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An experimental study of ground-borne vibration from shield tunnels

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ABSTRACT

Along with the ongoing development of urban railways, ground-borne vibration from trains has received considerable attention in the past decades. Various research studies have been conducted to study this problem. In order to simplify the problem for analysis, it us commonly assumed that tunnels have a uniform lining; however in reality this usually not the case. With the development of shield tunnelling, precast segmental linings are widely used. The existence of the joints between tunnel segments can significantly affect the dynamic behaviour of the tunnel. In this paper, results from a series of physical model experiments are described to explore the dynamic characteristics of segmental tunnel linings. Three different tunnel lining models were tested: uniform, straight–jointed segments, and stagger–jointed segments. In the experiments, vibration excitation was applied to the model tunnel invert by a shaker. The tunnel and soil responses at different locations were measured by accelerometers during the tests. Comparison of the results from the different tunnel lining models shows that the segment joints have a considerable effect on the dynamic behaviour of the tunnel lining. Due to the effects of interface damping at the segment joints, the response of both types of segmental linings was found to be significantly smaller than the response of the uniform tunnel lining. The experimental results also show that the segment joints have less impact on the soil response and mainly affect the soil response in the frequency range below 80 Hz.

1. Introduction

There have been significant developments of underground railways in recent decades to relieve traffic congestion in major cities (Broere, 2016). Various studies have been conducted to model the construction of shield tunnels (Xu et al., 2015, 2016; Kavvadas et al., 2017). On the other hand, train induced ground-borne vibration has become a major environmental concern in urban areas. Vibrations are generated from the transit of vehicles on rails and propagate through the ground or structure into receiving buildings. This can cause perceptible vibrations as well as re-radiated noise, which may have a significant impact on the comfort of residents. Therefore, a lot of research has been conducted to understand the mechanisms of propagation of ground-borne vibration to design effective remediation measures.

Many analytical methods have been developed to study train-induced ground-borne vibration from a tunnel. Krylov (1995) presented a 2D model to calculate ground-borne vibration under a point load. Nejati et al. (2012) developed a 2D finite difference model to compute the surface vibration induced by train movement in the subway tunnel. The numerical model was verified by Metrikine and Vrouwenvelder's analytical model. However, the accuracy of 2D model analyses is limited due to its inability to consider both longitudinal and circumferential directions simultaneously (Hunt, 2001). In order to give absolute vibration transmission predictions, Müller et al. (2008) developed two 3D models based on a coupling of FE and analytical methods. These models accounted for tunnels with circular and rectangular cross-sections. Yaseri et al. (2014) used a 3D coupled scaled boundary finite-element/ finite-element method to analyse ground vibrations induced by underground trains. The media around the tunnel was modelled using the scaled boundary finite-element method (SBFEM). The accuracy of SBFEM was proved by comparison with an extended mesh method (EMM) analysis. Real et al. (2015) presented a 3D numerical finite element (FE) model to predict railway induced vibrations, as well as two different 2D FE models which followed the same assumptions as those in the 3D model. By using different combinations of numerical analyses and field measurements, Kuo et al. (2016) explored the application of a hybrid modelling procedure to the problem of railway induced vibrations. However, the computing time usually tends to be very long in these 3D models. Forrest and Hunt (2006a, 2006b) developed a semi-numerical method, called the Pipe-in-Pipe (PiP) model,

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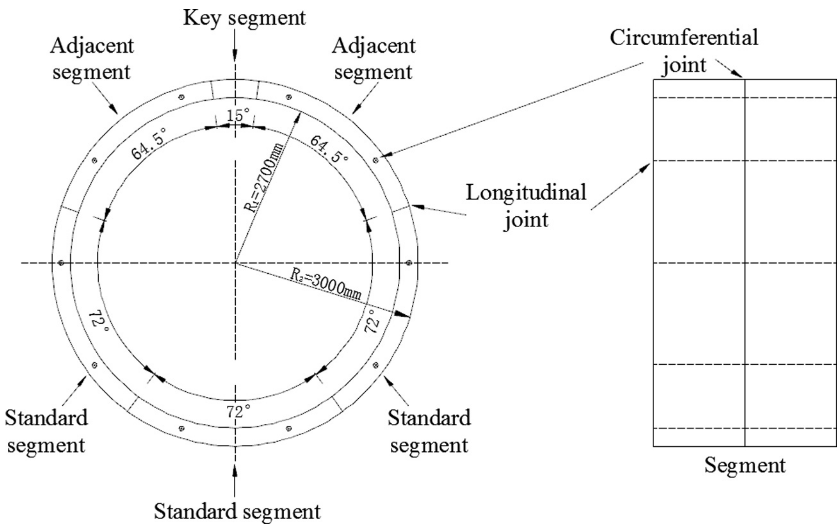

Fig. 1. Illustration of segmental lining.

