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Long-term prediction of track geometry degradation in high-speed vehicle–ballastless track system due to differential subgrade settlement

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ABSTRACT

To predict long-term track degradation of ballastless track due to evolution of differential subgrade settlement in high-speed railway, an iterative approach is put forward. A detailed vehicle–track coupled dynamic model taking account of track weight and local contact loss between track and subgrade is employed to obtain the short-term behavior of the system in terms of wheel–rail interaction, vehicle acceleration and interlaminar forces of track structures. The calculated track–subgrade dynamic stresses induced by a high-speed vehicle are imported into an empirical power model for long-term subgrade settlement. The profile of the subgrade settlement is updated by a self-adaptive passing number of vehicles governed by a settlement threshold, and the dynamic responses of the coupled system are re-calculated consequently. On this basis, a demonstration case is carried out aiming at a typical Chinese high-speed vehicle–double-block ballastless track system with an initial subgrade settlement described by the cosine wave. The attained results reveal the high resistance of deformation on high-speed rail subgrade, together with the significant influence of the initial differential subgrade settlement on track geometrical evolution, in particular, the initial condition with severe unsupported areas between track and subgrade. The abnormal dynamic responses inflicted by the differential settlement are gradually alleviated during the long-term operation.

1. Introduction

Post-construction settlement of subgrade, especially differential settlement is one of the major problems for track maintenance. The track geometry degradation accounting for subgrade settlement may result in higher dynamic wheel–rail interactions and further track settlement, which will produce extra maintenance costs and poor ride quality [1]. Since the service life of the high-speed railway subgrade in China is designed to be 100 years, the accumulated settlement during its service life must remain within the design limit in order to provide adequate serviceability and safety [2,3]. Knowledge of accumulated subgrade settlement and the corresponding geometrical evolution of the ballastless track under repeated traffic load are therefore essential for the proper design and maintenance planning.

A great deal of attention has been paid on the prediction of ballast track settlement due to cyclic train load. Mauer [4] presented a preliminary interactive model for settlement prediction where the track model was static and the influences of various initial conditions were investigated. Computational procedures involving track dynamics were adopted by Nguyen et al. [5] and Vale et al. [6], while the vehicles were simplified as axle loads. The results showed significant influences of the track geometry defects and vehicle speed on the evolution of vertical track profile. Integrated models of vehicle–track coupled dynamics system were developed and applied on predictions of track settlement in turnouts and rail joints [7,8]. Varandas et al. [9] as well as Nielsen and Li [10] further improved the track model by taking the non-linear aspect, the latent hanging sleepers into account. The prediction of track settlement in transition zones and the geometry degradation due to differential ballast settlement were investigated. Besides, Shaer et al. [11] carried out a reduced scale experiment to study the dynamic behavior and the settlement of ballast tracks. Gong et al. [12] combined a multi-body vehicle–track system and a finite element track model to predict the lateral deterioration of track with traffic flow. Commonly used accumulation laws of the ballast track were summarized by Dahlberg [13].

To meet the acquirements of high alignment and regularity of high-speed railway lines, ballastless tracks become the preferred track type. Unlike the traditional ballast track, the concrete structures with high stiffness and strong integrity increase the maintenance difficulty [14]. Once there is differential settlement, the concrete track is suspected to lose contact with the soil subgrade locally, giving rise to discontinuous subgrade support. Due to the long-term impacts of the high-speed

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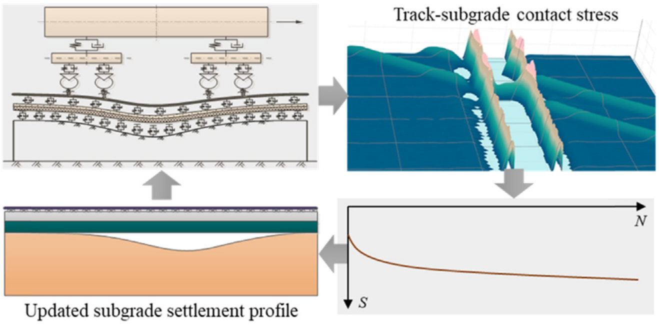

Fig. 1. Schematic diagram of the simulation procedure.

trains, these unsupported areas will be compressed periodically, and the induced irregularities of track geometry and stiffness will simultaneously affect the running safety, ride comfort, and damages of wheel and rail.

There is still little concern engaged to the long-term track deterioration prediction of the ballastless track systems. This work presents an iterative approach on the basis of vehicle–track coupled dynamics theory and an empirical model for cumulative plastic deformation of subgrade. The approach is applied to analyze the long-term subgrade degradation with an initial differential settlement and the corresponding track geometry evolution as well as the dynamic behaviors of the coupled system. It basically consists of 4 aspects as shown in Fig. 1: the numerical integration of the vehicle–track coupled dynamics; the calculated track–subgrade dynamic stress which is an input of the settlement evolution simulation; the empirical model for long-term settlement prediction; and the updated profile of subgrade settlement which is re-input into the dynamic model. In each iterative step, instantaneous track–subgrade dynamic stress induced by the moving vehicle is acquired through the dynamic simulation of the vehicle–track coupled model, which takes into account the track self-weight and nonlinear support from subgrade. Accordingly, the accumulated subgrade settlement under repeated vehicle load is calculated, where the number of loads is adaptive by introducing a threshold value to update the profile of the subgrade settlement. To demonstrate this approach, a typical Chinese high-speed vehicle coupled with the double-block ballastless track in operation is employed. Track degradations under long-term train loads initiated by different differential subgrade settlements in cosine-type are compared.

