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Simulation and mitigation analysis of ground vibrations induced by high-speed train with three dimensional FEM

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ABSTRACT

The high speed railway, which acts as a safer and faster means of transportation, has grown rapidly around the world, especially in China. Meanwhile, the vibration induced by high-speed train (HST) arouses increasing concerns and cannot be ignored. This paper describes ground vibrations with three dimensional models formulated in the time domain using the finite element method (FEM). Absorbing boundaries and Rayleigh damping approach are used to prevent wave reflections from the artificial edges and to simulate the material damping, respectively. Investigations of ground vibration caused by unit load under different speeds and frequencies are given. An inclined classification of ground vibration and the sensitive frequency ranges of surface ground are then found. Moreover, the effects of subgrade treatment and sub-soil treatment on vibration isolation are discussed. It concludes that due to the attenuation effects of subgrade structures on high frequency range, noticeable reductions can be obtained in surface ground vibration. And when a high subgrade or a composite one is applied, the effects are better. The depth of sub-soil treatment would have more positive influence on ground vibration isolation and costs relatively less, compared with its replacement ratio and width. Negative influence may even occur when the sub-soil treatment width becomes larger. Additionally, some useful recommendations are proposed in this paper.

1. Introduction

Conveniences and efficiencies have been brought to passengers with the rapid extension and wide use of the high-speed railway. However, the vibration induced by high-speed train (HST) may cause discomfort to people, misalignment of sensitive equipment and even harm to the nearby buildings [1]. This kind of environmental vibration has been arousing wide concern with the rapid development of the high speed rail network, especially in China, South Asia and Europe.

Many prediction models have been established to investigate the HST induced vibration. Wang and Zeng [2] and Balendra et al. [3] presented two dimensional (2D) finite element method (FEM) models to simulate the vibration induced by HSTs and subways, respectively. An efficient two-and-half dimensional (2.5D) finite element numerical modeling approach was developed by Hanazato et al. [4], Bian et al. [5] to simulate traffic induced wave motions. The approach assumed that the track structure and supporting ballast were invariant in the track direction and the transformation between 2D and 3 dimension (3D) was then realized through the Fourier Transform. After that, an infinite absorbing element boundary was introduced to 2.5D-FEM models by Yang et al. [6] to study the transmissibility of soils for vibrations induced by trains at different speeds. Moreover, a high efficiency 2.5D coupled finite element-boundary element model was proposed by Galvin et al. [7]. Despite this, these 2D or 2.5D models based on the plain strain assumption would be limited in application range [8]. Therefore, Kouroussis et al. [9–11] developed a 3D model in the time domains with FEM for the vertical dynamical coupling of railway track through the soil. This model separated the whole dynamic analyses into two sub-models, one mainly for the train-track interaction and another for ground vibration. A 3D-FEM model was also proposed by Connolly et al. [8], which was capable of simulating nonlinearities at the wheel-rail interface together with the ground vibration. Nevertheless, high calculation costs were needed and then some scoping prediction tools [12,13] were developed for ground or in-door vibration prediction.

Generally, ground abatement can be achieved at the source, during wave transmission path or at the receivers with proper vibration reduction/isolation measures or devices. Focusing on the source attenuation, Kouroussis et al. [14] analysed the influence of rolling stock dynamics on ground vibration level and Grassie [15] concluded that rail re-profiling was effective in reducing low frequency noise. The

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floating slab track [16,17], under sleeper pads [18], new sleeper pads [19] and other elastic elements [20] were also developed and investigated in vibration reduction. The benefits of using rubber-modified asphalt concrete and ballast mats in high-speed railway subgrade were discussed by Wang et al.[21] and Alves Costa et al. [22], respectively. Additionally, the precision straightened rail, continuous welded rail and wheel truing were also introduced [23,24]. However, the effects of such measures on ground-borne vibration attenuation are usually limited to higher frequency range [23,25]. On the way of wave transmission, isolation methods to reduce ground vibrations were investigated including construction of open trench [26–28], in-filled trench [26–30], rows of piles [31], soil improvement next to the track [26,32] and even shaped landscape [33]. And the design, installation and guidelines for the optimization and the efficiency of a vibration isolating screen have been reported in [29,30,34]. Under the subgrade/embankment, some countermeasures in train-induced vibration isolation were studied in detail, such as wave impeding blocks (WIB) [25,27], honeycomb WIB [35] and subgrade stiffening [25]. Moreover, satisfactory mitigation can also be achieved by the stabilization column [36] and combined countermeasures [37]. The vibration attenuation measures at the receivers have been generally summarized by Connolly et al. [38].

