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Impact of train speed on the mechanical behaviours of track-bed materials

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ABSTRACT

For the 30,000 km long French conventional railway lines (94% of the whole network), the train speed is currently limited to 220 km/h, whilst the speed is 320 km/h for the 1800 km long high-speed lines. Nowadays, there is a growing need to improve the services by increasing the speed limit for the conventional lines. This paper aims at studying the influence of train speed on the mechanical behaviours of track-bed materials based on field monitoring data. Emphasis is put on the behaviours of interlayer and subgrade soils. The selected experimental site is located in Vierzon, France. Several sensors including accelerometers and soil pressure gauges were installed at different depths. The vertical strains of different layers can be obtained by integrating the records of accelerometers installed at different track-bed depths. The experimentation was carried out using an intercity test train running at different speeds from 60 km/h to 200 km/h. This test train was composed of a locomotive (22.5 Mg/axle) and 7 "Corail" coaches (10.5 Mg/axle). It was observed that when the train speed was raised, the loadings transmitted to the track-bed increased. Moreover, the response of the track-bed materials was amplified by the speed rise at different depths: the vertical dynamic stress was increased by about 10% when the train speed was raised from 60 km/h to 200 km/h for the locomotive loading, and the vertical strains doubled their quasi-static values in the shallow layers. Moreover, the stress–strain paths were estimated using the vertical stress and strain for each train speed. These loading paths allowed the resilient modulus M_r to be determined. It was found that the resilient modulus (M_r) was decreased by about 10% when the train speed was increased from 100 km/h to 200 km/h. However, the damping ratio (D_r) kept stable in the range of speeds explored.

1. Introduction

Nowadays, there is a growing need to reduce travel time in railway transportation. On the other hand, most of the European railway networks are composed of conventional lines with a service speed limited to 220 km/h. In France, almost 94% of the operational lines are conventional ones (Duong et al., 2015). Several studies aiming to describe the effect of train speed on railway track-bed materials were conducted (Hall and Bodare, 2000; Madshus and Kaynia, 2000; Alves Costa et al., 2010; Ferreira, 2010; Hendry et al., 2013; Ferreira and López-Pita, 2015). It is recognised that it is important to well understand the mechanical behaviours of the materials constituting the track-bed in order to optimise the upgrading operations (Haddani et al., 2011). In this context, the "INVICSA" project was initiated by SNCF (French Railway Company) in 2011, aiming at studying the impact of train speed on the behaviours of conventional tracks. Note that the main difference of track-bed between the conventional and the new high-speed tracks is the presence of a heterogeneous "interlayer" below the ballast layer in the conventional track (Cui et al., 2014). This layer was created mainly by the interpenetration of ballast grains and subgrade soils (Trinh et al., 2012; Cui et al., 2013; Duong et al., 2014). The nature and thickness of the interlayer depend on the site-specific conditions as well as the loading history of track.

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Several authors studied the behaviours of track-bed materials under the effects of train passages (Bowness et al., 2007; Hendry, 2007; Powrie et al., 2007; Le Pen, 2008; Priest et al., 2010; Le Pen et al., 2014). Field monitoring is often adopted for this purpose (Hall and Bodare, 2000; Aw, 2007; Lamas-Lopez et al., 2014a). Fröhling (1997) studied the effect of spatial variation of track stiffness on track degradation. Aw (2007) studied the mud-pumping phenomenon in a track with saturated soft soils; larger surface deflections were measured when the subgrade was composed of soft soils, and there was a significant variation of pore pressure in the subgrade soil during train passing. A photo-sensitive array method was applied after some stability problems were observed in the presence of soft soils in the subgrade (Hendry, 2011; Hendry et al., 2010, 2013). It was also observed that the amplification of sleeper deflection increased with the increasing train speed, depending on the track characteristics and other subgrade mechanical properties such as damping ratio. Madshus and Kaynia (2000) analysed the relationship between the surface Rayleigh wave velocity and the amplification of track deflection, showing that the surface wave velocity was the key parameter in controlling the track deflections at a given train speed. Connolly et al. (2014) and Madshus et al. (2004) synthesised the influence of surface wave velocity on the deflection amplification. In addition, the track type is also an important factor for the amplification of deflection (Kempfert and Hu, 1999). Ballasted tracks are superior to slab tracks in amplifying the track-responses.

Some semi-analytical models were developed by Sheng et al. (2004) and improved by Alves Costa et al. (2015) to describe the track deflection amplifications. Finite element analyses were also conducted to investigate the influence of train speed on the behaviour of tracks (Kouroussis, 2009; Alves Costa et al., 2010; Connolly et al., 2013; Woodward et al., 2013). Some results showed a decrease of elastic modulus of track-bed materials with increasing train speed (Alves Costa et al., 2010).

