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# A 3D BEM-FEM methodology for simulation of high speed train induced vibrations

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**Abstract**

This work presents an efficient methodology for the analysis of vibrations in a railroad track system, induced by the passage of conventional and high-speed trains. To this end the Boundary Element Method is used to model the soil-tie system within the framework of impulse response techniques. Conventional Finite Element Methods along with Newmark's integration is used for the modeling of the rail system. The two methods are coupled at the tie-rail interface and the solution is obtained following a staggered, time marching scheme in an efficient manner. The methodology accounts for Soil-Structure Interaction and traveling wave effects. In addition, this work identifies the parameters that affect the efficient modeling of railroad track systems as they pertain to the proposed solution methodology.


*Keywords:* High-speed trains; Soil-structure interaction; Boundary element methods; Impulse response

## 1. Introduction

High-speed rail transportation is quickly becoming a popular form of mass transit throughout the world. Train technology has been evolving in Asia and Europe over the past four decades, improving train efficiency and speed. Meanwhile, plans are being made in the United States for several high-speed rail systems to be constructed over the next several decades. The definition of high-speed trains (HST) typically suggests a passenger train traveling in excess of 160 km/h (100 mph), though HST's may travel as fast as 300 km/h (186 mph). As the train speeds continue to increase, potential problems arise. In particular, HSTs traveling over soft soils having relatively low wave velocities, as compared to HST speeds, may cause excessive vibrations in the track systems, train suspension, and nearby structures. In the present work, HSTs traveling at speeds below the soil's shear wave velocity are described as traveling at subcritical speeds. Train speeds equal to the shear wave velocity in the soil are termed critical speeds, and supercritical speed refers to trains traveling at speeds in excess of the soil shear wave velocity. Trains moving at subcritical speeds generally do not produce unexpected large vibrations. However, the vibrations may become problematic as the train speed increases to critical or supercritical levels. In such cases, a compressed wavefront field is generated that travels through the soil and arrives at a monitoring point concurrently with, or after the passage of, a HST. Such an event is equivalent to a sonic boom and indicates a strong presence of dynamic Soil-Structure Interaction (SSI) phenomena. These vibrations may contribute to the passenger discomfort, or they could potentially cause serious damage to the track and train. Additionally, nearby structures experience the effects of the vibrations causing discomfort and a sense of an unsafe environment to the occupants. Unfortunately, it is difficult to circumvent soft soil sites since tracks must be placed in nearly straight paths in order to maintain large turning radii to avoid high centripetal accelerations on the train and passengers.

Modeling of SSI effects is generally accomplished using Finite Element Methods (FEM), Boundary Element Methods (BEM) or hybrid techniques. The use of FEM is advantageous as the procedures are general in nature and well-established among others [1,2]. Matrices generated using FEM procedures are sparse and symmetric allowing for the use of efficient solution techniques. Drawbacks of the FEM appear in problems that require modeling of infinite

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domains. Since the discrete domain size is finite, the radiation boundary conditions at infinity must be taken into consideration through non-standard FEM techniques to prevent spurious modes due to boundary reflections from participating in the solution [3]. Alternatively, the infinite soil region can be modeled using Boundary Element Methods where the radiation condition at infinity is implicitly satisfied in the associated Boundary Integral Equations. Comprehensive literature reviews on BEM formulations have been reported by Beskos [4] and Mackerle [5,6]. Coupling the BEM and FEM methods retains the advantages of each method and eliminates their shortcomings. Such studies have been reported in the literature for problems in dynamic and seismic analysis of coupled soil-structure systems involving stationary loads [3,7,8].

Availability of experimental data and in situ measurements on HST induced vibrations is limited. Degrande and Shillemans [9], Kaynia, et al. [10], Madshus and Kaynia [11], Hall [12], and Sheng et al. [13] have presented in situ measurements recorded from track sites in Europe. Much of the available research reported in the literature on this topic is based on analytic and numerical techniques, such as in the work of Bode et al. [14], Hall [12], Ekevid and Wiberg [15], Yang et al. [16], Ekevid et al. [17], and Mohammadi and Karabalis [18], among others.

This work presents an efficient direct time domain solution approach to study the transient response of a soil-track system due to passage of HSTs through computer simulations. To this end, the well-established Boundary Element Method and Finite Element Method are coupled in the direct time domain. An efficient coupling scheme originally introduced in Rizos and Wang [3] is further developed to accommodate moving loads. Improvements of the efficiency of the numerical solution process are proposed in this work based on impulse response techniques, normalization and scaling procedures. A series of parametric investigations identify the parameters that contribute significantly to the proper modeling of the problem under consideration. A comparison of numerical results with in situ measurements reported in the literature demonstrates the applicability of the proposed method.

## 2. System idealization and models of constituent domains

The physical system under consideration consists of a straight steel track supported on concrete ties, which in turn, rest on the foundation soil. The vehicle dynamics of the HST are ignored in the present study. The BEM is applied on the soil region and considers the kinematic interaction with the ties, in order to account for the traveling wave effects, and the through the soil interaction of adjacent ties. The FEM method is used for the modeling of the rails. The two solution domains are coupled at their interface, i.e. the tie-rail contact points. A diagram of the system is shown in Fig. 1, and the models of the constituent domains are discussed next.

### 2.1. Soil-tie model

The soil region is modeled as homogeneous linear elastic half space with a horizontal free surface. The ballast and sub-base are not considered, however, they can be accommodated in the proposed method in a straightforward manner. Hence, ties are assumed to rest directly on the free surface of the halfspace with which they remain always in contact. A reference soil having a relatively high shear wave velocity is used in the analysis, whereas the effects of soils of various properties are accounted for through a mere scaling operation of the system response of the reference soil and discussed in Section 3.1.1. The ties are considered to be rigid and only kinematic interaction effects are accounted for in the soil-tie model. Inertia interaction effects due to the tie's mass are accounted for in the track-rail model and the FEM solution. The tie's dimensions are 2.5 m long × 0.285 m wide with center to center spacing of 0.955 m, yielding an edge-to-edge spacing of 0.67 m

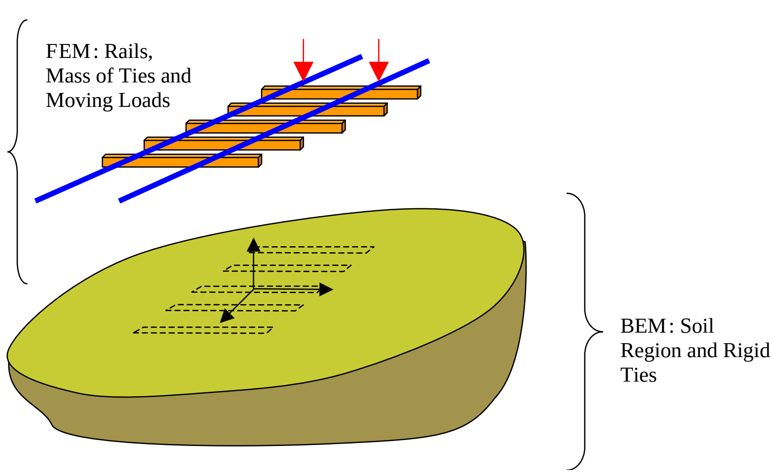


Fig. 1. Models of constituent domains.