on the basis of cylinder theory by using a 2.5D approximation. In the PiP model, a tunnel is assumed to be embedded in a full space soil. Based on the model, Hussein et al. (2006) established a model for analysing vibrations from railway tunnels in a half-space. The free surface effects on the propagation of vibration were studied. Sheng et al. (2003, 2004) presented a 2.5D model to analyse ground vibration due to vertical track irregularities. In their numerical models, the moving axle load and the vertical rail irregularities were both considered, however, these models only apply to circular tunnels. Clouteau et al. (2005) and Degrande et al. (2006) assume that cross-section of the tunnel-soil system along the tunnel axis direction is periodic rather than invariant so the Floquet transform can be applied. Only discretization of a single reference cell is needed in this model to solve the dynamic track-tunnel-soil interaction problem. Gao et al. (2015) assumed the wheel-rail-soil system to be a series of moving point loads on an Euler-Bernoulli beam resting on a visco-elastic half-space. Based on this assumption, numerical simulations of ground vibrations induced by high-speed trains were presented. In all of these numerical and analytical models, the tunnel lining is assumed to be a uniform cylinder.

Physical modelling is also widely used to study ground-borne vibration from an underground tunnel. The 1*g* (where *g* is Earth's gravity) experimental work presented by Tamura et al. (1975) and Asano and Kumagai (1978) can be considered to be the earliest physical models developed to study ground-borne vibrations from tunnels. Tamura et al. (1975) measured model tunnel deformations due to train induced dynamic load in a 1:100 scaled cut-and-cover tunnel-soil model. Asano and Kumagai (1978) performed a study on the propagation characteristics of ground-borne vibrations by testing a model of the Shinkansen tunnel buried in a loam layer. Both impulsive loading and harmonic excitation were applied to the tunnel. Trochides (1991) measured the dynamic response of box-type structures in a 1:10 scaled tunnel-soil-building model by using approximate impedance formulas and simple energy considerations at 1*g*. He found that the accuracy of the results depends on the distance of the structure from the tunnel, since the simple method obtains better estimation in small distances. Thusyanthan and Madabhushi (2003) presented a 1*g* experimental study to investigate the effects of the lining material on the tunnel and soil dynamic response. Vibration loads are applied on the ground surface by a dropping hammer and a motor. Both brass and plastic (PVC) lining were tested in the experiment. The peak particle velocity (PPV) of the tunnel and soil were calculated. The results shown that the impedance of the tunnel and soil has large influence on the energy transferred from soil to tunnel. Tsuno et al. (2005) studied the tunnel and soil dynamic response under railway induced vibration by centrifuge testing. The relationship between the material damping coefficient and excitation frequency were calculated from the centrifuge results. Yang et al. (2013a, 2013b) used centrifuge modelling to study the soil non-homogeneity effects on the propagation of ground-borne vibration from a surface source and an underground tunnel. A small shaker was placed onto a surface foundation and an underground tunnel to apply dynamic loads, respectively. The model responses at different locations were measured by accelerometers. The experimental results show that in order to have an accurate estimation of the soil dynamic response, it is important to consider the soil non-homogeneity effects.

Many field measurements have been conducted to study this problem. Degrande and Schillemans (2001) measured free field vibrations and track responses on the line L1 between Brussels and Paris. The measured ground vibration results were used for comparison with numerical predictions by Degrande and Lombaert (2001), Paolucci and Spinelli (2006) and Galvín and Domínguez (2007). Auersch (2005) conducted three field measurements of ground vibration due to trains running on the ballasted track near Würzburg. Test results showed that medium-frequency ground vibration is mainly affected by track irregularities. Ju et al. (2009) measured ground vibrations of the HSR-700T high speed train running on an embankment and in a tunnel with train speed of 270 km/h. Zhai et al. (2015) carried out a series of field measurements of ground vibration on the Beijing-Shanghai high-speed railway. The effect on time-domain peak values and frequency-weighted vertical acceleration levels of train speed and distance from the track centreline was investigated.

It is noted that the tunnel lining was commonly assumed to be a uniform cylinder to simplify this problem. However, this is not usually the case. Nowadays, shield machines are widely used for tunnel construction in urban areas. In a shield-drive tunnel, the lining is made up of precast segments which are connected together using bolts and dowels to form a complete ring (Fig. 1). Therefore, there are numerous circumferential and longitudinal joints between segments. The existence of these joints has an important influence on the stiffness and strength at the joint area and could significantly affect the dynamic behaviour of the tunnel lining (Klappers et al., 2006; Ye et al., 2014). At present, there is little knowledge about the effect of joints on railway induced ground-borne vibrations. Therefore, in this study, a series of physical model tests were conducted to explore the dynamic characteristics of segmental linings and to examine the joints effect on the lining behaviour. This paper is divided into three main sections. Section 2 provides details of the experimental modelling, followed by results and discussion (Section 3), and finally conclusions (Section 4).