

Dynamic characteristics of ballastless track and numerical modeling for high-speed railway application in Vietnam

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Abstract

Ballastless track systems are increasingly adopted in high-speed railway networks due to their high structural stiffness, long service life, and reduced maintenance requirements. However, their performance is strongly influenced by subgrade conditions and environmental effects, which are particularly critical in regions with soft soil and tropical climates such as Vietnam. This paper presents an overview of ballastless track structures and their dynamic characteristics, and proposes a numerical modeling framework for analyzing the coupled vehicle–track–subgrade system. The proposed model provides a basis for evaluating the applicability and long-term performance of ballastless track in future Vietnamese high-speed railway projects.

Keywords: Ballastless track, slab track, high-speed railway, vehicle–track interaction, dynamic analysis, soft subgrade

Introduction

High-speed railway has become an essential component of modern transportation infrastructure. Countries such as Japan, China, France, and Germany have successfully implemented high-speed rail systems with operating speeds exceeding 300 km/h. One of the key technological developments supporting these speeds is the adoption of ballastless track systems.

Vietnam is currently planning the development of a North–South high-speed railway corridor. Due to the high construction cost and long design life of high-speed rail infrastructure, the selection of track structure plays a critical role in ensuring safety, durability, and economic efficiency. Ballastless track is considered a promising solution; however, its applicability under Vietnam’s soft soil conditions and tropical climates must be carefully investigated.

Structure Of Ballastless Track

Ballastless track replaces the traditional ballast layer with a rigid or semi-rigid concrete slab, resulting in a stiffer load transfer path and improved track geometry stability.

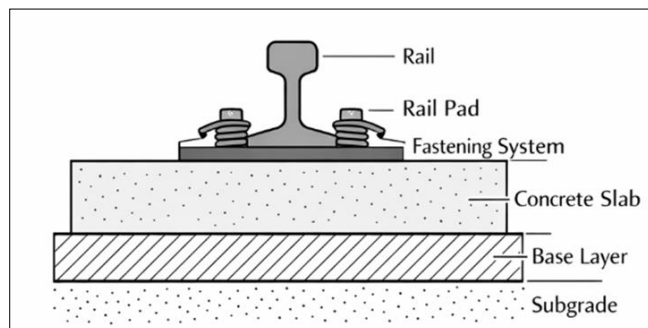


Fig 1. Typical structure of ballastless (slab) track system

A typical ballastless track consists of:

- rail
- fastening system
- rail pad
- reinforced concrete slab

- base layer
- subgrade

The absence of ballast reduces maintenance requirements but increases the sensitivity of the system to foundation deformation and thermal stress.

Dynamic Characteristics Of Ballastless Track

1. Rail vibration model

The rail is modeled as an Euler–Bernoulli beam resting on an elastic foundation:

$$EI \frac{\partial^4 w}{\partial x^4} + m_r \frac{\partial^2 w}{\partial t^2} + c_r \frac{\partial w}{\partial t} + k_r w = P(x, t)$$

EI – rail bending stiffness

m_r – rail mass per unit length

k_r – foundation stiffness

This formulation is widely used in vehicle–track dynamic analysis.

Challenges In Vietnamese Conditions

Vietnam’s geological profile is dominated by soft clay deposits with low bearing capacity and high compressibility. These conditions may cause:

- excessive settlement
- differential deformation
- increased slab stress
- reduced ride comfort

In addition, tropical climate leads to significant temperature gradients in concrete slabs, which may induce thermal curling and additional stress.

