Tunnelling and Underground Space Technology 79 (2018) 67–75

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

An experimental study of the dynamic response of shield tunnels under long-term train loads

Wenbo Yang, Lingui Li, Yingchao Shang, Qixiang Yan*, Yong Fang, Chuan He, Zhaoyang Xu

Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu 610031, Sichuan, China

ARTICLE INFO

Keywords:
Dynamic response
Shieldtunnels
Long-term train loads
Segment joints

ABSTRACT

In this paper, results are presented from a series of physical tests aimed at studying the influence of long-term train loads on the dynamic response of a tunnel lining and the surrounding soil. In the tests, the train loads were constantly applied at the tunnel invert by an electromagnetic shaker. The dynamic response of the tunnel lining and surrounding soil were measured initially and after 160,000, 330,000, and 600,000 loading sequences (each sequence representing the passage of a model train). The peak particle acceleration and frequency response function (FRF) of the model were calculated at each of these loading cycles. Two tunnel lining models were used in the experimental tests: stagger-jointed and uniform. The results show that the peak particle acceleration of the tunnel is amplified only after long-term train loads are applied. However, the peak particle acceleration of the soil shows an almost linear increase with loading cycles. The frequency domain results show that the dynamic characteristics of the soil could be significantly affected by the long-term train loads. Due to the variation of confining stress induced by long-term train loads, a clear 'shift' of soil FRFs with loading cycles was found. Test results also show that it is important to consider segmental joints when studying long-term train load effects on tunnel response.

1. Introduction

Hundreds of underground transportation lines have been built around the world to alleviate traffic pressure (ITA, 1990; Broere, 2016). Comparing to road traffic, underground railways have many advantages, such as efficiency, energy conservation, safety and comfort, however vibrations from underground railways represent a major environmental concern. As a result of wheel-rail interaction, vibration is generated at the rail and can propagate though the tunnel lining and surrounding soil into buried and ground surface structures. These vibrations can induce noise which can have significant impact on the comfort of building residents (Croy et al., 2013; Smith et al., 2013). Furthermore, for existing structures which may be particularly vulnerable to vibrations (e.g. cracked masonry), long-term repeated train-induced vibrations could lead to serious damage (Ge et al., 2016).

Various analytical and numerical methods have been employed to research vibrations from underground tunnels. Sheng et al. (1999) presented an analytical model to study ground vibration due to harmonic and constant moving loads. Using cylindrical elastic theory, Forrest and Hunt (2006a,b) presented the Pipe-in-Pipe (PiP) model to calculate the dynamic response of a tunnel and soil under point loads from an underground tunnel embedded in an elastic continuum. Hussein et al. (2014) developed an extension of the PiP model to consider the tunnel embedded in a multi-layered half-space. This analytical model assumed that the free surface or ground layers do not affect the tunnel displacement, which is computationally efficient but has some inaccuracies when dealing with shallow tunnels. Zhou et al. (2017) used an analytical tunnel model, coupled with a train-track system, to calculate the dynamic response of a tunnel embedded in saturated soil. Most of these analytical methods are only applicable to simple geometries and deep tunnels. In order to overcome this drawback, various 2D or 3D numerical methods have been developed. Degrande et al. (2006a) presented a 3D coupled finite element-boundary element model (FEM–BEM) to simulate the dynamic interaction between the tunnel and soil due to the running of metro trains. Two different metro tunnels were considered: a shallow tunnel and a deep tunnel. Mülle et al. (2008) used a coupled finite element method-integral transform method (FEM-ITM) to study the interaction between a moving train and an underground railway tunnel. By assuming that the geometry of the tunnel structure was invariant along the longitudinal direction, Amado-Mendes et al. (2015) presented a 2.5D numerical model, based on a coupled method of fundamental solutions and finite element method

---

* Corresponding author at: No. 111, The Second Circled Road North, Chengdu, Sichuan 610031, China.
E-mail addresses: yangwenbo1179@hotmail.com (W. Yang), 2293406935@qq.com (L. Li), 2538612632@qq.com (Y. Shang), 764365015@qq.com (Q. Yan), fy980220@home.swjtu.edu.cn (Y. Fang), chuanhe21@swjtu.edu.cn (C. He), 314328279@qq.com (Z. Xu).

https://doi.org/10.1016/j.tust.2018.04.031
Received 31 January 2018; Received in revised form 5 April 2018; Accepted 27 April 2018
0886-7798/

(MFS-FEM), to predict the track and soil vibrations due to an underground railway. Yaseri et al. (2014) developed a scaled boundary finite-element method (SBFEM) to analyze 3D vibrations from underground tunnels. The tunnel and surrounding soil was modeled by the SBFEM, and the track was modeled by the finite-element method (FEM). Real et al. (2015) compared the results of 2D and 3D FEM models which followed the same assumptions and concluded that the 2D models were inaccurate, though they benefited from lower calculation times. By considering segmental joints, Gharehdash and Barzegar (2015) used a 3D elasto-plastic finite difference method (FDM) to study the dynamic response of a tunnel and surrounding soil under a vibrating load. Xu et al. (2016) developed a mixed 2D and 3D finite-element model to investigate the dynamic interaction among track, tunnel and soil by considering track irregularities.