In order to analyse the contribution of each track-bed constitutive layer to the settlement of a whole track, strain measurements using multi-depth deflectometers (MDD) or strain gauges were conducted (Fröhling, 1997; Hall and Bodare, 2000; Mishra et al., 2014). Comparisons between the displacements obtained with MDD and the integration of geophone records were made (Priest et al., 2010). Moreover, full-scale physical modelling was performed in several studies to analyse load amplifications considering the concrete slab effect (Chen et al., 2013a; Xu et al., 2013; Bian et al., 2014).

To the authors' knowledge, there have been few studies on the mechanical behaviours (stress and strain) of conventional track-bed materials at different train speeds based on site monitoring under cyclic loading conditions. Some interesting studies only involved numerical analysis of the effect of train speed on track-bed materials (Yang et al., 2009) or a comparison between the site and laboratory measurements (Hendry et al., 2013; Paixão et al., 2013) for investigating the cyclic behaviours of track-bed soils. In particular, the estimation of mechanical properties such as the resilient modulus based on the response of embedded sensors has not been attempted. In this study, the values of displacements were first determined by double-integrating the signals of accelerometers, allowing the determination of vertical strains of different layers. Then, with the values of stresses recorded at different depths, the stress–strain hysteresis loops were established for the interlayer and subgrade soils in the case when train ran at 6 different speeds from 60 km/h to 200 km/h. Finally, the evolution of kinematic variables (such as acceleration and displacement) and the mechanical responses (such as stress and strain) as well as their influences on the resilient modulus and damping ratio were discussed.

2. Site monitoring and test programme

The "INVICSA" project includes the development of one in situ full-scale experimental site on a conventional line. The experimental site was selected within the 30,000 km French conventional network (Cui et al., 2014; Lamas-Lopez et al., 2014b). The selection criteria involve the train speed limit (200 km/h, close to the maximum speed of 220 km/h on European conventional lines), the main characteristics of track (the alignment to have a similar loading level at both sides of the track, the cutting zone to analyse the effect of drainage system and soil saturation after rainy periods, the proximity to electrical connection for facilitating instrumentation) and the states of the rails and sleepers (with low maintenance operation rate since the last renewal works due to the good behaviour of the track under the existing traffic loadings at the site). The selected experimental site is located near Vierzon, France, at the kilometric point PK+187 of the line, connecting Orléans and Montauban. The instrumented section of the experimental site is 30 m long. Different sensors such as accelerometers, soil stress sensors and strain gauges on rail (used as triggers to register signals when trains were passing through) were installed at different depths and positions along the site. Vertical linear variable differential transformer (LVDT) sensors in contact with sleepers were also used in previous phases of this study to be compared with double-integrated accelerometer signals at similar positions. Representative cross and longitudinal sections of the track are presented in Fig. 1. The installation depths and distances between sensors are also indicated in Fig. 1. However, to facilitate the representation of sensors' positions in Fig. 1, the stress sensors appear under the opposite rail of accelerometer sensors' track-side, even though in reality all sensors were installed under the same track-side and underwent the same train loading.

The selected site was located in a cutting section of 2.5 m high with bi-block sleepers. The site consists of 50 cm fresh ballast of 31.5 mm–50 mm in diameter. The bottom of the fresh ballast corresponds to the depth of the drainage system. Beneath the fresh ballast there is a 40 cm thick interlayer (ITL) soil mainly composed of coarse grains mixed with fines. The ITL soil was formed by ballast attrition and interpenetration of ballast and subgrade (Trinh et al., 2012; Duong, 2013; Cui et al., 2014; Duong et al., 2015). The soils from the boreholes performed on the track during the sensor installation process were collected. The ITL soil consists of ballast grains and silty sand from the subgrade (SBG); about 10% grains are finer than 80 μm; the D_{50} (grain diameter obtained from the 50% of the total weight) is around 10 mm (see Fig. 2a). Below the ITL, there is a 20 cm deep transition layer (TL). The TL is composed of the same fines as in the ITL but the proportion of ballast grains (larger than 20 mm in diameter) is limited to 15%. The D_{50} of the TL is 1 mm (see Fig. 2a). The differences between ITL and TL in conventional French tracks were discussed in details in Duong et al. (2013) and Lamas-Lopez et al. (2016). The bottom of TL corresponds to the bottom of the drainage system (60 cm in depth). The SBG is composed of silty sand (Lamas-Lopez, 2016; Lamas-Lopez et al., 2016), which seems to be homogeneous for the first 3 m ($D < 2$ mm). The D_{50} of the SBG is 0.3 mm (see Fig. 2a). According to the Unified Classification System (USCS), the fines from ITL soil is a ML (low plasticity silt), while the ITL and SBG soils are CL (low plasticity clay) (see Fig. 2b). During the prospections, the water table was found stable, situated at $z = -1.2$ m in depth, corresponding to the beginning of the SBG and the bottom of the drainage system. A detailed analysis of a geotechnical characterisation of this site is shown in Lamas-Lopez et al. (2016). Note that although most of the load will impact the first meter of track (Selig and Waters, 1994; Lamas-Lopez, 2016), this study only focuses on these first layers.

The recorded data obtained from two embedded soil stress sensors and three embedded capacitive accelerometers were