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Finite element model of ballasted railway with infinite boundaries considering effects of moving train loads and Rayleigh waves

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ABSTRACT

This paper proposes a three-dimensional model incorporating finite element (FE) meshes with infinite element (IE) boundaries for ballasted railways. Moving train loads are simulated with sliding motions of moving elements which have hard contact feature at the interface with supporting rails. Dynamic responses of ballasted railway under different train speeds are investigated in time domain and frequency domain to identify the predominant frequency and critical speed. Rayleigh wave (R-Wave) propagation is simulated using the combined FE-IE model to determine the velocity of R-Wave in the layered embankment model and its relationship with the critical speed of the ballasted railway. The proposed model is successfully validated against the results of Euler-Bernoulli Elastic Beam (E-BEB) model.

1. Introduction

With a growing demand for increasing train speeds and axle loads in railway transportation, the performance of widely used ballasted railway is requiring more extensive research matching the industry development. In addition to the laboratory [1,2] and field investigations [3], numerical simulation is becoming a promising alternative to evaluate and analyse the geotechnical behavior of railway track to aid decision making in terms of technical and economic feasibility.

At the present stage, most numerical simulations have a limited application with two-dimensional (2D) models and elastic geo-material properties [4,5], which could be appropriate for the static response of the railway. However, the actual loading conditions for railway tracks are rather dynamic and transient [6]. Vibrations of railway are amplified under increasing train speed especially when the critical speed is approached [7–9]. Therefore a more complex three-dimensional (3D) model is necessary which involves the interplay between components along the moving direction and reflects the dynamic effect. A number of studies presented 3D model studies on the response of railway during the train passage. Hall [10] used 3D finite element (FE) models with linear elastic material to analyse the train-induced ground vibration in both time domain and frequency domain. He concluded that 2D models could be used for certain effects of the ground vibration but the 3D analyses were necessary to achieve a better simulation. Sayeed [8] created 3D model for ballasted railway track foundation subjected to high-speed moving trains and the vertical boundaries were connected to viscous dampers to represent infinite boundary conditions. The study proposed a critical train speed at which the dynamic response reaches a peak and related it to the theoretical R-wave velocities of the geo-materials. These aforementioned 3D models applied triangular pulse distributed between three nodes of rail beam to simulate the moving point load. The railway induced vibrations involves three major components, viz. the train, the track structure (rails, sleepers, ballast and subballast) and the subgrade soil. The critical speed is identified when the speed is in the vicinity of the Rayleigh wave velocity of the ballasted foundation, which often exhibits large vibrations. This phenomenon is generally observed for soft soils [11].

Wu and Yun [12] employed dynamic FE model to simulate the dynamic response of railway due to action of multi-roller carriage under the high speed moving loads. Wu and Thompson [13] assessed vibrations of railway track with multiple wheels on the rail using FE model. Salleb and Kumar [14,15] presented an alternative solution of structural dynamic problems of moving load with three approaches, (i) moving mass, (ii) moving load and (iii) moving oscillator (sprung mass), and contact feature were used to simulate the sliding motion. The demonstrated numerical examples validated the implementation of the solution in the large-scale finite element software.

Due to the large scale of railway model (such as size of

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80 m × 36 m × 12 m [8] and 285,000 elements [16]) and the complexity of applying moving train load with triangular pulses [8,10], the numerical simulation of the ballasted railway usually consumes a large amount of time or requires high configurations of the computer. The huge cost hinders the extensive use of 3D models for accurate simulation of ballasted railway under moving train loads. However, assuming continuity in loading and geometry along the track longitudinal direction often yields unrealistic stress distribution in 2D FE analysis employing plane strain condition.

This paper proposes a 3D FE model suitable for economic application of the large amount of numerical analyses using a commercially available software package ABAQUS, version 6.14 [17]. The model incorporates the infinite element (IE) for boundaries surrounding the FE meshes in order to reduce the model scale and eliminate the wave reflection at the boundaries which interferes the main domain simulation. Moving train loads are applied on the rails by sliding motions of moving elements with hard contact feature at the interface. Dynamic responses are investigated in the time domain and frequency domain. Comparisons are made between the models under different train speeds to investigate the characteristics of dynamic responses in the frequency domain with the increasing train speeds. Using the combined FE-IE model, Rayleigh wave is simulated and the velocity is measured in a half-space model with homogeneous material and a layered model with granular embankments (ballast, subballast) and subgrade layers.

