Soil Dynamics and Earthquake Engineering 76 (2015) 29–43

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Track and ground vibrations generated by high-speed train running on ballastless railway with excitation of vertical track irregularities

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ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form
3 January 2015
Accepted 9 February 2015
Available online 20 March 2015

Keywords:
High-speed railway
Track irregularities
2.5-dimensional finite element (2.5D FE)
Thin-layer element (TLE)
Vehicle–track–soil dynamic interaction
Ground vibrations

ABSTRACT

Track irregularities generated during the running service of high-speed railways aggravate vibrations of the track and the surrounding ground environment. To better understand the propagation of vibrations induced by high-speed train running on irregular tracks, a 2.5-dimensional (2.5D) finite element model combining with thin-layer elements was applied to establish a vehicle–track–foundation coupled dynamic analysis model. A quarter-car model was used to derive the equation for wheel–rail interaction force considering track irregularity. The track structure and the underlying foundation were simulated using the 2.5D finite element model, and the subsoil boundary was simulated using thin-layer elements. Compared with the field measurements of the Beijing–Shanghai high-speed railway, the reliability of the established numerical model in analyzing vibration response was verified. A spectrum analysis of the response data obtained from the field measurements reveals that for a newly constructed high-speed railway, track alignment is in good condition due to the operation of grinding and leveling, and vehicle parameters dominate the vibration response of the track structure. Then influences of track irregularities of four typical wavelengths on the vibrations of the track and the surrounding ground environment were investigated. It is found that track irregularities of smaller wavelengths induce higher vibration frequencies and significantly higher vibration responses from the track and the ground compared to track irregularities of longer wavelengths. However, the low-frequency vibrations induced by the latter propagate to a longer distance compared to the former. The critical velocity of the ballastless slab track–ground system is greater than the Rayleigh wave velocity of the soft layer of the subsoil. When train speed is lower than the critical velocity, track irregularity substantially affects the vibrations of the track and the surrounding ground. When the train speed exceeds that critical velocity, the ground vibration is determined by the train wheel weight.

1. Introduction

High-speed railways have been developed worldwide due to their fast, comfortable and safe operation. Trains running at high speeds (300–350 km/h) place a high demand on the alignment of the rail lines. To meet the requirements of such high alignment, ballastless slab tracks are typically used in high-speed railways. In other words, concrete structures of high stiffness have replaced the traditional ballast layers in order to improve the alignment and stability of the tracks.

Unlike traditional low-speed rail transportation, the impact of the load inflicted by high-speed trains on the track and surrounding ground environment will increase significantly as the train speed increases. Esveld [1] evaluated the overall performance of the ballastless track and concluded that it has long-term vertical and horizontal stability, and can greatly reduce stress in the subgrade soil, ensuring rail straightness and a 70–90% reduction in maintenance costs. The disadvantages include high initial costs, poor vibration and noise absorption capacity and relatively high sensitivity to uneven settlement. In Taiwan, in order to avoid vibration disturbances caused by high-speed railway on the precision of instruments in the Tainan high-tech park, active measures to reduce vibrations were implemented, including foundation reinforcements and elastic damping walls [2]. With long-term operation of the high-speed railways, the rail surfaces will inevitably generate wavy wear; uneven subgrade settlement will also lead to track irregularity. In Germany, due to the track irregularities, the wheel–rail interaction forces of the Berlin–Hannover high-speed railway were intensified and the vibration intensity of the track structure increased nearly four-fold at train speed of 250 km/h [3]. Therefore, for ballastless slab tracks it is necessary to examine the impact of the track irregularities on the vibrations of the track and the surrounding ground environment during operation.

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http://dx.doi.org/10.1016/j.soildyn.2015.02.009
0267-7261/

Shamalta and Metrikine [4] examined the two-dimensional dynamic response of an embedded slab track to a moving load and compared it to a simplified one-dimensional model. The critical velocity of the moving load and changes in the vertical displacement of the track slab in conjunction with changes in the speed and frequency of the moving load were obtained. The critical velocity is the speed on which train movement will cause track–ground resonance and dramatic ground vibration amplification. Auersch [5] used an analytical method to investigate the response of beam models under different support conditions, including finite/infinite soil, semi-infinite space and Winkler support. The study concluded that, in general, soil stiffness determines low-frequency vibrations, whereas the bending stiffness and the beam mass determine high-frequency vibrations. Steenbergen et al. [6] applied a generalized equivalent dynamic stiffness integration theory to investigate the influence of the slab on the vibration of the overall track structure. However, the ground response was not examined. All of the above models used a constant axle weight as the wheel–rail force and did not take into consideration the wheel–rail dynamic interaction; hence, the high-frequency vibration response caused by trains may have been underestimated. To overcome this problem, a vehicle–rail coupled model is required [7–9]. Galvin [10] used the three-dimensional finite element-boundary element methods to calculate the vibration response of a coupled vehicle–rail–subsoil system. The three -dimensional model can take soil heterogeneity into consideration; however, in order to obtain an exact high-frequency solution near the rail track, mesh refinement is needed, which often leads to huge memory space and overly long computing times. Galvin [11] then compared the vibration properties of the ballasted track system and those of the ballastless track system in high-speed lines. They concluded that the flexibility of ballasted tracks is much larger than that of ballastless tracks. The vibration levels in ballasted tracks are much higher than those in ballastless tracks, but the vibrations attenuate much slowly in ballastless tracks. The critical velocity of the ballasted tracks is close to the Rayleigh wave velocity of the soft soils. When the train speed approaches the critical velocity, Mach effect is observed and the soil displacements are amplified. While in ballastless tracks lying on the same subgrade, the Mach effect is not observed that remains in the same condition due to the track's lower flexibility. Lei and Zhang [12] established an explicit analytical vehicle–rail–ground coupled model, and the vehicle was modeled with 10 degrees of freedom system. A parametric analysis on a slab track system was performed, including parameters of fasteners, cement–asphalt–mortar (CAM) layer, and ground. Cai et al. [13] further studied dynamic responses of a track on a poroelastic half-space soil medium subjected to moving train passages, taking into account saturated ground. These studies all used smooth tracks to establish the analysis model. Bian et al. [14,15] and Jiang et al. [16] also established full-scale physical model to investigate the dynamic responses of the slab track–subgrade system under train moving loading.

