Soil Dynamics and Earthquake Engineering 89 (2016) 12–27

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

The effect of boundary conditions, model size and damping models in the finite element modelling of a moving load on a track/ground system

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ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form
9 May 2016
Accepted 10 July 2016

Keywords:
Critical speed
Infinite element
Finite Element Method (FEM)
Moving load
Time domain
Half-space
Layered ground
Viscous damping

ABSTRACT

An investigation is presented of the use of finite element models in the time domain to represent a load moving on a railway track on a flexible ground. A systematic study is carried out to compare different sizes and shapes of finite element mesh, different boundary conditions intended for suppressing reflections from the truncated model boundaries, and different models of soil damping. The purpose is to develop guidance to assist in selecting appropriate finite element models for moving load problems. To prevent reflections from the boundaries of the finite domain two approaches are compared. A 40 m radius hemispherical finite element mesh has been used first with infinite elements around the perimeter. This approach gives good results for a point harmonic load at the centre of the domain but some problems are highlighted when it is used for moving load calculations. An alternative approach has therefore been investigated based on a cuboid mesh. The base was fixed to prevent rigid-body motions of the model and, rather than use infinite elements at the sides, these were also fixed. It is shown that, provided that a suitable damping model is used, the spurious reflections from the sides of the model can be suppressed if the model is wide enough. On the other hand, if infinite elements are used, the calculations are found to be considerably more costly with little added benefit. Different models of soil damping are also compared. It is shown that a mass-proportional damping model gives a decay with distance that is independent of frequency, making it particularly suitable for this application. The length of model required to achieve steady state has been investigated. For a homogeneous half-space it is found that the required length increases considerably in the vicinity of the critical speed, up to 130 m in the present example, whereas for the layered ground a more modest length is sufficient for all speeds.

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1. Introduction

Due to the demands of increasing population and environmental concerns, the high-speed train has become an important means of transportation in many countries. However, as the speed of trains approaches that of waves in the ground, track deflections can become large and severe vibration can occur [1]. This is particularly important on soft soil where the wave speeds in the ground are relatively low. For example, there has long been a speed restriction at Stilton Fen on the East Coast Mainline in the UK where the subgrade consists of peat with some clay to a depth of about 7 m. Measurements in 1993 showed that vertical rail deflections increased from about 6 mm to 12 mm when the speed was increased from 130 to 185 km/h [2]. In 1998, a site measurement was carried out at a location with very soft soil at Ledsgård, Sweden [3,4]. The vibration of the rail, embankment and ground induced by an X-2000 passenger train increased to very high levels when the train speed was increased to 200 km/h. The maximum amplitude of track vibration was around 15–20 mm which exceeded the limit for safety and stability. This phenomenon is known as critical velocity behaviour [5]. In planning new high speed lines, particularly in areas of soft soil, it is important to be able to assess potential critical velocity effects and to mitigate against them. Therefore for railway engineering, models are required of moving loads on a track supported on ground.

In early research on the subject of track vibration due to moving loads, the ground was usually neglected or combined with the track model as part of a continuous damped elastic Winkler foundation [1,6,7]. In a different approach Eason [8] studied a moving point load applied on the surface of a three-dimensional semi-infinite homogeneous elastic solid. It was shown that the displacement becomes significant when the load speed

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http://dx.doi.org/10.1016/j.soildyn.2016.07.004
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approaches the Rayleigh wave speed. Krylov [9,10] included the track and showed that severe rail displacement would occur when the load speed is close to or exceeds the Rayleigh wave speed. Dieterman and Metrikine [11,12] studied a moving load acting on a finite-width beam supported by an equivalent stiffness to represent the half-space ground. This equivalent stiffness depends on frequency and the wavenumber of waves in the beam. Kaynia et al. [3] developed a model based on Kausel and Roësset's [13] layered ground model and extended this by using Dieterman and Metrikine's method to simulate the dynamic responses from a high-speed train. Good agreement was found between the results from the simulation and measurements at Ledsgård.

In many papers the track system is assumed to be continuously supported. Vostroukhov and Metrikine [14] compared track models with continuous and discrete supports and found that the response in the vertical direction due to excitation by the train is almost identical in these two cases. Knothe and Grassie [15] indicated that differences between the continuous and discrete support models only occur for calculation frequencies above 500 Hz in the vertical direction and 400 Hz in the horizontal direction.

Sheng et al. [16–18] developed a more complete analytical model for the coupled track/ground system. The track system included the rail, railpads, sleepers and ballast; this was coupled to a layered elastic ground. The solution was obtained in the wavenumber/frequency domain and included motion of the load. A similar analytical model of a three-dimensional track/ground system, including rail, pad, sleeper, ballast, subgrade and semi-infinite layered ground, was developed by Karlström and Boström [19]. Euler-beam theory was used for the rail whereas the sleepers in this case were assumed to be an anisotropic Kirchhoff plate; the layered ground was again modelled using linear viscoelastic layers. The solution was based on a Fourier transform in time and along the track direction. The embankment vibration in the transverse direction was developed as a Fourier series, and the vibration in the half-space was obtained by a Fourier transform. Recently Costa, et al. [20] developed a simplified approach to assess the critical speed based on Sheng's model which showed good accuracy and has good computational efficiency.