2. Modelling of finite element ballasted railway with infinite element boundary

A ballasted railway with geometrical dimensions in Fig. 1 is analysed as a demonstration of the proposed model. The model is composed of (from the top) train wheels, steel rails, concrete sleepers, ballast layer, subballast layer and subgrade layer. A 3D model implemented in ABAQUS is demonstrated in Fig. 2, combining FE domain and IE boundaries. Due to half symmetry, the model is established with the symmetrical boundary at the centre surface between two steel rails. In the FE domain, layers of the track section were modelled using 4-noded tetrahedral elements with reduced integration (C3D4R) and 8-noded linear brick elements with reduced integration (C3D8R). The shape functions are the same as for the C3D4 and C3D8 elements and can be found in [18,19], respectively. Train wheels are treated as rigid bodies. For economy, finer meshes are created close to the sleepers and coarser meshes are gradually made towards far boundaries. The finite element meshes are surrounded by the infinite elements at the bottom and side boundaries for absorbing stress waves at boundary surfaces. The half model has 59,707 elements in total.

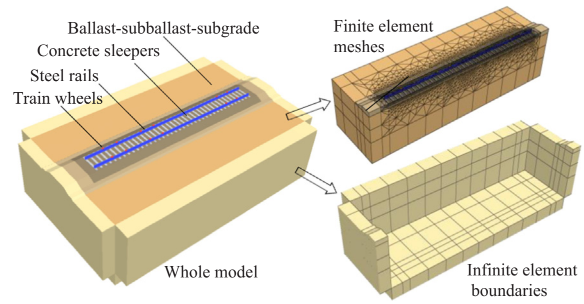

Fig. 2. Modelling of ballasted railway rail.

A steel rail is constrained at the bottom to the top surface of sleepers. The interaction between sleepers and the surrounding ballast is set to be "hard contact" together with a friction of "rough". Each train wheel is simulated by a rigid body element located at the top of the steel rail with the interaction of "hard contact" together with "frictionless" to simulate the wheel moving. The block is subjected to a wheel load $F = 125$ kN (representing an axle load of 25 t) and moved at a specific speed along the rail. Eight moving carriages are involved with total 32 wheels moving onto the rail one after another at designated distances between each other as per the train configuration adopted in this study shown as an inset (refer Fig. 1).

Table 1 summarises the material properties for each component in the model. Steel rail and concrete sleepers are simulated as elastic materials. The geo-materials including ballast, subballast and subgrade are adopted as elastic materials or elastic-perfectly plastic materials following Mohr-Coulomb (MC) failure criterion using drained shear strength parameters. The comparison of results using such different approaches is shown in subsequent sections. The numerical analyses are carried out using explicit time integration approach.

3. Responses of ballasted railway under moving train load

Different train speeds ranging from 100 km/h to 440 km/h have been analysed using the proposed combined FE-IE model. Under a specific train speed V, a basic frequency f_1 can be defined by

$$f_1 = V/L \quad (1)$$

where L is the carriage length (refer to Fig. 1). It is apparent that f_1 is relatively low because L is usually large. The basic frequency f_1 is assumed to represent the frequency characteristics of the response of geo-materials in a number of studies in the past [7,20–23]. This view will be

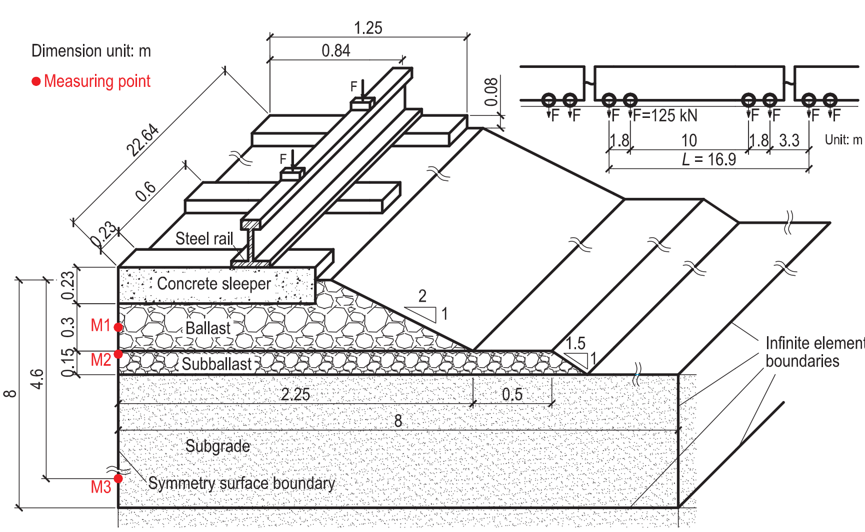

Fig. 1. Geometrical dimensions and physical components of ballasted railway model.