day models consider some simplifying assumptions at the expense of modeling accuracy. In addition to the simulation of the load transmission through a partial profile of track structure, the most disastrous is the modeling of the high speed moving loads at their contact with the rail. The problem of moving loads was addressed by many investigators. A classical algorithm for numerical resolution in the time domain using the finite difference and element techniques is to apply equivalent nodal forces and moments on loaded beam elements by means of the shape functions [15–18]. However, the performance of this approach is strongly influenced by the mesh size essentially in the case of high frequency moving loads. This shortcoming can be overcome by employing a refined domain but at the expense of significant increase in computational time.

On the other hand, special techniques were developed to resolve the dynamic problem in a moving reference system. Krenk et al. [19] were the first to use the FE method in a convected coordinates system moving with the load. They presented a FE model for convective wave propagation in a bi-dimensional (2D) continuum in order to account for an infinite medium. Since then, many researchers [20–22] have investigated this approach. Andersen et al. [20] have presented a FE time domain analysis in convected coordinates with a simple upwind scheme, including a special set of boundary conditions permitting the passage of outgoing waves in the convected coordinates system. Zhai and Song [21] have proposed a 3D FE model in a convected coordinates system moving with the load used to assess the transient vibration of railway/ground model. Recently, Mezeh et al. [22] have proposed an adaptive method called the periodic configuration update PCU method to solve the dynamic problems of infinite beam resting on continuous foundation. However, this approach is complicated and difficult to embed in commercial software.

The analysis of wave propagation in structures and media with complex geometric and material properties necessitates the use of numerical models formulated in a fixed reference system. This article proposes an advanced three-dimensional finite difference modeling for the prediction of track/ground induced vibrations due to passage of high speed moving loads. In order to ensure a good representation of the wheel/rail interaction, the moving load is simulated by an adaptive meshing scheme based upon the creation of a load-attached moving node on the rail rolling surface. The novel feature of the formulation is the use of mesh superposition to produce spatial refinement in the transient problem. The Load-Attached Moving Node (L-AMN) scheme that is used to perform the spatial adaptation of the mesh is efficiently implemented in the FLAC^{3D} software in which a Matlab subroutine has been created to allow a rapid development of the generic input files.

For accurate representation of wave transmission through the model and to prevent numerical distortion, the spatiotemporal mesh parameters are investigated, and appropriate recommendations are provided. Numerical results for high range frequency dynamic loading as well as for velocities that exceed the Rayleigh wave speed of the subsoil layer prove the efficiency of the proposed numerical model.

The article is organized as follows: Section 2 presents a detailed description of the adopted reference case with the geo-mechanical and dynamic properties of the system components. Section 3 is concerned with the adaptive meshing scheme that has been developed and coupled to finite difference modeling, and the impact of this process on the modeling convergence. The last section presents a thorough analysis of the dynamic response of the track/ground interaction model for a wide range of frequency and velocity loading.

2. Description of the reference case

This section describes the studied ballasted railway track in order to present its geo-mechanical and dynamic properties. Fig. 1 shows the cross section of the adopted track structure with the considered dimensions (measured in mm). It consists of a flat framework made up of two parallel rails discretely supported by uniformly spaced horizontal sleepers which in turn rest on a ballast layer. The ballast bed lies on a sub-ballast layer which forms the transition layer to the subsoil. The track is located at the surface of a homogeneous clayey soil that represents a soft soil with total depth H = 5 m.

2.1. Geo-mechanical properties

In this study, the ballast, sub-ballast and subgrade are considered to be linear and homogeneous; however mechanical or/and geometric nonlinearities could be easily taken into account since the integration of the equilibrium equation is performed in the time domain. Table 1 gives

Table 1
Mechanical properties of railway track foundation materials (elastic).

Track part	E [GPa]	ν	ρ [kg/m^3]
Ballast	0.13	0.4	1600
Sub-ballast	0.08	0.4	1600
Clay	0.025	0.45	1800