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Implementation of spectral analysis of surface waves approach for characterization of railway track substructures

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ABSTRACT

Monitoring and identifying the changes in mechanical properties of the railway track due to climatic fluctuation and operation are crucial. Few systematic methods exist for measuring the mechanical properties of the ballast and foundation layers of a railway track. The Spectral Analysis of Surface Wave (SASW) approach, a nondestructive seismic testing method to measure mechanical properties, has been implemented to evaluate the subsurface conditions of pavements. Due to its straightforward method of data analyses, the possibility of automation and the similarities in layering mechanism and stress distributions in the railway tracks and the pavements, the SASW approach can be employed for rapid assessment of the subsurface conditions of the railway tracks. However, the application of the SASW approach to railway tracks is challenging due to the presence of ties and rails over the tracks and the large variations in characteristics of the ballast and subgrade. This study paper presents the means of studying the complication related to the implementation of the SASW for railway tracks and a suggested alternative in implementing the approach in an optimal manner.

Introduction

A ballast layer, forming the top-most layer of a railway track, consists of coarse and angular aggregates. These aggregates that usually range between 75 mm and 5 mm in size are responsible for draining the excess water, maintaining a uniform support and reducing the deformation due to dynamic train loads.

An effective evaluation of the railway track stiffness is essential in ensuring the structural integrity of the railway infrastructure. Climatic fluctuation (e.g., rainfall, change in ground water table) and track operation (e.g., dynamic train loads) impact the stiffness of the ballast and foundation layers. Excessive moisture in the ballast may accelerate the track degradation and may reduce its shear strength or stiffness. Contamination with fines from deteriorated ballast and subgrade may also lead to the degradation of the ballast stiffness [1,23]. Vibration from train loads may exaggerate the deterioration of the aggregates forming the ballast, and consequently, excessive track deformation. Several railway incidents in the past have been attributed to the unstable tracks caused by the degraded ballast [9,2,18].

Several recent laboratory and field studies have focused on characterizing the ballast. Huang et al. [9] used a shear box to determine the shear strength of clean and fouled ballast. Parsons et al. [23] used soil resistivity to measure the level of ballast contamination. Roberts et al. [26] illustrated the use of the ground penetrating radar (GPR) to determine the fouling conditions in the railway tracks. De Bold et al. [3] studied the potential use of the impulse response technique for evaluating the in situ stiffness of the ballast.

The critical issues and adjustments necessary for characterizing the railway track bed with the Spectral Analysis of Surface Wave (SASW) approach rapidly and properly are presented in this paper. To achieve this goal, a series of small-scale testing, large-scale testing and field testing were devised and implemented. The process followed and conclusions drawn are detailed below.

Background

The foundation of seismic surface wave testing is based on the integrated knowledge of wave propagation theories, signal processing methods and inverse modeling techniques [5]. Seismic surface wave testing has been comprehensively explained by several investigators [29,25,4,13]. Since the adoption from the geophysical field, seismic surface wave tests have been used in diverse geotechnical site investigation and pavement evaluation projects (e.g., [32,30,10,20]). Some of the seismic surface wave testing approaches are the Spectral Analysis of Surface Waves

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(SASW, [16], Multichannel Analysis of Surface Waves (MASW, [22] and Refraction Microtremors (ReMi, [11]). The major differences among these approaches are the way the field data are collected and the way the collected signals are analyzed as discussed by Nazarian [13] amongst others.

SASW approach

The fundamental principle of the SASW approach is based on the measurement of the surface wave velocity propagating through a material to estimate the corresponding shear wave velocity [17].

The components required for the SASW approach are impact energy sources, two or more receivers, and a data acquisition/analysis system. A complete procedure with the SASW approach consists of the following three steps:

1. Field experiments to obtain the time domain signals (a.k.a. time records) from the receivers.
2. Pre-processing to construct a dispersion curve by interpreting the time records, and
3. Post-processing to derive a representative shear wave velocity profile by analyzing the dispersion curve through an inversion process

