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Evaluation of condition of gravel ballast layer on high-speed railway using surface wave method based on harmonic wavelet analysis of waves

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ABSTRACT

In this research, a surface wave method based on harmonic wavelet analysis of waves was proposed to determine the condition of a gravel ballast layer in a railway as indicated by its shear wave velocity. To show the feasibility of the proposed method, a numerical simulation was performed, and the method was applied to determine the one-dimensional shear wave velocity profiles and two-dimensional shear wave velocity maps of a gravel ballast layer along the railway track direction in the field. The numerical simulation and field applications demonstrated the promising potential of the proposed method.

1. Introduction

A high-speed railway track consists of rails, concrete sleepers, gravel ballast, a reinforcing subgrade, and a subgrade, as shown in Fig. 1. The dynamic load generated by a train is transferred and dispersed from the rail to the subgrade through the gravel ballast layer, which supports the sleepers against vertical and lateral forces. Evaluating the condition of the gravel ballast layer is important for the maintenance and safety of a high-speed railway. Various type of non-destructive test methods have been investigated for this purpose [1–4]. Surface wave methods can also be used. These methods are non-destructive and determine the shear wave velocity profile, which is the square root of the ratio of the shear modulus and density. The shear modulus and density are engineering properties, and the shear wave velocity can be used to represent the condition of a gravel ballast layer.

Various surface wave methods have been developed and showed good performance in site characterization. Every surface wave method consists of three steps: (1) field testing; (2) evaluating the dispersion curve, which is a wavelength- (or frequency-) phase velocity relation curve, the shape of which depends on the structure of the shear wave velocity (V_s) profile of the site; and (3) determining the V_s profile by an inversion process. The field test configurations for surface wave methods rely on a data analysis method to determine the dispersion curve. Surface wave methods are generally of two types: two-channel tests, such as the SASW (Spectral Analysis of Surface Waves) method [5–7] based on the Fourier transform, and multi-channel tests, such as the *F–K* (frequency–wave number) method [8] or MASW (Multi Channel Analysis of Surface Waves) method [9,10] based on the *F–K* transform.

Multi-channel methods separate wave signals into mode components and determine the mode dispersion curve. These methods are affected less by background noise than two-channel methods. However, they require a long test line consisting of many receivers to obtain a sufficient resolution and wavelength range in the dispersion curve. The two-channel method based on the Fourier transform is relatively simple in field tests but is sensitive to background noise. Multi-channel methods have been applied to determine the shear wave velocity of a gravel ballast layer in model test sites that consist of a gravel ballast layer and subgrade without sleepers and have sufficient area for the multi-channel test to be applied [11,12]. In a high-speed railway track in the field, the thickness of the gravel ballast layer is generally 0.5 m, and concrete sleepers are buried at a depth of 0.2 m in the gravel ballast layer. These concrete sleepers act as obstacles when a surface wave is propagated in the direction of the railway. Therefore, the surface wave test should be performed in the small restricted area between the concrete sleepers. The rectangular area

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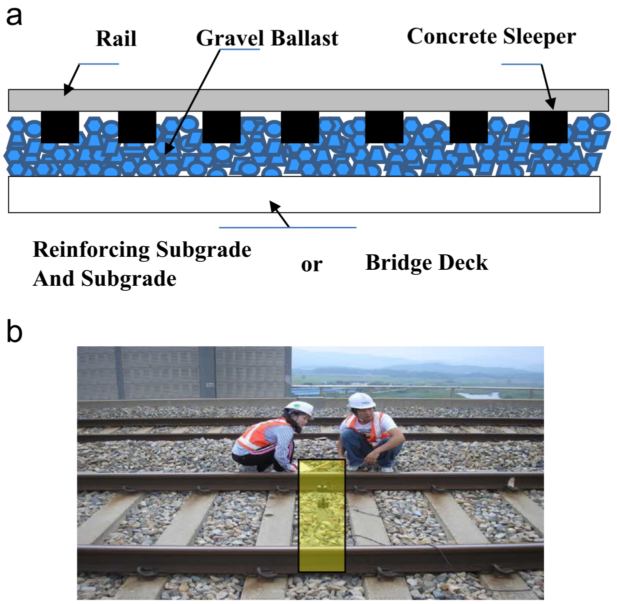

Fig. 1. Structure of high-speed railway track system and possible test area. (a) Structure of high-speed railway track. (b) Possible test area.

in Fig. 1(b) shows this area, which is approximately 0.6 m × 1 m in size. The high-speed railway track in the field has many reflection boundaries, which generate reflection waves that appear as background noise in the surface wave tests. Therefore, the surface wave method used to evaluate the condition of a gravel ballast layer should be able to determine the reliable dispersion curve under noisy conditions in the small area. Multi-channel methods generally require a much longer test line than 1 m.

