**Paper ID: CE 0387**

# Three-dimensional numerical modelling of ballastless railway track-subgrade system to simulate the dynamic response under high-speed train moving loads

**M. R. Farhan[1], M. A. Sayeed[2]**

[1]Department of Civil Engineering, RUET, Bangladesh (rahat.farhan205@gmail.com)
[2]Department of Civil Engineering, RUET, Bangladesh (sayeed.ce00@gmail.com)

**Abstract**

The ballastless railway track system is progressively used in modern railways due to its superior performance in terms of stability, durability, and maintenance. However, understanding the dynamic response of the ballastless railway track-subgrade system under the moving load of trains remains unclear due to the complexity of the system. This research paper presents a three-dimensional (3D) numerical approach to simulate the dynamic response of ballastless railway track-subgrade systems for high-speed trains (HST). The numerical model is developed using the finite element (FE) method and validated through comparison with available data given in the literature. The simulations for the FE model are performed using the commercial software package Midas-GTS, which is capable of modelling complex interactions between the track structure and the underlying soil layers. This study determined the time history curves for rail vertical displacement for the different elastic modulus of track slab, concrete base, road bed and subgrade layers. The obtained results offer valuable insights into the dynamic response of ballastless railway track-subgrade systems, which can be utilized to enhance the design and maintenance of modern railway infrastructure.

***Keywords:*** *Ballastless railway trac; finite element; high-speed trains; Midas-GTS; dynamic response.*

## 1 Introduction

The high operating speed, excellent smoothness, and greater riding comfort of high-speed train (HST), imposes extremely demanding requirements on the stability and durability of the lower supporting structure. The ballastless track-subgrade structure, characterized by its integrity, stiffness, and durability, is gradually replacing the traditional ballasted track structure and has gained widespread adoption worldwide. Currently, China has the biggest number of ongoing high-speed railway (HSR) projects, and it is estimated that by 2030, the total length of HSR railways in China will reach 45,000 km. Many of these projects employ the ballastless track-subgrade structure. Previous studies have shown that the appropriate stiffness of the subgrade and fastening system in HSR directly affects the smooth operation of the trains and the safety of passengers. Consequently, it is crucial to conduct a comprehensive investigation into the effects of these parameters on the dynamic vertical displacement of the ballastless track-subgrade system.

Early research on the dynamic behavior of the track-subgrade structure in HSR primarily relied on 2D structural models. Balendra et al. (1989) utilized a 2D finite element (FE) model to analyze the vibration responses of a subway when exposed to harmonic waves of different frequencies. Yang et al. (2009) developed a 2D FE model for the track-subgrade structure and discovered that the stress and displacement of the soil significantly increased beyond a certain train speed. As numerical methods progressed, the application of finite element-boundary element (2.5D) and 3D finite element techniques became widespread. Additionally, innovative experimental techniques have made dynamic studies on track and subgrade feasible through field or laboratory tests.

Yang et al. (2018) utilized the 2.5D finite/infinite element method to examine the track vibration for different train moving speed, depth of soil layer and shear wave velocity of soil. Zhou et al. (2019) developed a 2.5D model to investigate the interaction between tunnels and saturated soil and offered a proficient method for predicting the vibration response of underground railways.

Bian et al. (2015) employed the 2.5D finite element method to simulate the embankment and subgrade and investigated the contrasting dynamic responses of the track structure and the ground under both low-speed and

