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# Dynamic responses of subgrade under double-line high-speed railway

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## ABSTRACT

The majority of high-speed railways around the world is in China and more than 90% of the high-speed railways in China are double-line. At present, studies on the dynamic responses of subgrade under double-line high-speed railways are quite limited due to the complexity of these railways. In this study, a three-dimensional finite element model was developed using ABAQUS software for a double-line ballastless track-subgrade system subject to 8-carriage moving constant loads. The dynamic responses (specifically the vertical stress, displacement, velocity and acceleration) were determined at three points on the subgrade surface (Point A, Point B, and Point C) for trains travelling at different speeds (250, 300, and 360 km/h) and line patterns (unidirectional and bidirectional operations). The vertical stress distributions at selected points on the subgrade surface at these train speeds and line patterns are presented, and the vertical stress distributions along the soil depth of the subgrade at Point A and Point B are discussed. The key findings of this study are as follows. The maximum vertical displacement at the three observation points decreases as the train speed increases whereas the absolute maximum vertical velocity slightly increases as the train speed increases. In bidirectional operation, the maximum vertical stresses occur under the rails on the subgrade surface and the stress distributions are asymmetric. At Point A (point on the subgrade surface underneath the left rail in the left line), the vertical stress decreases along the soil depth and the vertical stress attenuation is more pronounced for bidirectional operation. However, at Point B (point at the centre of the subgrade surface), the vertical stress increases along the soil depth. The vertical stresses at Point A and Point B tend to be close to one another with an increase in soil depth such that the values are nearly coincident in the embankment layer within the range of train speeds investigated in this study.

## 1. Introduction

Nowadays, there is a great interest in the construction of high-speed railways worldwide, and high-speed railways have been built to connect major cities in countries in Asia and Europe, making travelling easier for passengers. While high-speed trains enable passengers to arrive at their destination faster, the high speeds also lead to several problems in the sub-systems of high-speed railways, which will threaten passenger safety. This is indeed evident from the statistics of accidents that occur on high-speed railways. In 1998, the Inter City Express (ICE) derailed near the village of Eschede, Germany, due to fatigue fracture of the double hub wheel of the high-speed train under dynamic loads. In 2000, two pairs of wheels of a Eurostar high-speed train travelling at full speed (300 km/h) derailed because of the uneven subgrade, resulting in 14 casualties. In 2004, a brand-new high-speed train was overthrown in Turkey as a result of derailment, which is likely because the old rail was not suitable for the new high-speed train. In 2013 and 2015, an AVE Talgo high-speed train and a TGV high-speed test train derailed as the trains sped around the corner. All of these train accidents indicate that it is crucial to investigate the performance of high-speed railway systems (i.e. train, track, and subgrade) under dynamic loads.

At present, the main models of high-speed trains comprise the Shinkansen series (Japan), TGV series (France), Eurostar series (United Kingdom), ICE series (Germany), AVE series (Spain), and CRH series (China) with axle loads ranging from 11.3 to 20 t. There are two types of track structure: (1) ballasted track and (2) ballastless track. Ballastless tracks provide smoother, comfortable ride, superior durability, and lower maintenance compared with conventional ballasted tracks. Therefore, ballastless tracks are typically used for high-speed railways with train speeds of 250 km/h and above. Subgrade is the subsystem of high-speed railways with a relatively small stiffness and it serves as the foundation for the train and track structure. The stress distributions of the subgrade structure subject to dynamic loads (particularly, high-speed dynamic loads) are intrinsically complex. The safety of high-speed railway systems will be greatly affected if the dynamic responses of the subgrade structure exceed permissible limits.

Studies on the dynamic responses of subgrade structures can be

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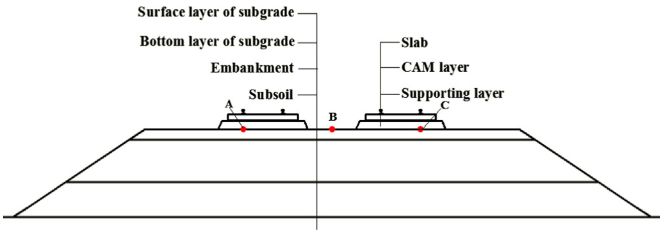

**Fig. 1.** Cross section of the Beijing-Shanghai double-line low-embankment high-speed ballastless slab track railway.

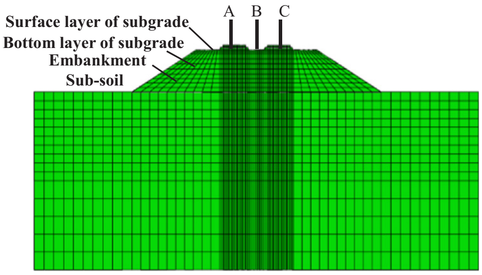

**Fig. 2.** FE model of the double-line ballastless track-subgrade structure.

**Table 1**
Key simulation parameters of the ballastless track-subgrade structure.

| Type | $E$ (MPa) | $\mu$ | Density (kg/m$^3$) | Internal friction angle (°) | Cohesive strength (kPa) |
|---|---|---|---|---|---|
| Rail | 210,000 | 0.3 | 7800 | | |
| Slab | 35,000 | 0.16 | 3000 | | |
| CAM layer | 92 | 0.4 | 2000 | | |
| Supporting layer | 30,000 | 0.16 | 2700 | | |
| Surface layer of subgrade | 400 | 0.3 | 2400 | 35 | 70 |
| Bottom layer of subgrade | 250 | 0.3 | 1920 | 32 | 60 |
| Embankment layer | 250 | 0.3 | 1900 | 28 | 50 |
| Ground | 40 | 0.3 | 1800 | 25 | 30 |

