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Experimental investigation into ground vibrations induced by very high speed trains on a non-ballasted track

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ABSTRACT

A field measurement of ground vibration was performed on the Beijing – Shanghai high-speed railway in China. In this paper, the experimental results of vertical ground vibration accelerations induced by very high speed trains running over a non-ballasted track on embankment with speeds from 300 to 410 km/h are reported and analyzed in detail for the first time. Characteristics of ground vibration accelerations in both time and frequency domains are analyzed based on the test data. It is shown that the periodic exciting action of high-speed train bogies can be identified in time histories of vertical accelerations of the ground within the range of 50 m from the track centerline. The first dominant sensitive frequency of the ground vibration acceleration results from the wheelbase of the bogie, and the center distance of two neighboring cars plays an important role in the significant frequencies of the ground vibration acceleration. Variations of time–response peak value and frequency-weighted vertical acceleration level of ground vibration in relation with train speed as well as the distance from the track centerline are also investigated. Results show that the time-domain peak value of ground vibration acceleration exhibits an approximately linear upward tendency with the increase of train speed. With the increasing distance from the track centerline, the frequency-weighted vertical acceleration level of the ground vibration attenuates more slowly than the time-domain peak value of the ground vibration acceleration does. Severe impact of high-speed railway ground vibration on human body comfort on the ground occurs at the speed of 380–400 km/h. The results given in the paper are also valuable for validating the numerical prediction of train induced ground vibrations.

1. Introduction

In the last century, the operation speeds of high-speed trains in the world were rarely more than 300 km/h. After the start of the 21st century, with the rapid development of high-speed railway technology, a number of new high-speed railway lines were put into service in China, where operation speeds are commonly at 300 km/h and occasionally up to 350 km/h, heralding a new era of high-speed railway.

With the rise of train speed, the environmental vibrations along railway lines become a major concern. Many scholars have carried out a series of theoretical analysis and numerical simulation to investigate the ground vibration caused by railway transportation. In the theoretical analyses, the ground vibrations induced by moving train loads were mainly analyzed through track – foundation models [1–4]. In the numerical simulation, the finite element method (FEM) [5–8], the boundary element method (BEM) [9,10], the combined FEM – BEM [11–15], and the combined FEM – IFEM (infinite element method) [16,17] were used to investigate the environmental vibration due to railway traffic. In the authors' previous study [18], high-speed train induced ground vibration was predicted with a train – track – ground system model, in which the vehicle – track coupled dynamics model [19] was applied to obtain the wheel – rail dynamic forces and these forces were then used as the exciting loads inputted to the track – ground system.

Meanwhile, for understanding of the characteristics of ground vibration and verification of the above-mentioned theoretical models, many experimental research activities have been performed on the ground vibration excited by high speed trains in the last decade. Degrande and Schillemans [20] measured the ground vibration near Brussels – Paris high-speed railway line with train speeds between 223 and 314 km/h, and the measured ground vibration data was used to validate a numerical prediction model. Auersch [21] performed three series of measurements of ground vibration during the test runs of the ICE train on the built track near Würzburg. There has been a ballasted track on a surface over stiff soil, and the train speed