high-speed train loads. El and Woodward et al. (2013) developed a 3D FE model that incorporated the subgrade to examine the influence of soil damping on track vibration. Van Hoorickx C et al. (2017) explored the impact of double wall barriers to reduce the vibration transmission through ground. Using a 3D multi-body boundary element model to investigate vibrations induced by train loads on both ballasted and ballastless tracks, it is conccluded that the soil vibration behavior with the ballastless track exhibiting significantly weaker vibrations than the ballasted track. (Galvin et al., 2018). Connolly et al. (2013) evaluated the impact of vibration on track performance and developed an assessment method to determine the critical speed and track critical speed. Zhang et al. (2019) confirmed through the use of a discrete element method (DEM) that loading frequency significantly affects the permanent deformation of the ballast. Through experimentation, Connolly et al. (2014) discovered that embankments effectively reduce vibrations in both the near and far fields. Vibration energy propagates outward through the track and subgrade system. Therefore, examining the impact of varying subgrade and foundation stiffness on the vibration displacement of the track subgrade system can offer insights into vibration levels and potential control measures for areas located further away from high-speed railways (Shan et al., 2017).
Due to the challenges of conducting field or laboratory tests that involve replacing materials in different layers of the track-subgrade system, the FE numerical simulation serves as an excellent alternative. Thus, this paper focuses on constructing a 3D FE model for a representative ballastless track-subgrade section. The dynamic vertical displacement of the rail surface for varying elastic modulus of track-subgrade layers.

## 2 Numerical Modelling of Railway Track Foundations

In this study, the dynamic response of railway track-subgrade system subjected to HST moving loads at different train speeds and with different elastic modulus of subgrade layers is investigated through an advanced 3D FE numerical modelling using the commercial software package Midas-GTS (MIDAS IT. Co. Ltd., 2013). The FE modelling and simulations are briefly described in this section

### 2.1 Finite Element Model

The model used in the numerical study is developed by generating 3D meshes extruding from 2D mesh, in which The track dimensions considered are 48 m in length, 33 m in width, and 14 m in height. Figure 1 illustrates the components of the cross-section of the track-subgrade system, based on which the initial 2D mesh is created. From this mesh, 3D meshes are extruded to represent different components, including a 0.2 m thick track slab, a layer of cement asphalt mortar (CAM) over a 0.3 m thick concrete base, a 0.4 m thick roadbed, a 2.3 m thick subgrade, and a 10.9 m deep subsoil.

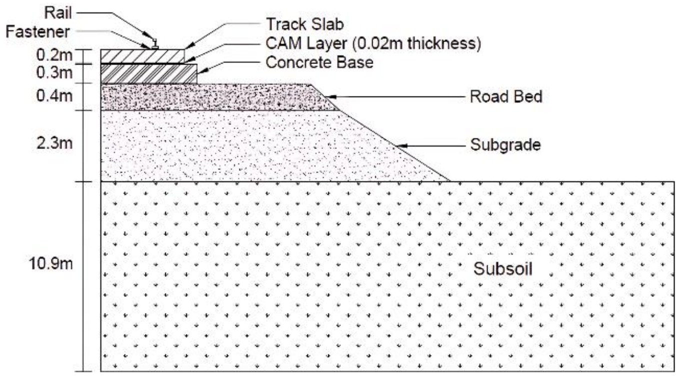
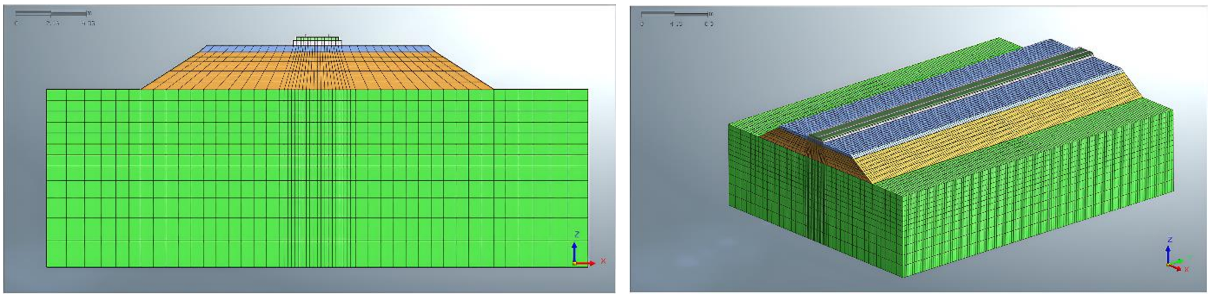



Figure 1. Components of track-subgrade system

The efficiency and accuracy of results depend on the geometric shape of the elements used. The aspect ratio refers to the length ratio between the width and length of a 2D element, and a value closer to 1 is considered ideal. If the aspect ratio is very small, it can significantly impact the analysis results. Similarly, the skew angle measures how much the shape deviates from a rectangular shape (90 degrees) and is measured in angles. Fig. 2 displays a 2D cross-sectional view of the elements in the 3D FE model, consisting solely of quadrilateral shapes while avoiding triangular shapes. To maintain accuracy, tolerance limits are set at 8 for aspect ratio, 45 for skew angle, 25 for warpage, and 0.25 for taper.