As well as these analytical methods, a wavenumber finite element/boundary element (FE/BE) model was introduced by Sheng et al. [21] and a similar 2.5D FE/BE track-ground model was introduced by François et al. [22]. Both of these methods used finite elements to model the track and boundary elements to model the soil and they operate in the frequency domain. The use of boundary elements allows the infinite medium to be included, avoiding reflections at the edge of the modelled domain. As an alternative, a 2.5D finite element/infinite element method was developed by Yang et al. [23] and used to study the transmission of vibration induced by trains moving at different speeds [24]. Again, the infinite elements are used to minimise the influence of the domain boundaries.

As has been seen, many of these models involve calculations of the dynamic response in the frequency domain or involve a transfer from the frequency to the time domain by means of a Fourier transform. This approach is restricted to linear steady-state problems In order to include non-linear effects in the track or soil, or transient effects, a time-domain approach will be required [25]. A number of authors, e.g. [25–27], have used the finite element method for modelling ground-borne vibration induced by high-speed trains in order to consider soil nonlinearity. However, modelling the unbounded medium is the most difficult issue with such a method. Wave reflections will occur at the boundaries, which can influence the results unless a very large model is applied [28,29].

A special technique, called the moving finite element method, was developed by Lane et al. [30] to model the track/ground response due to a moving vehicle. In this approach the soil material moves relative to the FE mesh after a certain number of time steps, so that the vehicle does not need to move relative to the mesh. This gives a better efficiency and smaller demand of model size. However, this approach is complicated and difficult to embed in commercial software.

An alternative, in which an artificial boundary is created to absorb the reflections, has been widely implemented in finite element modelling of ground-borne vibration induced by moving dynamic loads. A three-dimensional finite element model with three-dimensional viscoelastic dynamic artificial boundary was implemented by Zhai et al. [31] and Shan et al. [32]. However, the accuracy of such a viscoelastic artificial boundary is very sensitive to the spring stiffness acting in the radial direction, which can result in severe oscillation. Furthermore, the geometry of the boundary is still an important issue.

The perfect matching layer approach was implemented by Wang et al. [33] to investigate the vibration from maglev train-guideway-tunnel-soil interaction. A special scheme that uses several layers of elements with increasing size and material damping to attenuate the incident wave was implemented by Gardien et al. [34] to investigate the element size, soil stiffness, damping, boundary conditions and finite element method software for soil vibrations from railway tunnel. However, the parametric study was based on a two-dimensional model and the assessment of critical speed effect was not investigated. A time-dependent absorbing boundary was developed by Ju et al., for complex modelling and good agreements were found compared with site measurements [35,36]. Dashpot absorbing elements have been commonly used in combination with the finite element method due to their simple theory and good absorption ability [37] and these have been implemented in the commercial FE software ABAQUS [38]. Kouroussis [39,40] produced a model of the track/ground system using a hemispherical finite element model of the soil together with the infinite elements in ABAQUS; good agreement was found compared with the results from measurements [39,41]. A similar approach was used by Connolly et al. [42] in which a coupled vehicle/track/ground interaction model was implemented in ABAQUS. The ground was modelled using an elongated hemisphere in order to limit the depth of the model. Calculations were performed in the time domain and were verified using experimental data. Other studies have used a cuboid FE models combined with infinite elements to determine the dynamic response from the train-track system by using a similar approach [43–46]. None of these artificial boundaries allow the incident wave to be transmitted perfectly at the boundary in every situation. Specific restrictions are required for different artificial boundary models to obtain better accuracy. The infinite element method (dashpot absorbing elements) is chosen as an example here to investigate the use of the commercial software, ABAQUS.

The infinite element method has become popular as a means of simulating an infinite domain due to its simplicity and the ease with which it can be combined with the finite elements. Furthermore, it can be used both in the time and frequency domains and soil nonlinearity can readily be considered within the FE domain. However, the absorption efficiency of the infinite elements relies on the domain geometry. Usually they should be located in the far field and orientated perpendicular to the incident wave field. Even though an improved development of this method was introduced in [47] by modifying the expression of the energy ratio, the results are still strictly related to the incident angle of the wave propagation. Furthermore, a small reflected component may still exist due to this non-perfect absorption, requiring a larger model to obtain improved accuracy [39].

Another issue has been found when modelling a moving load in the time domain by using the FE method [44,45]. It is found that

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