Research Methodology

The study adopts a combined analytical and numerical approach:

1. Development of a theoretical vehicle–track dynamic model

2. Construction of a finite element model of ballastless track
3. Parametric study on subgrade stiffness and train speed
4. Evaluation of applicability to Vietnamese conditions

Coupled Vehicle–Track Dynamic Model

1. Vehicle model

The railway vehicle is represented as a multi-body system consisting of:

- car body
- bogies
- wheelsets
- primary and secondary suspensions

The governing equation of motion is:

$$M_v \ddot{q}_v + C_v \dot{q}_v + K_v q_v = F_w$$

2. Track and subgrade model

The ballastless track is modeled as a layered system, where:

- rail → beam elements
- slab → plate elements
- subgrade → elastic foundation

The equivalent stiffness of the support system is:

$$k_{eq} = \left(\frac{1}{k_{pad}} + \frac{1}{k_{slab}} + \frac{1}{k_{sub}} \right)^{-1}$$

3. Coupled system formulation

The complete vehicle–track system is expressed as:

$$M \ddot{q} + C \dot{q} + K q = F(t)$$

Where M , C , and K are the global mass, damping, and stiffness matrices.

4. Moving load model

Wheel loads moving at speed v are represented by:

$$P(x, t) = \sum_i P_i \delta(x - vt - x_i)$$

This allows investigation of resonance and dynamic amplification at high speed.

Schematic of Vehicle–Track Interaction

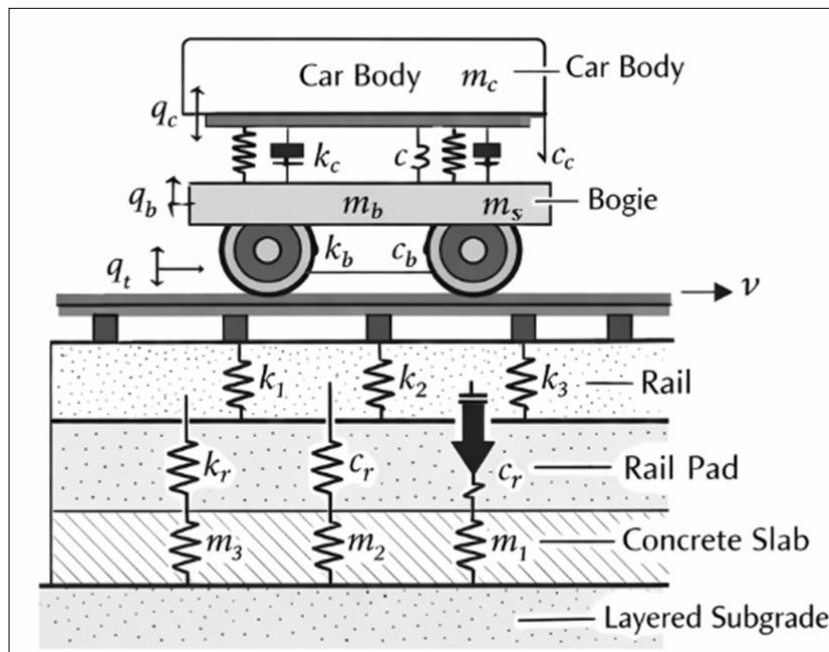


Fig 2. Coupled vehicle–track dynamic model

The model includes the car body, bogie, wheelsets, rail, rail pad, concrete slab, and layered subgrade. Springs and dampers represent suspension and foundation stiffness.

This schematic serves as the basis for numerical implementation in finite element software.

Discussion

Ballastless track provides excellent geometric stability and reduced maintenance; however, its high stiffness results in higher dynamic forces transmitted to the subgrade. In soft soil regions such as the Mekong Delta and Red River Delta, these forces may lead to

excessive deformation and long-term performance issues.

The proposed numerical model enables systematic evaluation of these effects before large-scale implementation of ballastless track in Vietnam.

Conclusions

This paper presented:

- an overview of ballastless track structure
- theoretical formulation of vehicle–track dynamics
- and a proposed modeling framework for Vietnamese conditions

The study demonstrates that ballastless track can be a viable solution for high-speed railway in Vietnam, provided that detailed dynamic analysis and subgrade improvement measures are incorporated into the design process.

References

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