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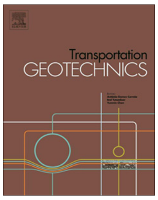

Three-dimensional numerical modelling of ballasted railway track foundations for high-speed trains with special reference to critical speed

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ABSTRACT

Due to recent congestion of highways in many countries around the world, railways have become the most popular means of public transportation, which has increased the demand for heavier and faster trains. High speeds and heavy loads of trains are usually accompanied with large vibrations in the train–track–ground system, especially when train speed reaches its critical value, leading to possible train derailment and track damages. This unwanted scenario makes it important for railway geotechnical engineers to investigate the behaviour of ballasted railway track foundations for high-speed trains, with special reference to critical speed. In the current paper, a sophisticated three-dimensional (3D) finite element (FE) modelling was developed to simulate the dynamic response of ballasted railway tracks subjected to train moving loads, and the critical speed was investigated for various train–track–ground system conditions. The results were presented in terms of the evolution of the coefficient of dynamic amplification of sleeper deflection versus train speed, which have been synthesized into simple sensitivity charts that can be used to determine the critical speed corresponding to the conditions of a particular train–track–ground system.

Introduction

The development of high-speed train (HST) networks is rapidly growing in many countries around the world to meet the increasing demand for faster transportation. For instance, the Japanese railways authority constructed the 4072 km long *Shinkansen* network for trains running at a speed of 320 km/h. Recently, using the magnetic levitation technology, the Japanese bullet train broke the world train speed record in a test conducted in 2015 for a train running at a blazing speed of 603 km/h (Wener-Fligner, 2015). On the other hand, China has the world largest HST network which is about 16,000 km long, and the Chinese railway authority expects that the train speeds in China will increase to up to 400 km/h in the near future. As train speeds continue to increase, new challenges and problems relating to the performance of railway foundations may arise, primarily due to the significant amplification effect of the train–track–ground vibration (Priest and Powrie, 2009; Wanming et al., 2010). The train-induced ground vibration is dictated mostly by the relationship between the train speed and the corresponding propagating wave velocity of the ground medium. The train speed at which the dynamic response of railway track and surrounding ground are intensely amplified and extraordinary large vibration occurs due to resonance is called the 'critical speed' (Krylov, 1994; Madshus and Kaynia, 1999;

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Yang et al., 2009). The tremendous increase of the vibration level associated with the critical speed is not only a possible source of detrimental environmental effect and human disturbance, but can also increase the risk of several train operation issues. These include the train safety, degradation/deformation of track foundations, fatigue failure of rails and interruption of power supply to trains (Madshus and Kaynia, 2000).

The adverse impact of high speed of trains invoked a flurry of research activities as manifested in the experience of the Swedish Rail Administration (SRA). In 1997, SRA (Banverket) started running the X-2000 passenger HST along the West Coast Line between Göteborg and Malmö. Just after commencing the service, excessive vibrations in the railway embankment and the surrounding soil were observed at the Ledsgard site (where the railway track was founded on soft soils). Inspection of the track revealed that the train speed approached the critical value (Woldringh and New, 1999), and the train speed was immediately reduced by the SRA authority as a consequence. This incident highlighted problems ensuing from the critical speed. Due to the practical significance of this matter, several efforts (e.g. Madshus and Kaynia, 1999; Kaynia et al., 2000) were made to understand the track responses and determine the optimum running speed of the X-2000 HST at the Ledsgard site using different empirical methods. Subsequent to this case study and long after, several analytical and numerical approaches were proposed by a number of researchers to assess the critical speed and associated issues (e.g. Grundmann et al., 1999; Sheng et al., 2004; Bian and Chen, 2006; Auersch, 2008; Bian et al., 2014; Alves Costa et al., 2015). However, to assess the critical speed of the train–track–ground system, most of the abovementioned studies considered cyclic loading or single wheel (or surface) moving load rather than true (dynamic) train moving loads. The drawback of assuming cyclic loading is that it does not consider the role of the principal stress rotation on behaviour of soil (Powrie et al., 2007, 2008). In addition, the consideration of a single wheel moving load is highly arguable as the actual loading regime of a running train is characterised by a series of wheel loads with different amplitudes and geometry (hence the role of frequency). These loading conditions are expected to produce critical speed conditions that are considerably different from those obtained from a monotonic or cyclic loading regime. Therefore, the actual train geometry and magnitude of individual axle load need to be accounted for in the analysis considering the critical speed, which will be the case in the current presented work.

In the current study, an advanced three-dimensional (3D) finite element (FE) numerical modelling is developed to simulate the dynamic response of railway track foundations under true train moving loads, with special reference to the critical speed. Various conditions of the train–track–ground system affecting the critical speed are investigated, including the nonlinearity of track material, modulus and thickness of track subgrade soil, amplitude of train loading and train geometry. The obtained results are synthesized into simple sensitivity charts from which the critical speed under various conditions of the train–track–ground system can be readily obtained. The paper also discusses the practical implications of the obtained outcomes on track design.

Numerical modelling of railway track foundation system

In this section, the dynamic response of railway track foundations subjected to train moving loads was investigated via 3D FE numerical modelling using the commercial software package Midas-GTS (MIDAS IT. Co. Ltd., 2013). It should be noted that the thrust of the numerical modelling performed in this study has been to investigate and produce sensitivity charts for the critical speed of trains under various conditions of the train–track–ground system. Therefore, it was critically prudent to ensure that the FE modelling process is capable of providing reliable outcomes. To this end, it was decided to perform an initial analysis on a case study that is well documented in the literature to ascertain that the model can reproduce field results of compiled measurements obtained from this case study. Then for the sake of simplicity and ease of simulation, another track with simplified substructure than that of the case study was adopted to investigate the critical speed and produce the sensitivity charts, as will be seen below.

Modelling of the X-2000 HST railway track at the Ledsgard site

The selected case study for initial analysis of the numerical modelling was for a ballasted railway track of the X-2000 HST at Ledsgard site just outside Göteborg (Hall, 2003). This case study was selected because it contains detailed description of all track components and material properties needed for the FE modelling, as well as field measurements of the track and ground vibration parameters.

Track geometry and materials

The geometry and subgrade profile of the X-2000 HST railway track at the Ledsgard site (Hall, 2003) are shown in Fig. 1a, whereas the 3D FE model developed to simulate the problem is depicted in Fig. 1b. The model dimensions are 80, 36 and 12 m in the longitudinal, horizontal and vertical directions, respectively. The rail was modelled using one-dimensional (1D) I-beam section running across the length of the modelled track. A *UIC*-60 section was assumed for the rail, which was fixed to the sleepers by rail pads characterized by an elastic link (spring-like) element of stiffness equal to 100 MN/m. All other track components (i.e. sleeper, ballast, interface and subgrade) were modelled using 3D solid elements. For model geometry, a total of 133 sleepers were placed along the rail at 0.6 m interval spacing. The rail and sleepers were considered as linear elastic (LE) materials, whereas the ballast and interface layer were modelled using elastoplastic Mohr–Coulomb (MC) materials. The subgrade (formation) soils (see Fig. 1a) were modelled using nonlinear materials in which the nonlinearity was taken into account via an equivalent