Soil Dynamics and Earthquake Engineering 99 (2017) 203–212

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Development of a simple 2D model for railway track-bed mechanical behaviour based on field data

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ARTICLE INFO

Keywords:
Field data
Track-bed displacement
Dynamic amplification
Vibration attenuation
Propagation of vibrations
2D analytical model

ABSTRACT

From a practical point of view, it is important to empirically predict the mechanical behaviour of railway track-bed of multi-layers using simple models. In this study, Field monitoring was performed using several accelerometers installed in different layers along a conventional railway track. The accelerometer signals were recorded during the passages of train at 6 different speeds from 60 to 200 km/h. The particle displacements were estimated by integrating the acceleration data. Emphasis was put on the dynamic amplification with speed, the attenuation of vibration over depth and the wave propagation along longitudinal direction in a given layer. The obtained results showed that the measured dynamic amplification with train speed depends on the relationship between the train speed and the surface wave velocity. The amplitude attenuation over depth can be represented by an exponential expression. In addition, it was found that the propagation of vibrations along the longitudinal direction had a sinusoidal shape, exponentially attenuated in distance, similar to the displacements calculated by the Winkler beam model. Based on these three mechanisms identified as well as the field data, a 2D analytical model was developed, allowing the prediction of conventional railway track-bed deflections with the axle loads and train speeds. Comparisons between prediction and measurement showed the relevance of the proposed model.

1. Introduction

In France, the railway network is composed of conventional lines (94%) and high-speed lines (6%). As opposed to the new lines, conventional lines were built by putting ballast directly on the subgrade without sub-layer. An Interlayer (ITL) was then created over time, mainly by the interpenetration of fine particles from subgrade and the attrition of ballast grains [1,2]. On the other hand, in order to increase the train speed and axle weight for improving the service of the conventional lines, the track dynamic behaviour needs to be investigated. From a practical point of view, it is necessary to find a method to predict the wave propagation and the corresponding track vibration under the effect of trains at different speeds, especially in the case of conventional lines with the presence of ITL [1–5].

The train induced vibrations of track and track-bed are largely studied using empirical [6,7], analytical [8–10] and numerical methods [11–16]. For the purpose of modelling the railway track behaviour, Winkler model was first considered by Kenny [17]. It is supposed that the foundation can be considered as a beam supported by visco-elastic springs. This model is limited to the calculation of surface deformation and does not take train speed into consideration. In practice, an empirical dimensionless impact factor is adopted by American Railroad Engineering Association (AREA) and National Society of French Railways (SNCF) to calculate the dynamic wheel load [6,7], but the interaction with track-bed was not clearly accounted for. In order to investigate the dynamic behaviour of railway tracks, Auersch [8] developed a method allowing the determination of the response attenuation in horizontally layered soils using functions of loading frequency and distance when a moving punctual loading acts on the soil surface. Using numerical calculations, Krylov [9] theoretically illustrated a large increment in vibration if the train speed exceeds the velocity of Rayleigh surface waves. Sheng [10] developed a semi-analytical mathematical model to predict the ground vibrations generated by surface trains. This model incorporates the necessary compo-

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http://dx.doi.org/10.1016/j.soildyn.2017.05.005
Received 24 August 2015; Received in revised form 28 January 2017; Accepted 5 May 2017
0267-7261/

nents of the railway system: the vehicles, track and ground. Connolly et al. [17] experimentally analysed ground-borne vibration levels generated by high speed rail lines on various earthwork profiles. Connolly et al. [18] provided insights into the uncertainties in railway ground-borne vibration prediction. Hall [11] analysed the response of a ground consisting of soft soil using the three-dimensional finite element method code ABAQUS. A variety of 2.5D and 3D models using finite element formulations were developed by several authors [12–15], but the corresponding calculation time is often extremely long.

In this paper, a simple semi-analytical model is developed, which consists of three parts: vibration amplification with train speed, attenuation over depth and vibration propagation along longitudinal direction. The proposed model uses track parameters with clear physical meanings. Moreover, it is quite simple and can thus be easily applied in practical railway engineering. Comparisons between the model prediction and field monitoring data showed the performance of the developed model.

2. Field monitoring and particle displacement determination

2.1. Site description

The experimental site is located in Vierzon, France, along the conventional line 'Orleans - Montauban'. It was selected due to the good state of the different track elements, its geographical situation and traffic conditions on the line. An Intercity train was employed for the experimentation, which consists of one locomotive BB22000 and seven ‘Corail’ coaches. The configuration of the test train is shown in Fig. 1. Its wheel loads (half-axle) are 112.5 kN and 52.5 kN for the locomotive and the Corail coaches, respectively. Six train speeds were considered for the experimentation: 60 km/h, 100 km/h, 140 km/h, 160 km/h, 180 km/h and 200 km/h.

