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Full waveform inversion applied in defect investigation for ballastless undertrack structure of high-speed railway

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ABSTRACT

Until the end of 2015, China will build a national high-speed railway network with total mileage of exceed 20,000 km. The Ballastless undertrack structure is wildly used in this network. Filed investigation shows that the damage and defects in ballastless undertrack structure will grow by long-term dynamic loading during the operation and bring potential risk to the operation safety. For better characterization of these internal problems, a time-domain full waveform inversion (FWI) method based on quasi-linear method and random search algorithm is developed as nondestructive testing (NDT) method. Tikhonov regularization is adopted to alleviate the ill conditioned matrix. Also, cross convolutions between observed data and forward response waveforms are employed to allow this FWI method to get rid of the influence of the source. According to filed investigation, two numerical case studies considered with horizontal discontinuity of material are carried out. It is verified that the presented technical is capable for characterizing anomalies of various zones in buried low-velocity layers. Meanwhile the FWI method is applied to experimental data in a real full scale model of ballastless high-speed railway undertrack structure. The inversion work successfully reveals the preset defects and damages inside the CA mortar layer and embankment. The results are generally consistent with the preset model.

1. Introduction

As part of its rapid urbanization efforts, China has spent billions of dollars over the last decade on building a national high-speed railway network. Until the end of 2015, there will be 42 high-speed passenger railway lines built and operated. At that time, its total mileage will exceed 20,000 km (Wang, 2005). But during the operation, it is found that the damage and defects will be generated in the high-speed railway undertrack structure under the long-term dynamic loading from locomotive. What is more, the damage and defects will be grown and bring potential risk to the operation safety. As a result, the detection methods to reveal internal problems, especially the nondestructive testing (NDT) method, have been attracting more and more attention.

Generally, most of the high-speed railways are operated on ballastless track and its undertrack structure contains four parts (from top to bottom): track slab, cement asphalt (CA) mortar, support plate and embankment, as shown in Fig. 1. The track slab and support plate are made of reinforced concrete and the embankment is built by dense-graded stone asphalt mixtures, Because the strengths of CA mortar and embankment are relatively weak, damage and defects are mainly concentrated on this two layers, such as separation, void, permeation and cracks (Yang and Gao, 2004).

The defect investigation on ballastless high-speed railway undertrack structure can be regarded as a process of revealing the soft sandwich layer with low S-wave velocity. Many traditional geotechnical methods has been used, such as the travel time methods using arrival signals of wave components (Song et al., 2003), the surface wave methods involving wave velocity dispersion (Feng et al., 2009) and the ground penetrating radar (GPR) methods based on the reflection of electromagnetic wave (Cassidy and Millington, 2009). It is reported that the low-velocity regions are not well characterized by travel time methods since the medium contrasts are approximated as gradient regions (Sheehan et al., 2005). Also, in the case of shear wave velocity reversals and high stiffness contrasts, the higher modes will get more energy and become dominant in wave velocity dispersion, as a result, the information of strata below low-velocity layers cannot be well revealed by surface wave methods (O'Neill et al., 2003). For the track slab is built with high reinforcement density, the GPR methods will be greatly restricted by the electromagnetic wave shield. Moreover, the GPR methods have some limitations in required quantitative evaluations because of the insensitivity to elastic parameters like elastic modulus and Poisson ratio (Xu et al., 2006).

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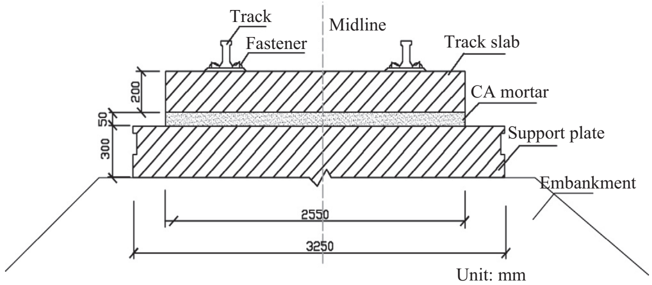

Fig. 1. Sketch of ballastless high-speed railway undertrack structure.

Many studies show that the full waveform inversion (FWI) method is capable of characterizing anomalies of low- and high-velocity zones (Virieux and Operto, 2009; Tran and McVay, 2012). It offers higher resolution of target medium and feasibility for the detection on buried low-velocity layers, so it is potential for quantitative investigation on high-speed railway undertrack structure. The FWI method grasps property information from received response waveforms and it is available for various elastic parameters of underground medium. It iteratively improves an initial model of the subsurface by fitting the observed with modeled data (Bunks et al., 1995; Brossier et al., 2009). However, as a computationally demanding task, the application of FWI method in geotechnical engineering is still in start-up and there are still obstacles to its full solution, such as the presence of ill-posedness and dependency on initial model. Many algorithms have been developed for overcoming above obstacles. Sheen et al. (2006) introduced reciprocity principle and convolution theorem for calculating partial derivatives explicitly, resulting in a significant decrease on the amounts of memory and computation for Jaccobian and approximate Hessian matrices. Romdhane et al. (2011) performed a full-waveform inversion algorithm involving both body and surface waves for near-surface investigation on a small scale model.

