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Research Paper

# Dynamic subsoil responses of a stiff concrete slab track subjected to various train speeds: A critical velocity perspective

Ernest Nsabimana, Young-Hoon Jung *

*Dept. of Civil Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-Si, Gyeonggi-Do 446-701, Republic of Korea*

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ABSTRACT

The advent of new high-speed trains with increased operation speed has made the slab track structure a viable alternative to the traditional ballast track. However, the high rigidity of the stiff slab layers that replaces the ballast material make the dynamic responses of concrete slab tracks very different to those generally expected in ballast tracks. Inclusion of stiff layers between the rail and subsoil in a concrete slab track obscures understanding of dynamic subsoil responses with respect to theoretical critical velocity. In this study, we systemically investigated the dynamic responses of the concrete slab track to various train speeds and subsoil stiffnesses. A complete finite element model including the vehicle, rail, track, and subsoil in two dimensions was developed. Numerical results revealed that the degree of retardation of the elastic strain energy related to the critical velocity for the subsoil dominated the delayed arrival of the peak vertical displacement, thereby expanding the hysteretic loop of the stress paths, resulting in erratic distribution of the elastic strain energy in the subsoil.

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## 1. Introduction

Despite the advent of new high-speed trains and the use of concrete slab tracks, the design philosophy of railways still relies greatly on the traditional framework based on the theory of a beam on springs [1–3]. For traditional ballast tracks, the ballast material bears the rail, which is subjected to moving trains. In modern slab tracks, reinforced concrete plates replace the ballast layer as a bearing component against static and dynamic forces from the train. Overall responses in ballast and slab tracks should be different, whereas the current structural design of both tracks only requires a representative spring constant to model the boundary condition of the subsoil [3–6]. To determine this spring constant, the subsoil is frequently assumed to show linear elastic behavior based on the notion of sufficiently low amplitude dynamic stresses induced by a moving train.

Limit state performance of railway tracks has been assessed by estimating the critical velocity and its related dynamic behaviors. It is believed that the track resonantly responds at the train speed of the critical velocity, resulting in maximum amplification of displacement and vibration [7]. Theoretical studies [8–11] have revealed that this phenomenon can occur when the train speed exceeds the phase velocity of waves in a homogeneous elastic half-space. However recent analytical and numerical studies reported the influence of the track, layered ground and vehicle parameters on the critical velocity.

Costa et al. [7] studied the influence of the ground layers and the properties of the track-ground system on the critical velocity via semi-analytical and 2.5 FEM-BEM approaches. The results showed that the critical velocity of the ballast track is quite similar to that of the slab track and is slightly less than the Rayleigh wave velocity in the homogeneous ground. In the layered ground, however, the critical velocity of both types of track depends on the characteristics of ground layers as well as the mechanical properties of the track-ground system.

Kouroussis et al. [12] investigated numerically the influence of vehicle and track parameters on ground vibrations induced by the railway traffic in the ballast track. They observed that the vehicle speed has a strong influence on the ground vibrations notably when the train speed becomes larger than the Rayleigh wave velocity of the ground. In their subsequent study on the ballast track, Kouroussis et al. [13] showed that in the homogenous ground the vibratory level notably increases at the train speed larger than the Rayleigh wave velocity, whereas the critical velocity in the layered ground is influenced by the depth of the layers and their dynamic characteristics.

Sheng et al. [14] conducted a theoretical study on the critical velocity of the track-ground system. Using analysis of the

* Corresponding author. Tel.: +82 31 201 2574; fax: +82 31 202 8854.
*E-mail addresses:* nsabimana@khu.ac.kr (E. Nsabimana), jyounghoon@khu.ac.kr (Y.-H. Jung).

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dispersion characteristics and receptances curves for the response of the track-ground systems, they revealed that for increasing track stiffness or decreasing track mass the critical velocity increases and becomes much higher than the Rayleigh wave speed of the upper layer in the layered ground.

For ballast tracks, the critical velocity calculated by existing simple theories appears to be practically reasonable, because the stiffnesses of the ballast and subsoil materials are fairly low compared to those of other track components, such as the rail. For concrete slab tracks, however, it is doubtful whether the same calculation of critical velocity is applicable, because the concrete slab plates that replace the ballast material have a much higher stiffness than the subsoil. To the best of our knowledge, no specific study has investigated the dynamic behaviors of the concrete slab track with respect to critical velocity.

To investigate the dynamic responses of a concrete slab track, we performed 2-dimensional finite element analyses. A complete 150-m long vehicle-rail-track-subsoil system was modeled in a single configuration. A simple vehicle model accounting for the interaction between the wheels and rail was implemented. Theoretical aspects of critical velocity in the railway track were considered. We investigated dynamic responses in vertical displacement, stress path, and strain energy for train speeds from 100 to 700 km/h and a wide range of subsoil stiffnesses.