A geophysical and geotechnical prospection of the experimental site was performed [5,20]. From the prospection results, a geological profile was defined with four different layers as shown in Fig. 2: Ballast, Interlayer (ITL), Transition layer (TL) and Subgrade (SBG). The thickness of ballast layer is 50 cm in average with 41 cm fresh ballast and 9 cm fouled ballast. The size of fresh ballast is between 61 and 25 mm. The fouled ballast was invaded by small grains of about 2 mm but still considered as ballast because water can easily seep through this layer. The average thickness of Interlayer (ITL) is 40 cm. This is an impermeable and high density coarse-grained soil mixed with fine-grained soil from subgrade. The ITL contains 10% fine particles from the subgrade soil. Below the ITL is the Transition layer (TL) with more fines and lower quantity of coarse grains from ballast or ballast attrition of 20 cm size. In contrast to ITL, the mass ratio of ballast grain ($>$ 20 mm) in TL is lower than 15% [21]. The subgrade soil (SBG) consists of a sandy silt ($D_{50}=0.3$ mm, $I_P=18$).

A static modulus of $E_{v2}=100$ MPa on the top of ballast was determined using LWD (light weight deflectometer), a dynamic plate loading method [20,22]. The average shear wave velocity of the first 5 m of track-bed was found to be about $v_s=200$ m/s by MASW (Multiple Analysis of Surface Waves), and a damping ratio $D=0.05$ for the ITL soil was estimated from large-scale triaxial tests [1,4,23,24].

2.2. Site instrumentation and displacement determination

In order to monitor the acceleration amplitudes developed by long wavelengths, accelerometers with high accuracy in low-frequency range [4] were used in this study. The sensor arrangement is specified in Fig. 2. Based on the site prospection results, capacitive accelerometers were installed at sleeper, −0.9 m (ITL), −1.2 m (TL) and −2.3 m (SBG) depths under the rail. Fine soil was used firstly to fill the gap around the sensors to ensure a good contact between sensors and soil. Afterwards, the borehole was filled by compaction with an artificial ITL soil prepared in the laboratory.

After the accelerometers were installed, the test train passed over the experimental site at six different speeds and the temporal response of each sensor was recorded. Fig. 3a shows a typical time-acceleration curve in ITL and TL for a train running at 60 km/h. The accelerometer signals can be integrated to determine the particle displacement [4,25], as shown in Fig. 3b. Butterworth high-pass filters are applied before the signal integration to avoid baseline error [26]. The power spectrum density (PSD) analysis which gives the signal energy distribution in the frequency domain illustrates that the most energetic frequencies in the low-frequency range are between 1.5 and 25 Hz, corresponding to the frequencies excited by the bogie and axle wavelengths for the considered speeds [25]. These wavelengths caused more than 98% of the total displacements amplitude. By integrating the accelerometer signals, the axles, bogies and cars can be clearly identified on the curve of displacement *versus* time (Fig. 3b). For further comparison of different data, the signals are virtually-translated to a same initial position. The moving positions x_i (Fig. 3a) is defined by the distance between two boreholes (Fig. 2) as well as the train speed.

Fig. 4a shows the comparison of time domain displacements at 60 km/h (ITL) and 200 km/h (TL). In order to analyse the amplitude attenuation along the track, X-axis is converted to distance. After multiplying time by train speed, the vibrations in distance domain are obtained (Fig. 4b). Note that the axle or bogie location (peaks) at 60 km/h and 200 km/h keep consistent. As the amplitude validation was done at other depths, the integration method applied is thus justified. The front and rear parts of the signals, representing the vibrations while train approached or left away from the sensor position, are highlighted in spotted frames.

3. Field data analysis and vibration model development

3.1. Dynamic amplification factor

In this section, the normalized displacement responses to changes of

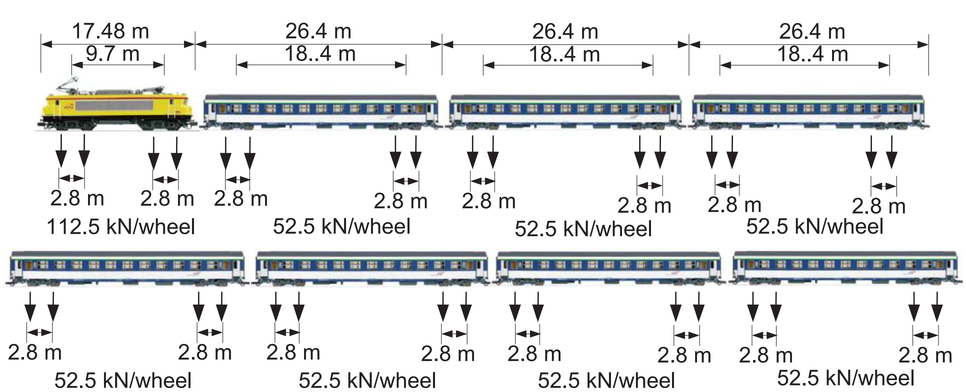

Fig. 1. Scheme of Intercity train and static wheel load.