2. Numerical model of vehicle–track coupled system with differential subgrade settlement

2.1. Characterization of the model

In the simulation procedure, the accumulated subgrade settlement depends on the instantaneous track–subgrade contact state stimulated by the moving vehicle, which can be obtained from the vehicle-track coupled dynamic model. In the present work, a detailed high-speed vehicle–double-block ballastless track model with differential subgrade settlement is applied based on the theory of vehicle–track coupled dynamics proposed by Zhai [15], as shown in Fig. 2.

The vehicle subsystem is modeled as a four-axle mass-spring-damper system, which consists of a car body, two bogie frames, four wheelsets and two stage suspensions. For the multi-rigid system, the vertical and pitch motion for both car body (Z_c, β_c) and bogies (Z_t, β_t) together with the vertical motion of each wheel (Z_w) are considered, 10 DOFs in total. Through wheel–rail dynamic interaction, the vehicle subsystem is coupled with a track subsystem.

The double-block ballastless track, which is widely constructed in Chinese high-speed railways, consists of rails, highly-elastic fasteners, double-block sleepers, concrete roadbed and hydraulic concrete supporting layer from the top down. In the model, the ballastless track subsystem is simplified as composite beams on the non-tension Winkler foundation. The rail is modeled as the Euler-Bernoulli beam of finite length discretely supported by viscoelastic supports. The length of the rail in the simulation is 200 m such that the boundary effects can be ignored at the center of the model. The roadbed and the supporting layer are equivalent to one single concrete layer through the method of the equivalent section in view of their high integrity. The concrete layer is also modeled as an Euler beam. Taking the subgrade settlement along the railway line into account, the track self-weight is considered, and since subgrade does not provide any tensile resistance in practice, nonlinear springs are applied to account for the non-tension subgrade support. Therefore, settlement-induced contact loss between the concrete track and the soil subgrade can be involved. During vehicle passes by, the contact may be re-established or remain lost. This will have large effect on the long-term subgrade settlement and in turn the dynamic performance of the system.

2.2. Equations of motion

The motions of the coupled system can be assembled in the following matrix equations:

$$\begin{bmatrix} \mathbf{M}_V & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_T \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{X}}_V \\ \ddot{\mathbf{X}}_T \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_V & 0 \\ 0 & \mathbf{C}_T \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{X}}_V \\ \dot{\mathbf{X}}_T \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_V & 0 \\ 0 & \mathbf{K}_T \end{bmatrix} \begin{Bmatrix} \mathbf{X}_V \\ \mathbf{X}_T \end{Bmatrix} = \begin{Bmatrix} \mathbf{P}_V \\ \mathbf{P}_T \end{Bmatrix} \tag{1}$$

where the subscripts 'V' and 'T' denote the vehicle system and track system respectively; **M**, **C** and **K** denote the mass, stiffness and damping sub-matrices; **X** and **P** are the displacement and force sub-vectors of the system. The dynamic equations of the vehicle subsystem are detailed in Ref. [15], and the equations of the ballastless track will be explained below.

As Euler beams considering self-weight, the vibration differential equation of both the rail and the concrete layer can be described as:

$$EI\frac{\partial^4 Z(x,\,t)}{\partial x^4} + m\frac{\partial^2 Z(x,\,t)}{\partial t^2} = F(x,\,t) + mg \tag{2}$$

where EI represents the flexural rigidity of the cross-section of the beam; m is the mass per unit length; $Z(x, t)$ is the vertical displacement and $F(x, t)$ is the external force on the beam.

Based on the Ritz method, Eq. (2) can be rewritten into the second order differential equation. For the rail and the concrete layer, they have a form as follows:

$$\begin{cases} \ddot{q}_{rk}(t) + \frac{E_r I_r}{m_r}\left(\frac{k\pi}{l}\right)^4 q_{rk}(t) = -\sum_{i=1}^{N_r} F_{pi}(t) Y_{rk}(x_i) + \sum_{j=1}^{4} p_j(t) Y_{rk}(x_{wj}) \\ \qquad + C_{rk}, \quad (k = 1\sim NM_r) \\ \ddot{q}_{bk}(t) + \frac{E_b I_b}{m_b}\left(\frac{k\pi}{l}\right)^4 q_{bk}(t) = \sum_{i=1}^{N_r} F_{pi}(t) Y_{bk}(x_i) - \sum_{j=1}^{N_b} F_{bi}(t) Y_{bk}(x_j) \\ \qquad + C_{bk}, \quad (k = 1\sim NM_b) \end{cases} \tag{3}$$

where the subscripts 'r' and 'b' denote the rail and the concrete layer respectively; $q(t)$ and $Y(t)$ are the generalized coordinate and the modal function of the simply supported beam; NM is the selected orders of vibration modes and the subscripts 'k' is the kth order of the modes; N_r and N_b are the numbers of fastener springs and the subgrade springs; $F_p(t)$ and $F_b(t)$ are the forces of fastener spring and subgrade spring; $p_j(t)$ is the wheel-rail vertical force; x_i and x_j are the position coordinates of these springs and x_{wj} is the position coordinate of the jth wheelset; C is the additional function relevant to the beam weight which can be calculated by integration.

$$C_k = \frac{\sqrt{2ml}\cdot g}{k\pi}(1 - cosk\pi) \tag{4}$$

where l is the length of the beam.