Construction and Building Materials 148 (2017) 548–558

Contents lists available at ScienceDirect

Construction and Building Materials

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

Finite-infinite element coupled analysis on the influence of material parameters on the dynamic properties of transition zones

Yao Shan [a,b,*], Yao Shu [a,b], Shunhua Zhou [a,b]

[a] Department of Urban Rail Transit and Railway Engineering, Tongji University, Shanghai, China
[b] Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai, China

HIGHLIGHTS

- A finite-infinite element model of a high-speed railway transition zone is proposed.
- The influence of simultaneously varied parameters on system dynamics is investigated.
- The recommended dynamic elastic moduli of the subgrade components are recommended.

ARTICLE INFO

Article history:
Received 3 February 2017
Received in revised form 28 April 2017
Accepted 6 May 2017
Available online 15 May 2017

Keywords:
Transition zone
High speed railway
Vehicle-track-subgrade coupling model
Finite-infinite element method
Dynamic response

ABSTRACT

Based on the theory of vehicle-track coupling dynamics, a plane stress finite-infinite element model of a high-speed railway subgrade-bridge transition zone is proposed. With this model, the influence of 2 simultaneously varied subgrade material parameters on the dynamic response of the vehicle-track-subgrade system in a high speed railway transition zone with the slab track is investigated. The results indicate that the influence of the dynamic elastic modulus of the graded broken stone on the dynamic response of the vehicle system is larger than that of the dynamic elastic modulus of the subgrade bed surface layer. The recommended dynamic elastic moduli of the subgrade bed surface layer and the graded broken stone are chosen as 4000 MPa and 2000 MPa, respectively.

1. Introduction

The operation safety of high-speed trains and the ride comfort of passengers requires high smoothness of the railway track. Rail geometry irregularities and abrupt changes in track stiffness have the most significant influence on the track smoothness. These issues occur most frequently in the subgrade-bridge transition zones of a high-speed railway with a slab track due to the unreasonable stiffness matching of the transition zone components.

Previous studies have shown that a reasonable stiffness matching of the transition zone components plays an important role in improving the transition performance and controlling uneven settlement of transition zones. A large number of studies have been performed to analyse the influence of the track stiffness and the track geometry irregularities on the dynamic response of the vehicle-track system. Different models have been employed due to different research concerns.

In some studies, the dynamic response of the vehicle system was chosen as a criterion. As a result, vehicle-track models (Zhai and Sun [1], Thompson et al. [2], Lei and Noda [3]), in which the subgrade is always simplified as layers of springs and dampers, are usually employed. Luo [4] investigated the influence of the variation of the track stiffness and the sudden permanent settlement of the rail on the dynamic response of the vehicle system. The results indicated that the sudden permanent settlement of the rail has the most significant influence on the vehicle system dynamics, while the track stiffness plays an insignificant role. Lei and Mao [5] utilized a finite element method to investigate the dynamic response of the coupled vehicle-track system on a bridge-embankment transition zone. The results showed that the sudden permanent settlement of the track profile is the main source of vibration amplifications. Varandas et al. [6] employed a one-dimensional numerical model that accounts for the track deflection, rail support stiffness variation and hanging sleepers to study the dynamic behaviour of the track on a transition zone during train passage. The results revealed that loading transferred through the sleeper to the ballast can be significantly affected by the track stiffness variation and the hanging sleepers. In these

---

* Corresponding author at: Department of Urban Rail Transit and Railway Engineering, Tongji University, Shanghai, China.

E-mail address: shanyao@tongji.edu.cn (Y. Shan).

http://dx.doi.org/10.1016/j.conbuildmat.2017.05.071

vehicle-track models introduced above, the interaction between the vehicle and the track can be well simulated. However, the subgrade and the foundation of the track in these models are simplified as layers of mass, springs and dampers. There is still no reasonable theoretical basis of the equivalent method, especially for the equivalent stiffness and the vibration mass of the subgrade. Consequently, with the vehicle-track model, the support stiffness of the track cannot be correctly simulated, and the wave propagation in the subgrade cannot be considered.

Some scholars focused on the dynamic response of the track components and the subgrade on the transition zones. As a result, some track-subgrade models (Sheng et al. [7], Dahlberg [8], Andersen et al. [9], Giner and Pita [10], Bian et al. [11], Dalen et al. [12]) were established to investigate the influence of the material parameters and configurations of the transition zones on the dynamic response of the track-subgrade system (Dimitrovová and Varandas [13], Dahlberg [14], Shan et al. [15], Coelho and Hicks [16], Varandas et al. [17]). The track components and the subgrade were treated as a continuous medium, and the wave propagation in the track and the subgrade can be well considered. Because the dynamic responses of the track-subgrade system were selected as criteria, the vehicle system was always simplified as moving loads. In this way, the vehicle-track interaction cannot be simulated.