**Table 2**
Simulation cases.

| Case | Line pattern | Graphical representation | Train speed (km/h) |
|---|---|---|---|
| 1 | Unidirectional operation | Single-line | 250 |
| 2 | Bidirectional operation | Double-line | 250 |
| 3 | Unidirectional operation | Single-line | 300 |
| 4 | Bidirectional operation | Double-line | 300 |
| 5 | Unidirectional operation | Single-line | 360 |
| 6 | Bidirectional operation | Double-line | 360 |

divided into three categories: (1) theoretical studies, (2) experimental studies, and (3) numerical simulations. Theoretical studies are focused on the development of different subgrade models using analytical methods. In earlier theoretical studies, the entire subgrade structure was treated as an elastic half-space body.

Jones et al. [1] used the dynamic stiffness matrix method to investigate the attenuation of ground vibrations, where the ground was modelled as an elastic half-space body. Krylov [2] adopted the Green function method to study the effect of train speed on the ground dynamic response. Dieterman et al. [3] determined the equivalent stiffness of an elastic half-space body (sub-soil) using Fourier transform in the spatial and temporal domains and the results showed that the critical velocity results in resonance. Grundmann et al. [4] defined the sub-soil as a layered half-space body and analysed its dynamic response using the wavelet transformation method.

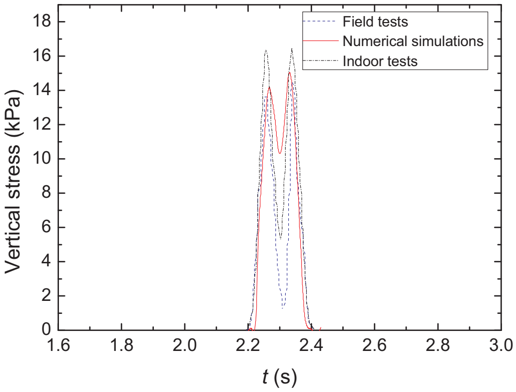

**Fig. 3.** Vertical stress-time history curves at Point A.

Due to the fact that the actual soil is not a completely elastic material, the elastic half-space model is gradually superseded by the viscoelastic foundation model. Hung et al. [5] studied the dynamic response of viscoelastic ground subjected to dynamic loads by using the Helmholtz potential and Fourier transform method. Alshaikh *et al.* [6] obtained the stress-time history curves at various locations using a two-dimensional layered viscoelastic model developed using Fourier transform with the method of characteristics. Bitzenbauer et al. [7] developed a layered viscoelastic subgrade model and studied its dynamic response using the Fourier transform method.

The emergence of coupling models have enabled researchers to obtain more accurate results on the dynamic responses of subgrades. Kaynia et al. [8] developed a track-ground coupling model, where a viscoelastic beam was used to simulate the embankment. The dynamic response of the subgrade was analysed based on the discontinuous stiffness matrix of the soil and the substructure principle. Takemiya et al. [9] developed a track-ground coupling model and studied its dynamic response using fast Fourier transform (FFT) and the results showed that the ground dynamic response was solely related to the characteristics of the vibration source. Sheng et al. [10] developed a vehicle-track-ground model and analysed the ground vibrations at various train speeds using Fourier transform.

With advances in experimental methods over the years, field tests and indoor physical model tests have become an indispensable means to investigate the dynamic responses of subgrade. Experimental techniques have advanced from low speeds to high speeds, ballasted tracks to ballastless tracks, and small-scale to large-scale models.

Tests have been carried out to determine the dynamic stresses of subgrade of an existing railway renovation project in Germany [11] and the results showed that the mean dynamic stress is significantly lower for the subgrade under ballastless track compared with that for the subgrade under ballasted track. Okumura et al. [12] analysed the test data of a Japanese railway line and concluded that the vehicle speed, vehicle length, and track structure have significant effects on the dynamic responses of subgrade. Madshus et al. [13,14] completed tests of a Norway-Sweden high-speed railway located on soft ground and proposed a subgrade vibration model. The Norwegian Geotechnical Institute conducted dynamic tests of Norway's first high-speed railway [15] and proved that the low-frequency peak is related to the subgrade stiffness. The Swedish National Railway Administration conducted experiments to study the dynamic response of subgrade subjected to X-2000 high-speed train loads at Ledsgard, Sweden [16,17] and the results showed that soft soil causes severe ground vibrations.

Researchers have also performed indoor physical model tests to study the dynamic responses of subgrade. Momoya et al. [18] conducted tests on a 1:5 scale ballasted track-subgrade model at low speeds and they highlighted that it is crucial to study the deformation of railway subgrade subjected to moving loads. Brown et al. [19]