Numerous experimental studies have also been conducted to simulate vibrations induced by underground railways. Trochides (1991) measured the dynamic response of a tunnel and soil in a 1:10 1 *g* scale model in the frequency range of 50–500 Hz. Results were compared with calculations which indicated that an approximate prediction of ground vibrations from underground tunnels can be obtained by using approximate impedance formulas and simple energy considerations. By applying impulsive and vibrating loadings, Thusyanthan and Madabhushi (2003) conducted a 1 *g* experiment to understand the propagation of waves through a tunnel and soil. Two different types of tunnel linings (brass and plastic) were used in the tests. Yang et al. (2013a, b) presented centrifuge modelling and numerical simulations to investigate the effects of soil non-homogeneity on the vibration generated from a surface source and an underground tunnel. Huang et al. (2015) created a 1:4 scaled 1*g* model to test a high-speed railway tunnel invert and its foundation soil. The dynamic train loads for different speeds were imposed by an electro hydraulic servo exciter and transmitted from two steel girders to the steel rails. The accelerations, dynamic coefficients and stresses of the tunnel and soil were measured in the tests. Lopes et al. (2016) compared experimental and numerical results relating to the vibrations inside buildings caused by an underground railway. The numerical model, based on the FEM, was composed of three sub-domains to simulate three parts of the problem: (i) generation; (ii) propagation; (iii) reception (Lopes et al., 2014a, b). The study showed that the numerical model was able to reasonably predict vibrations with a relatively simple structure. In addition, many field measurements have been carried out to study the propagation of ground vibrations due to high-speed trains (Auersch, 2005; Degrande et al., 2006b; Ju et al., 2009; Kouroussis et al., 2011; Zhai et al., 2015) and subway traffic (Vogiatzis, 2012; Vogiatzis and Kouroussis, 2015; Ma et al, 2016; Sadeghi and Esmaeili, 2017).

It should be noted that previous research focused on studying ground-bone vibrations from tunnels under dynamic load at a specific time. However, the dynamic characteristics of a tunnel lining and the soil under the action of long-term repeated train loads have not been studied. Furthermore, the tunnel lining in previous research was often simplified as a uniform cylinder. However, a shield tunnel is made up of numerous segments, with circumferential and longitudinal joints between segments. These joints have a significant influence on the mechanical properties of the tunnel lining and affect the dynamic response of the structure under train-induced vibrations (Ye et al., 2014). The behavior of segmental joints in response to long-term repeated train loads is also not clear. Therefore, this paper presents an experimental study to explore the influence of long-term train loads on the dynamic response of a tunnel lining and the surrounding soil, including a consideration of the effect of segmental joints. This paper is divided into three main sections. Section 2 provides details of the experimental modeling methodology. Section 3 presents the model test results and corresponding discussion, followed by conclusions in Section 4.

Table 1
Scaling factors for model tests.

Parameter	Scaling laws	Scaling factors (prototype/model)	Reference
Length	C_l	20	Iai. (1989) Iai et al. (2005)
Density	C_ρ	1	
Elastic modulus	C_E	30	
Velocity	$C_v = C_l C_\rho^{0.5} C_E^{-0.5}$	3.65	
Acceleration	C_a	1	
Acceleration of gravity	C_g	1	
Time	$C_t = C_l C_\rho^{0.5} C_E^{-0.5}$	3.65	
Frequency	$C_\omega = C_l^{-1} C_\rho^{-0.5} C_E^{0.5}$	0.274	
Axial force	$C_F = C_l^3 C_\rho$	8000	

2. Physical modelling of tunnels and soil behavior under long-term train loads

Vibration induced by trains is generally considered as a soil problem in the small strain range. Tunnel and soil behavior are commonly expected to be linear and elastic (Forrest and Hunt, 2006a; Gupta et al., 2007; Yang et al., 2013a, b; Real et al., 2015). Therefore, scaling laws for elastic models were used in the development of the physical model. The scaling factors applied in the tests are shown in Table 1. Length, density, and Young's modulus are the fundamental parameters; the others are obtained from these factors according to scaling laws for elastic models (Iai, 1989; Iai et al., 2005).

2.1. *Container and soil*

A rectangular container measuring 150 cm wide, 90 cm long and 135 cm high was manufactured to perform the tests. In order to reduce undesirable reflections of vibration waves from the container boundaries, an energy absorbing material, Duxseal (30 mm thick) (Pak and Guzina, 1995; Yang et al., 2013b) was placed on the interior walls of the container to absorb elastic waves arriving at the boundary.

To satisfy the scaling laws of the test, a mixed material of quartz sand, coal ash, river sand and oil is used as tested soil. The corresponding mass ratio is 54:27:12:7, respectively. Uniaxial compression tests were conducted to measure the mechanical parameters of the soil. The mechanical parameters of both soil prototype and model are given in Table 2. To prepare the test model, a tamping method is used. The tested soil is poured in nine layers and each layer is artificially compacted by hitting a small plate with a hammer, as shown in Fig. 1.

2.2. *Vibration package and data acquisition system*

To simulate the dynamic force, a JM-20 electromagnetic shaker was used. Vibration signals are first generated from a JM-1230 type wave generator which allows user defined vibration signals. The signal is then amplified by a power amplifier and transferred to the shaker. In order to measure the excitation force applied on the tunnel, a JM0710-001 dynamic load-cell was installed at the centre of the tunnel invert. JM0213 miniature accelerometers were used to measure the tunnel and soil response. A JM-16 dynamic signal acquiring DAQ card was used to record the signals from both the load-cell and accelerometers. The cross-sectional view of the experiment is shown in Fig. 2.

Table 2
Mechanical parameters of model soil.

Parameter	Prototype	Model
Elastic modulus (MPa)	63–72	2.1–2.4
Shear modulus (MPa)	24.3–27.9	0.81–0.92
Density (kg/m^3)	2000	2000
Poisson's ratio	0.3	0.3