To comprehensively investigate the dynamic response of the completed system, fully vehicle-track-subgrade coupled models were developed. Banimahd and Woodward [18] presented a three-dimensional coupled train-track-subgrade finite element model to analyse the train-track interactions in the vicinity of a transition zone. Galvín et al. [19] employed a fully three-dimensional multi-body-finite element-boundary element model to predict the vehicle-track-soil-structure dynamic interaction. The vehicle was modelled as a multi-body system, the track components were simulated by finite elements and the boundary element method was utilized to simulate the foundation soils. Huang et al. [20] developed a fully coupled three-dimensional train-track-soil model to study the dynamic response of the train-track-soil system. In this model, the ballast was modelled by a combination of mass, spring and damper. The soil was simulated as three-dimensional plane-stress finite elements. They highlighted the importance of modelling the ballast layer as a particulate medium. With these fully vehicle-track-subgrade coupled models, the system dynamics affected by the material parameters of the track and subgrade components can be obtained and the wave propagation can be considered as well as the vehicle-track interactions. However, the calculation requirement of a transient analysis of a 3D vehicle-track-subgrade model is huge, and the computational efficiency is limited. With the computational limitation of this kind of model, only the impact of a single parameter variation on the system dynamics in the transition zones can be investigated. Other parameters should be assumed to be constants. In this way, only a local optimization of the stiffness matching of the transition zone components can be obtained. To pursue a reasonable stiffness matching of the transition zone components, different parameters of the transition zone should be changed and evaluated at the same time. This kind of completed optimization of the components stiffness of the transition zone is not found in existing literature.

In this paper, a plane stress model is developed to calculate the dynamic response of a vehicle-track-subgrade system with high computational efficiency. In this model, a slab track with an inverted trapezoid transition zone (refer to Fig. 1), which is recommended in code for design of high speed railway in China [21], is simulated. With this model, the influence of the material parameters of the transition zone components on the vehicle-track-subgrade system dynamics is investigated by complete numerical experimentation. The results will provide the basis for determining the material parameters of the transition zone fillers and for optimizing the stiffness matching of the transition zone components. This will be helpful for guiding the design and construction of the transition zone.

2. Coupled vehicle-track-subgrade model

Based on the theories of vehicle-track coupling dynamics, a coupled vehicle-track-subgrade model is established by the finite-infinite element method. In this model, the vehicle is simplified as a multi-body system, where the vehicle body, bogie and wheelset form the vehicle system are considered rigid bodies. The vertical and pitch motion of vehicle body and bogie as well as the vertical motion of the wheelset are considered (Zhai and Sun [1], Lei and Mao [5]). The suspensions are simulated as springs and dampers. In this case, the vehicle system has 10 degrees of freedom (DOF), i.e., seven vertical displacements and three pitch motions. Rails are simplified as discrete supported Bernoulli-Euler beams, pads are simulated as springs and dampers and the substructure beneath the pads is simulated as a plane-stress model that is composed of solid elements. The infinite element method (I-FEM) is employed to prevent wave reflection on the boundaries of the transition zone model. Nodes on the bottom of the bridge abutment are fixed. A free boundary is utilized on the left side of the bridge abutment. The infinite elements are employed on the bottom and the right hand side of the subgrade. The coupling of the vehicle and the track is the wheel-rail contact force.

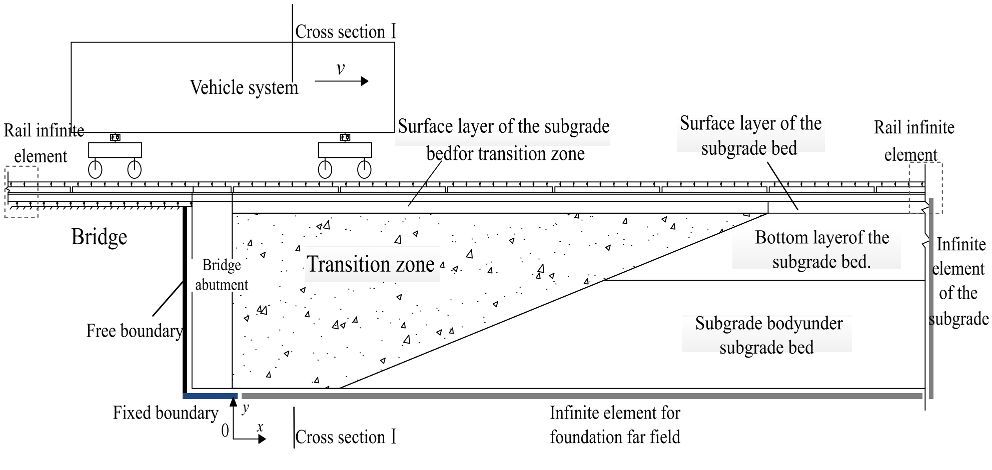

Fig. 1. Vehicle-track-subgrade model of the inverted trapezoid transition zone.