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was varied from 100 to 300 km/h. The ICE measuring series demonstrates that the axle-passage impulses are not always clearly identified in the ground vibrations, which is mainly influenced by the non-uniform soil, and track irregularities can explain the medium-frequency ground vibrations to a certain extent. Ju et al. [22] carried out free-field experiments of the HSR-700T high-speed train moving on an embankment and in a tunnel in central Taiwan with train speed of 270 km/h. The experimental results show that the magnitude of the measured vibration at the dominant frequencies generated by the train load is different from the theoretical results after the train-induced wave transfers from a complicated site with soil or tunnels. Galvin and Dominguez [23] measured the ground vibration of high-speed railway on a ballasted track in Spain. The train speed was between 151 and 298 km/h. Based on the field test, a comparative analysis of the measured data and the numerical simulation results were performed. Lombaert and Degrande [24] made a comparison of two free-field tests along railway for ballasted tracks. In these tests, vibrations of the track and the ground have been measured for several passages of the high-speed train (train speed from 218.1 to 326.1 km/h) and an InterCity train (train speed from 155.9 to 225.3 km/h). One of two main comparison conclusions is that for ground vibrations induced by InterCity and high-speed trains in the subcritical speed range, the quasi-static contribution dominates the track response, while the free-field response is dominated by the dynamic contribution. The other is that the dynamic excitation is due to random track unevenness, and the influence of the train speed on the free-field vibrations depends on the power spectral density (PSD) of the track unevenness. Galvín et al. [25] used the free field responses at the distance of 2, 12, 32, and 72 m from the outer rail of the track for the passage of a TGV Atlantique (TGVA) at a speed of 255 km/h to compare two calculation models. In one of the two models, the ballast and the embankment are modeled as a continuum using 2.5D solid elements, whereas a simplified beam representation is adopted in the other model. A very large difference is found for the free field responses of both models, which is due to the fact that the deformation of the cross section of the embankment is disregarded in the simplified representation. In the authors' earlier measurement tests (Zhai et al. [18,26]), two high-speed train running tests including ground vibration measurements were carried out on China's non-ballasted track lines with different train speed levels. One is for a 200 km/h speed level test on the Suining – Chongqing line, the other is for a 300 km/h speed level test on the Beijing – Tianjin high-speed line [26]. It can be concluded that so far, the high-speed railway ground vibration tests mostly concentrate on the ballasted track railways, especially in the case of the train speeds around 300 km/h. There is limited test data of ground vibrations induced by the high-speed trains at running speeds 350 km/h or above. It is not clear what the ground vibration characteristic and propagation regulation are when the train speed is above 350 km/h. It is also unknown whether the existing theoretical models can still be applicable to prediction of train induced ground vibrations at very high speed range.

Fig. 1. Testing site of ground vibration on the Beijing – Shanghai high speed railway.

This paper intends to introduce the most recent ground vibration experiment accomplished by the authors on China's Beijing – Shanghai high-speed railway with both the design speed and the construction standard being the highest in the world. The test train speed was between 300 and 425 km/h, regarded as "very high speed". In the experiment, the high-speed trains ran on a non-ballasted track with a high embankment. Detailed measurement results of ground vibrations in the case of train speed up to 410 km/h are presented and analyzed for the first time, including the characteristics of ground vibration in time domain and in frequency domain, the variation of ground vibration with train speed, and the attenuation of ground vibration with the distance from the track centerline.

2. Field experiment of ground vibration on high-speed railway

In January 2011, a free-field measurement on the Beijing – Shanghai high-speed railway was performed with train speed between 300 and 425 km/h. The measurement site was near Suzhou East station in the pilot test section from Zaozhuang West station to Bengbu South station shown in Fig. 1. The test was focused on the vertical acceleration of ground vibration aside the non-ballasted track on embankment.

2.1. High-speed test trains

Two types of high-speed trains made in China, named CRH380AL and CRH380BL, were adopted in the test, and today the trains have been put into daily operation on the Beijing – Shanghai high-speed railway. Both trains are of 16-car formation. The CRH380AL train is composed of 14 motor cars and 2 trailers with the head car and the tail car of the train being trailers. The CRH380BL train consists of 8 motor cars and 8 trailers. During this experiment, the high-speed trains were running empty, and the axle load was between 11 t and 12 t. The primary dynamic parameters of two types of trains are similar. Table 1 gives the inertial characteristics and suspension parameters of the test trains, which are the important parameters for modeling the effect of train dynamics on ground vibration [27,28]. In Table 1, M_c, M_t and M_w denote the mass of car body, bogie frame and wheelset, respectively; J_c and J_t are the moment of inertia of car body and bogie; K_p and C_p are the stiffness and damping of the primary suspension of the train (per wheelset); K_s and C_s are the stiffness and damping of the secondary suspension (per bogie).

Table 1
Inertial characteristics and suspension parameters of the high-speed train.

Car type	M_c (kg)	M_t (kg)	M_w (kg)	J_c (kg m^2)	J_t (kg m^2)	K_p (N/m)	C_p (N s/m)	K_s (N/m)	C_s (N s/m)
Head car & tail car	33786	2056	1627	1.66×10^6	2.59×10^3	1.772×10^6	2×10^4	4.5×10^5	2×10^4
Middle car	38884	3060	1517	1.91×10^6	3.2×10^3	1.772×10^6	2×10^4	4.5×10^5	2×10^4