(a) (b)

Figure 2. Three-dimensional FE model of track-subgrade system (a) cross-section of the model (not to scale); (b) 3D view of the model.

The rail is modelled using a one-dimensional (1D) I-beam section running across the track length. A rail section (similar to the UIC-60 section) is assumed for the rail, which is fixed to the sleepers by rail pads that are characterized by an elastic link (spring-like) element of stiffness equal to 45,000 kN/m. A standard gauge of 1.435m and fasteners with a spacing of 0.63m are provided to the model. The element size of the FE model is estimated based on the smallest wavelength that allows the high-frequency motion to be simulated correctly. Accordingly, the sizes of the 3D FE model, the elements used in the current study are taken as: 0.315 m × 0.14 m × 0.2 m; 0.4 m × 0.4 m × 0.4 m; and 0.6 m × 0.6 m × 0.6 m for the track slab, roadbed and subgrade, respectively. Hence, the track FE mesh consists of 176,098 elements and 173090 nodes. Properties that represent the physical attributes of the track-subgrade system are assigned to mesh sets according to the Chinese high-speed railway design code. The properties of the parameters are summarized in Table 1 (Cheng and Zhou, 2018).

In order to effectively absorb incoming S- and P-waves and simulate infinite boundary conditions, viscous dampers are employed to connect the vertical boundaries of the model. To replicate the behavior of bedrock, the nodes at the bottom boundary are fixed in all directions. Material damping in the finite element model is defined using mass and stiffness proportional coefficients, commonly known as Rayleigh damping, which is utilized in nonlinear dynamic studies. The generalized equation for Rayleigh damping is as follows:

$$[\mathrm{C}] = \alpha\,[M] + \beta\,[K]$$

Here $[\mathrm{C}]$ represents the damping matrix; $[M]$ represents the mass matrix; and $[K]$ represents the stiffness matrix. The mass and stiffness proportional damping coefficients are represented by the parameters $\alpha$ and $\beta$ with units s and $s^{-1}$ respectively. In this study, the Midas-GTS software is used to conduct an eigenvalue analysis, taking into account the subgrade reaction at the boundary of the layered material mesh in order to determine the natural frequency mode of the 3D model.

Table 1. Material properties of the track-subgrade model (Cheng and Zhou, 2018).

| **Material** | **Dynamic Young's modulus, *E* (MPa)** | **Poisson's ratio** | **Density ($kN/m^3$)** | **Cohesive strength (kPa)** |
|---|---|---|---|---|
| Rail | 210,000 | 0.3 | 76.50 | - |
| Track Slab | 35,000 | 0.3 | 29.43 | - |
| CAM Layer | 92 | 0.4 | 19.62 | - |
| Concrete Base | 30,000 | 0.16 | 26.48 | - |
| Road Bed | 400 | 0.3 | 23.53 | 70 |
| Subgrade | 180 | 0.3 | 18.83 | 45 |
| Natural Subsoil | 60 | 0.42 | 18.63 | 30 |

### 2.2 Simulation of train moving loads

To simulate the HST moving load for the 3D FEM, a CRH2-type train is selected. Two wheels of one bogie are spaced apart by about 2.5 m, while one carriage has two bogies that are spaced apart by roughly 17.5 m. Fig. 3 shows the schematic diagram of the CRH2-type HST with the spacing between the wheels and bogies.