However, due to the high critical velocity of ballastless tracks, track irregularity is considered to be the essential factor causing ground vibration, and therefore track irregularity should be taken into consideration [17]. Sheng et al. [18] established a rail–layered ground coupled model that included the effects of track irregularity. The moving axle load and track irregularity were used as input excitation to obtain the wheel–rail interaction force as well as the displacement spectra of the rail and the ground surface. Results show that static axle load determines low-frequency response, while track irregularity greatly impacts dynamic wheel load. Compared to a ballasted track, the bending stiffness of a slab track is large, not only reducing the vibration of the static axle load, but also reducing the high-frequency vibrations over 25 Hz by 20 dB. Lombaert and Degrande [19] established a three-dimensional vehicle–rail coupled model and calculated the vibration response for train speeds below the critical velocity. It was found that the quasi-static axle load determines the track response, whereas the dynamic load determines the free field response; in addition, the track response caused by the quasi-static axle load increases slightly as train speed increases. Zhai et al. [20] established a three-dimensional train–rail coupled vibration model, and focused on analyzing the rail and train vibration responses when the train ran on irregular tracks. Although a three-dimensional finite element method is adaptable, the number of the element mesh is huge. In addition, the coupling of the vehicle–rail system requires dealing with the iteration convergence of the two subsystems. As a result, the computation time is extensive, and places a high demand on the performance of the computer hardware.

Because the size and material properties of the track–subgrade structure are evenly distributed along the track, the 2.5-dimensional finite element (2.5D FE) method can be used to establish track–subgrade interaction models. With a Fourier transform with respect to the space dimension along the track direction, the 3-dimensional problem is transformed into a two-dimensional problem in the wavenumber domain [21–28]. Hanazato et al. [21] proposed a 2.5D finite element method coupled with thin-layer element method to analyze traffic-induced ground vibrations, and wave propagations to the far field has been dealt with effectively by using the thin-layer elements at both horizontal side boundaries. Yang and Hung [22] used a combination of 2.5D finite element and infinite elements to calculate the steady-state response of a semi-infinite body under moving loads. Based on this method, Yang et al. [29] investigated the effects of train speed, soil shear wave velocity, subgrade soil depth and other factors on the propagation of vibration response. Hung et al. [30] introduced geometric track irregularities into the vehicle–rail 2.5D finite element–infinite element model, and studied the effects of track irregularity on subway vibrations. The results showed that due to track irregularity, the vibration response of the soil above the subway line was magnified; use of a floating slab track in the subway can effectively reduce the high-frequency response components induced by track irregularity. Bian et al. [24,31–33] applied the 2.5D finite element method to simulate the ground response to high-speed trains running on railway tracks, and revealed resonance mechanism in the ground responses due to train running at speeds approaching the critical velocity of track–ground system.

On this basis, the present study used the 2.5D finite element/thin-layer element coupled analysis model to examine the vibration response caused by train moving loads. Comparing it with the semi-analytical method verified the reliability of the 2.5-dimensional finite element/thin-layer element combining models. A vehicle–track–foundation coupled analysis model for a ballastless slab track system was established specifically based on the typical track design in China. The vehicle consisted of a series of mass–spring–damper units, and between the wheel and the rail, cosine track irregularity was introduced. The track structure and the foundation underneath were simulated using the 2.5D finite element, and the ground lateral boundaries were simulated using the thin-layer element (TLE). Comparing the calculated results with the vibration velocities obtained from field measurements in the Beijing–Shanghai high-speed railway in China, the reliability of the proposed model in analyzing the vibration response of railway line was verified. After that, influences of track irregularities of four typical wavelengths on the vibrations of the track and the ground were investigated, and parametric analyses on the wavelength and amplitude of track irregularities, train speed and other factors were performed.

2. Vehicle–track–foundation coupled model

2.1. Vehicle model

To obtain the vehicle–rail contact force for a vibration analysis of the track and ground, a quarter-car model was used to deduce the equation for the wheel–rail contact force under the condition