In this work, the two-channel surface wave method based on harmonic wavelet analysis of waves is proposed for evaluating the shear wave velocity profile of a gravel ballast layer in the field. The data analysis method, test setup, and inversion process using a genetic algorithm for the proposed method are described. A numerical simulation of the multi-layered system is performed, and the validity of the proposed method is demonstrated in a small test area under noisy conditions. Finally, the proposed method is applied in the field to evaluate the V_s profile of a gravel ballast layer and the local loosened area, which can cause railway track settlement.

2. Evaluation of shear wave velocity profile of gravel ballast layer

2.1. Determination of dispersion curve

2.1.1. Determination of dispersion curve based on harmonic wavelet transform

Park and Kim [13] proposed a method that uses a harmonic wavelet transform to determine the phase and group velocities of the frequency components of waves. In this method, the harmonic wavelet transform decomposes the signals measured at two receivers on the surface into the frequency components in the time domain by determining the magnitude (or energy) and phase time–frequency maps [14,15]. These maps describe the instantaneous magnitude (or energy) and phase information of a signal in the time–frequency domain (Fig. 2) [13]. This method also determines the phase and group delays of each frequency component of the signals measured at the two receivers to determine the group and phase velocities as follows:

1) Determination of the group velocity
   a) Determination of the group delays of each frequency component
      - The group delays of each frequency component at receivers 1 and 2 are evaluated from the magnitude time–frequency map.
      - The group delays t_g^1 and t_g^2 at receivers 1 and 2 are defined as the time points corresponding to the maximum magnitude of each frequency component (Fig. 3(a)).
   b) If the receiver spacing is D, then the group velocity V_g at each frequency is calculated as follows:

$$V_g = \frac{D}{t_g^2 - t_g^1} \tag{1}$$

2) Determination of the phase velocity
   a) Determination of the phase delay of each frequency component
      - The phase delays of each frequency component at receivers 1 and 2 are evaluated from the phase time–frequency map.
      - The phase delay at receiver 1 is t_{ph}^1, which is the same as t_g^1, and the phase value θ_1, which corresponds to t_{ph}^1, is determined as shown in Fig. 3(b).
      - The phase delay at receiver 2, t_{ph}^2, is the time point that corresponds to θ_1 and is the closest to t_{ph}^2.
   b) The phase velocity V_{ph} at each frequency is calculated as follows:

$$V_{ph} = \frac{D}{t_{ph}^2 - t_{ph}^1} \tag{2}$$

2.1.2. Data recovery process for determining dispersion curve

In some cases, the data analysis procedure described in Section 2.1.1 does not work correctly. Fig. 4(a) shows an example shear wave velocity profile and the test setup. In this example case, the data analysis procedure described in Section 2.1.1 does not work correctly in some frequency bands. In Fig. 4(b), the correct dispersion curve was compared with the dispersion curve evaluated by the procedure described in Section 2.1.1 using time domain signals obtained by the numerical simulation in this case, as shown in Fig. 4(a). In Fig. 4(b), the dispersion curve obtained by the procedure described in Section 2.1.1 does not agree with the correct dispersion curve in some frequency bands (133–164 Hz, 277–286 Hz), which is due to a difference in the envelope shape between each frequency component obtained by receivers 1 and 2 in the time domain. Therefore, the variable t_{ph}^2 described in Section 2.1.1 is valid when the relative distortion of the envelope shape between each frequency component obtained by receivers 1 and 2 in the time domain is within some limit. The relative distortion can be determined by the period-normalized time difference factor Δt_T, which is defined as follows:

$$\Delta t_T = -\frac{1}{V_g}\frac{dV_{ph}}{d\lambda}D \tag{3}$$

where λ is the wavelength. The distortion increases with increasing Δt_T. Further, t_{ph}^2 is valid only when the absolute value of Δt_T is smaller than 0.5. If Δt_T is $N-0.5 < \Delta t_T < N+0.5$, where N is an integer, the phase delay time at receiver 2, which corresponds to the correct phase velocity, is located at (period corresponding to each frequency component) × N separate from the previously calculated t_{ph}^2. The period corresponding to each frequency component is the inverse of each frequency. The correct t_{ph}^2 is