## 2. Finite element model of the track and vehicle

In this study, the concrete slab track for the Korean high speed line between Osong and Kwangju, of which the design concept originates from German Rheda 2000, was modeled numerically using a FEA software, ABAQUS [15]. Following the German Rheda system, sleepers are embedded in the upper track concrete layer (TCL), which is supported by a hydraulically stabilized base (HSB). The reinforced roadbed (RRB) is placed beneath two concrete layers. The rail on the track is supported by concrete sleepers placed at 0.65-m intervals. Korean concrete slab track is characterized by inclusion of a roadbed layer between the upper two concrete layers and the subsoil layer.

Total length of the simulated track with a thickness of 4.2 m was 150 m. The finite element mesh of the railway track used in this study is illustrated in Fig. 1. The rail with UIC60 sectional properties [16] was modeled by Timoshenko beam elements [17] in a 2-dimensional plane. The beam elements for the rail were completely tied to the surface of the solid elements representing the 0.65 m-spaced discrete sleepers. Except for the rail, every component in the track, such as the TCL, HSB, and subsoil, were modeled by 2-dimensional continuum elements under the plane-strain condition. To remove unfavorable reflections of stress waves at the displacement boundaries, infinite elements [15,18] were applied to both lateral and bottom sides of the track model, as shown in Fig. 1. Similar cases of two-dimensional models can be found in Yang et al. [19] and Lee et al. [20]. It is worth noting that in dynamic analysis using ABAQUS, viscous boundaries are automatically applied at the border between finite and infinite elements [21]. Readers who have an interest in the viscous boundaries efficiency in the dynamic analysis can refer to Kouroussis et al. [22] who corrected the expressions that were initially developed by Lysmer and Khulemeyer [18] and adopted in the formulation of infinite elements under ABAQUS.

All materials used for the track and rail in this study were assumed to be linear elastic. The material properties of each component are summarized in Table 1. The effect of the magnitude of subsoil stiffness was investigated by varying the Young's modulus of the isotropic elastic material of subsoil from 10 MPa for very soft soil to 180 MPa for stiff soil.

In order to compare the response of the concrete slab track with that of the traditional ballast track at the critical velocity, supplementary simulations of a ballast track model were conducted. To build a FE mesh of ballast tracks, the TCL and HSB layers of the slab track in the existing mesh were replaced by ballast layer and the RB layer was replaced by subballast layer. For comparison, the same scenario with varying Young's modulus of the subsoil from

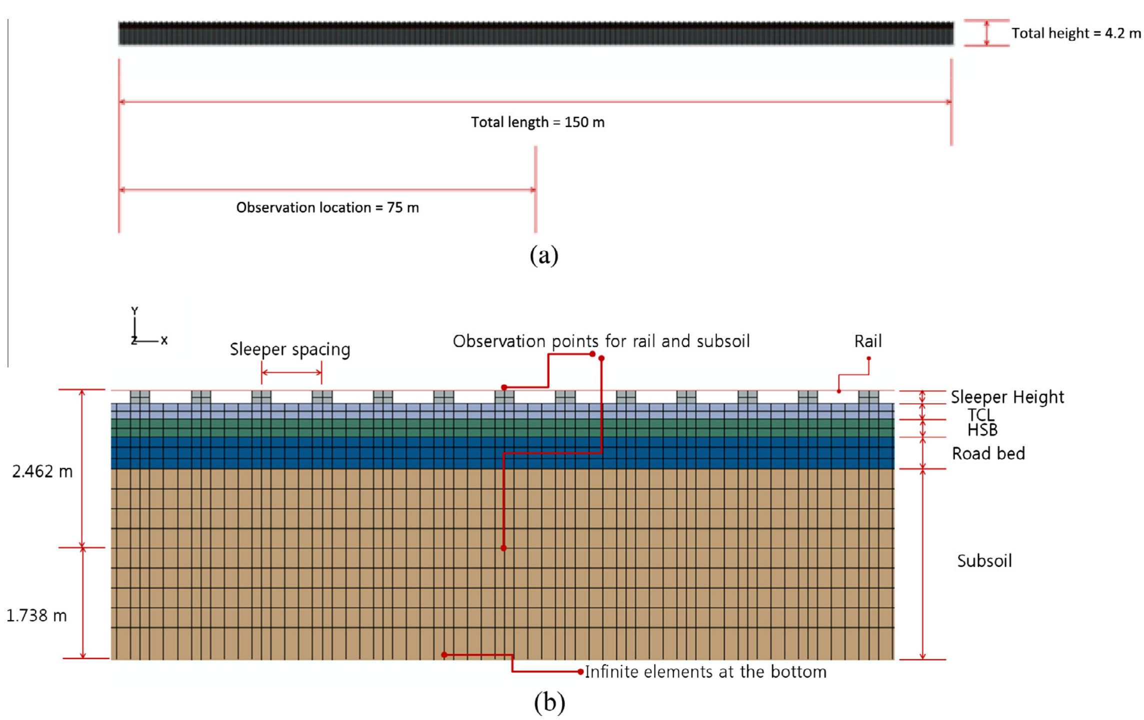


**Fig. 1.** Finite element mesh for simulated track structure: (a) full dimension; (b) detailed meshes.

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