The field experiments for the SASW tests include securing the receivers to the ground surface, impacting the ground surface appropriate impact sources and recording the time records sensed by the receivers. Typical time records from two receivers are shown in Fig. 1a. In the traditional SASW approach, each pair of time records collected are processed individually. To obtain the dispersion curve for each receiver pair, two time records are transformed into the frequency domain, and subjected to spectral analysis to obtain the so-called wrapped phase spectrum. An example of a wrapped spectrum is shown in Fig. 1b. The wrapped phase spectrum is unwrapped. Knowing the unwrapped phase, ϕ_u, at a given frequency, f, for a pair of receivers that are spaced a distance d_i, the phase velocity, V_{ph}, and wavelength, λ, can be estimated from:

$$V_{ph}(f) = 2\pi f\ d_i/\phi_u \tag{1}$$

$$\lambda = V_{ph}/f \tag{2}$$

Coherence functions, an outcome of spectral analysis when data collection is repeated with the same configuration, are usually used as a quality control tool. A low coherence value (typically less than 0.9) is an indication of the lack of seismic energy or the contamination of energy with higher-mode surface waves or body waves in one or both receivers. Phase data in the regions with low coherence are removed from the construction of the dispersion curve. To ensure that the near-field energy contamination is minimized, the frequencies where the unwrapped phase is greater than 180° (i.e. the wavelength is less than twice the distance between the receivers) should be used. To minimize the energy associated with the higher modes of propagation, phase velocities associated with phase greater than 720° are not used.

The most uncertain and tedious portion of this activity is the phase unwrapping. This process relies also on the consistency between the dispersion curves from different receiver spacings (distance between two receivers). The dispersion curves may not be consistent because of strong lateral heterogeneity of the site. As summarized in Nazarian [13], more numerically advanced algorithms are available for the determination of the dispersion

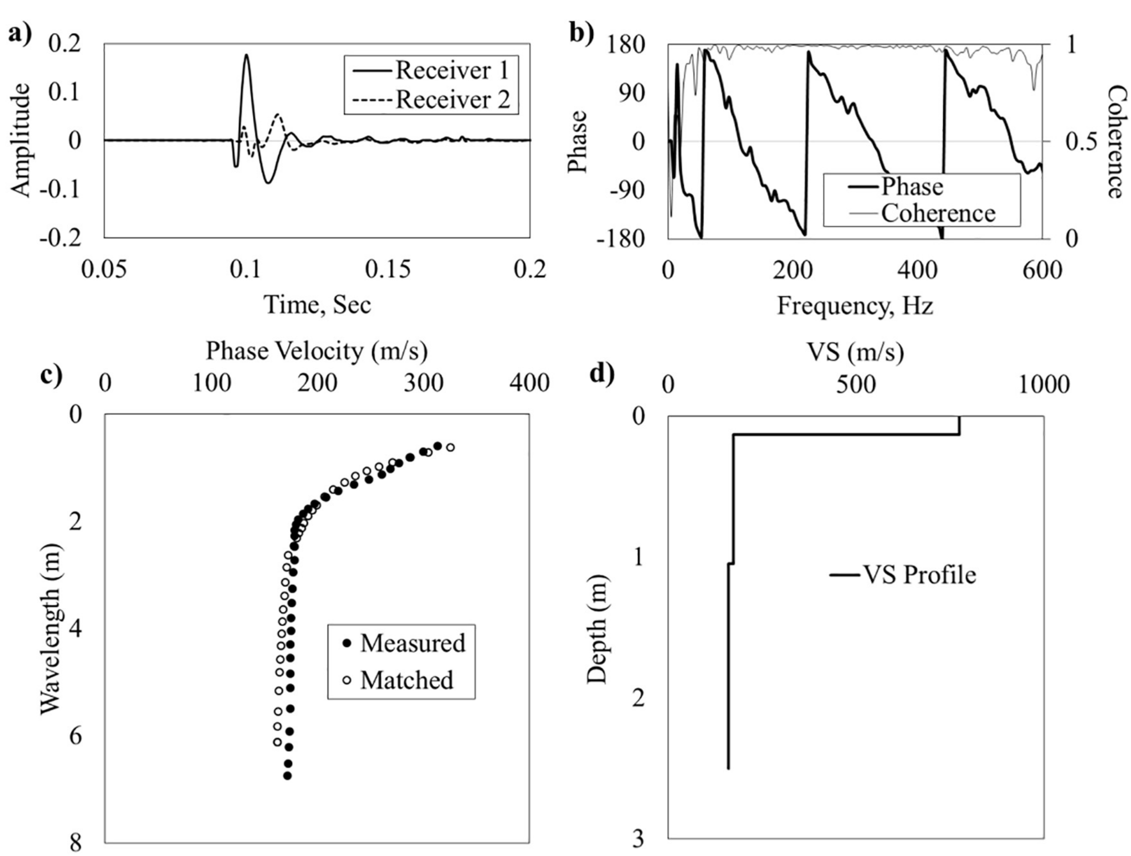

Fig. 1. Typical procedure of analyzing SASW data to obtain a shear wave velocity (VS) profile: Time records for near receiver and far receiver (a), a phase spectrum and coherence function (b), measured and matched dispersion curves (c), and a VS profile (d).