Herein, the framework of full waveform inversion method used in high-speed railway undertrack structure mainly contained two critical issues: the forward computation and inversion approach. In forward computation, accurate response waveforms in an undertrack structure model are generated by solving the elastic wave equation. In the inversion process, the initial model of internal structure iteratively improved by systematic fitting to the observed data. A time-domain full-waveform inversion algorithm based on a quasi-linear method (Crase et al., 1992) coupled with the random search algorithm (Huang and Kelkar, 1996; Brigham and Aquino, 2007) is developed for the revealing work of high-speed railway undertrack structure. Assume that the prior information is sufficient and the undertrack structure is simplified as a two-dimensional model. Two case studies, in which the damage and defects are mainly occurred in the layers of CA mortar and embankment, are carried out. The parameters to be extracted are concentrated on the S-wave velocities of distinguished regions in buried low-velocity layers. Besides that, in order to verify the resistance on noise, the noise-corrupted analysis is worked out. Based on numerical results, the FWI method is applied to real data from a full scale model of ballastless high-speed railway undertrack structure. Some artificial damage and defects are buried in CA mortar layer and embankment of undertrack structure respectively. The field tests including excitation and data acquisition are carried out on the surface of track slab. Before the inversion work, pretreatments including filtering and normalization are imposed on the field waveforms. Finally, the inversion work quantitatively reveals the defect and damages inside the CA mortar and embankment layer in undertrack structure.

2. Methodology

2.1. Forward modeling

The forward modeling is process of solving the elastic wave propagation equations by finite-difference time domain (FDTD) method. Two-dimensional elastic wave propagation is described by a set of the second-order linear partial differential equations as follows:

Navier equation in which body forces are ignored

$$\begin{cases} \rho \frac{\partial^2 u_x}{\partial t^2} = (\lambda + 2\mu)\frac{\partial^2 u_x}{\partial x^2} + (\lambda + \mu)\frac{\partial^2 u_z}{\partial x \partial z} + \mu \frac{\partial^2 u_x}{\partial z^2} \\ \rho \frac{\partial^2 u_z}{\partial t^2} = (\lambda + 2\mu)\frac{\partial^2 u_z}{\partial z^2} + (\lambda + \mu)\frac{\partial^2 u_x}{\partial x \partial z} + \mu \frac{\partial^2 u_z}{\partial x^2} \end{cases} \tag{1}$$

where (u_x, u_z) is the particle displacement vector, ρ is the mass density and λ, μ are the Lame' coefficients. At the source locations, the medium is perturbed as enforced displacement.

Because the inversion results are generated by fitting the observed data to responded waveforms estimated by forward modeling, it is important to accurately model the responded waveforms, so the finite-difference time domain (FDTD) method (Smith, 1985) is adopted. Meanwhile, the perfectly matched layer (PML) method (Berenger, 1994; Chew and Liu, 1996) is employed as absorbing boundary condition. The code is developed in Matlaband all displacements are calculated in matrix format and processed at each time step.

2.2. Inversion approach

The inversion work can be considered as an optimization process minimizing the residual between the observed data and forward response waveforms. The residual is usually measured by a least-squares error criterion as

$$Q = \|\boldsymbol{\varepsilon}\|_2 = \|\boldsymbol{F}(\boldsymbol{x}) - \boldsymbol{F}^{\text{obs}}\|_2 \tag{2}$$

where $\|\ \|_2$ denotes the L2-norm, Q is an objective function for the optimization process; $\boldsymbol{\varepsilon}$ is residual waveforms; $\boldsymbol{F}^{\text{obs}}$ and $\boldsymbol{F}(\boldsymbol{x})$ are observed data and forward response waveforms respectively; vector $\boldsymbol{x}$ is parameter vector of simplified model which is described as

$$\boldsymbol{x} = (x_1, x_2, \ldots, x_n)^{\text{T}}$$

where subscript numbers denote the target parameters in inversion respectively; n is the number of parameters to be extracted and T denotes the transpose.

To avoid influence of the source on the inversion work, the residual matrix $\boldsymbol{\varepsilon}$ is modified using cross-convolved waveforms (Cheong et al., 2006). In details, the forward response waveforms are convolved with a reference trace from the observed data while the observed data are convolved with a reference trace from the forward response waveforms. Here, we select the first trace as the reference trace because of its relatively higher quality in site. Thus the objective function is modified as

$$Q = \|\boldsymbol{\varepsilon}\|_2 = \|\boldsymbol{F}_j(\boldsymbol{x}) * \boldsymbol{F}_1^{\text{obs}} - \boldsymbol{F}_j^{\text{obs}} * \boldsymbol{F}_1(\boldsymbol{x})\|_2 \tag{3}$$

where the subscript numbers denote the jth trace and the symbol '*' denotes the convolution.

At the start of inversion, an initial parameter vector $\boldsymbol{x}^0$ is established by prior information, such as geotechnical investigation, parameter scales and design plan. Then the objective function Q is minimized by updating parameter vector $\boldsymbol{x}$ by Quasi-linear method. The parameter vector $\boldsymbol{x}$ in $(n + 1)$th iteration is obtained by

$$\boldsymbol{x}^{n+1} = \boldsymbol{x}^n + (\boldsymbol{J} + a\boldsymbol{E})^{-1}\boldsymbol{B} \tag{4}$$

where $\boldsymbol{E}$ is identity matrix. $\boldsymbol{J}$ is the Jacobian matrix, which can be obtained by taking the partial derivatives of forward response