Three dimensional models with good extension are necessary for the train induced vibration prediction. However, high accuracies of 3D models are often at the expense of high calculation costs. Three kinds of typical prediction models with different loading methods (moving load, moving mass and 1/4 moving car) were compared to achieve some balance between the computation precision and efficiency [39], previously. It is shown in Fig. 1 that the vertical displacement of moving load model, which was similar to Hall [40], has a good agreement with 1/4 train model, even when the track defects were included. Therefore, a 3D-FEM model subjected to a series of moving load (Fig. 2) is used in this paper. In this model, the slab, concrete-asphalt (CA) mortar, concrete base and subgrade are modelled using 8 nodes solid cubic elements. And the rail is modelled using Euler-Bernoulli beam element. To prevent wave reflections from the edge of the model, absorbing boundaries are used. The Rayleigh damping approach is also adopted here. Subsequently, the model is applied to investigate the ground vibration caused by unit load under different speeds and frequencies. Moreover, the effects of subgrade treatment and sub-soil treatment on vibration isolation are studied to illuminate the working mechanism of subgrade on ground vibration reduction. Additionally, detailed comparisons about the effects of different sub-soil treatment types and useful recommendations are proposed in this paper.

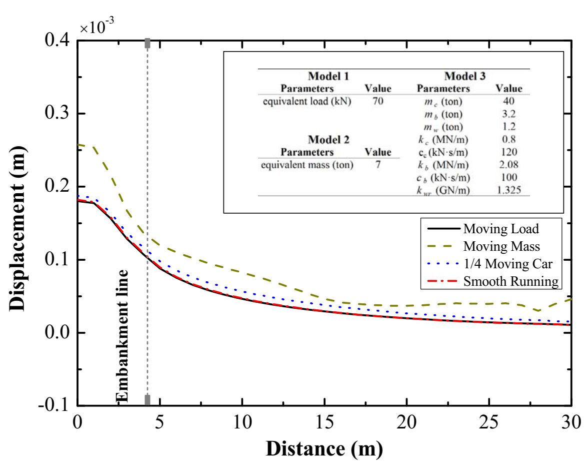

Fig. 1. Difference between the three kinds of models at speed 300 km/h.

2. Modeling approach

A 3D numerical model is established considering the symmetry of the Track-Subgrade-Ground system (Fig. 3) to the vertical direction (z-axle). In this model, train loads were assumed to be distributed symmetrically. Absorbing boundaries developed by Lysmer and Kuhlemeyer [41,42] are used to prevent wave reflections from the edge of the model. The Rayleigh damping approach [43] is also used to realize the vibration absorption of materials.

2.1. Train load

Since the straight railway lines account for a large proportion, this model mainly considers the vertical train load and vibration between the rails and HSTs. The train load F_{wr}, which is represented by a series of axles load f_{ni} located in the wheels-rail contact points (Fig. 2), is formulated with a constant moving velocity v. The geometry of a typical CRH3 train widely used in China is shown in Fig. 2. The train load consisting of N four-wheels-cars can then be described by:

$$F_{\mathrm{wr}} = \sum_{n=1}^{N}\sum_{i=1}^{4} f_{ni}(y+vt). \tag{1}$$

And the detail expression of f_{ni} is derived as follows:

$$f_{n1}(y+vt) = P_0\delta\left(y+vt-\sum_{k=1}^{n-1}L_c - y_0\right), \tag{2}$$

$$f_{n2}(y+vt) = P_0\delta\left(y+vt-a_0-\sum_{k=1}^{n-1}L_c - y_0\right), \tag{3}$$

$$f_{n3}(y+vt) = P_0\delta\left(y+vt-a_0-b_0-\sum_{k=1}^{n-1}L_c - y_0\right), \tag{4}$$

$$f_{n3}(y+vt) = P_0\delta\left(y+vt-2a_0-b_0-\sum_{k=1}^{n-1}L_c - y_0\right), \tag{5}$$

where y_0, a_0 and b_0 denote the distance to the “starting point”, the wheel spacing and bogie spacing, respectively. The L_c represents the car length and the notation P_0 denotes the equivalent axle load, which was set to be 70 kN (typical value for CRH3 train). And the δ is the Dirac's delta function.

2.2. Track and subgrade

The 60 kg/m rail and the CRSII track, which are commonly used in China, are selected in this model. A typical subgrade of one meter high is also adopted. Their geometries and material properties are listed in Figs. 2, 3 and Table 1. As the model is symmetrical in the track direction, only one rail, half of the track structure and subgrade are modelled. Generally, the rail pad, concrete-asphalt (CA) mortar, concrete slab and subgrade are modelled using 8 nodes solid cubic elements (approximately 0.3 m×0.3 m×0.3 m). The rail is modelled using Euler-Bernoulli beam element of 0.1 m in length.

2.3. Ground and boundaries

A typical kind of layered site identified between Shanghai and Anhui in China is adopted in present study. The properties of the ground are listed in Table 1. The ground is modelled as a 70 m (length)×50 m (width)×30 m (depth) cubic, under which is bed rock. The element length of the ground is set to 0.5 m. As the typical damping ratios of the soils are between 3% and 6%, a damping ration (ξ) of 5% [44–46] is used and realized with the Rayleigh damping approach. Absorbing boundaries are implemented to prevent wave reflections at the edges, but only the transverse direction is fixed in the