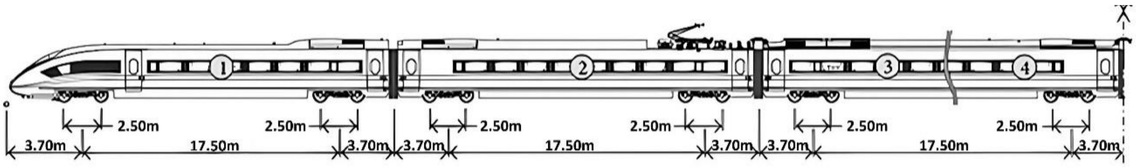



Figure 3. Schematic diagram of the CRH-2 type HST

The element size of the rails and the track slab is 0.315 m in the longitudinal direction. So, connecting every second node of the rails to the slab track ensures a fastener spacing of 0.63 m. In this study, the dynamic load feature of the Midas-GTS software is used to simulate moving train load. Fig. 4 shows the dynamic load table for an arbitrary node, where each rail is subjected to an axle load of 70 kN.

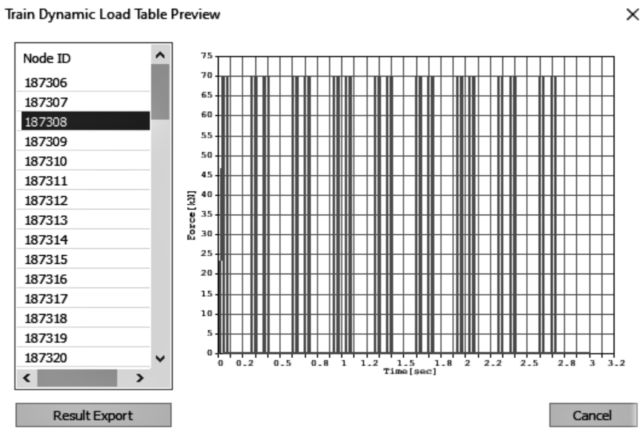



Figure 4. Train dynamic load table (for 270 km/h speed)

### 2.3 Validation of the 3D FEM

To assess the accuracy and reliability of the 3D FEM, a precise validation approach is conducted. The 3D FEM results are compared with the results of a full-scale physical model test conducted by Jiang et al. in 2014. In the physical model test, Jiang et al. measured and recorded the vertical soil stress at different locations beneath the track under the simulated train speed of 270 km/h. The comparison aims to assess the agreement between the research findings and the experimental measurements. By comparing the results, it is found that the vertical soil stress values obtained from the 3D FEM are in line with the measurements from the physical model test.

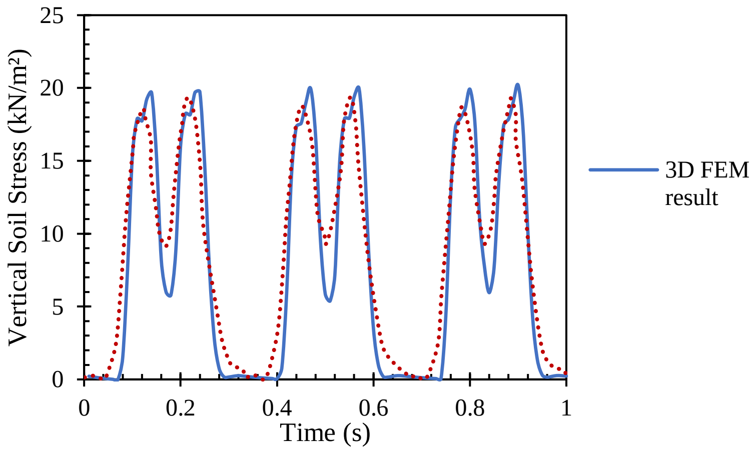



Figure 5. Comparison between FE predicted versus recorded physical model test result (Jiang et al., 2014) of vertical soil stress versus time at train speed of 270 km/h

Despite the minor discrepancies observed between the 3D FEM results and the full-scale physical model test measurements, the comparison confirmes that the 3D FEM effectively captures the vertical soil stress characteristics under high-speed train loading conditions. The validation with the physical model test results enhances the confidence in the accuracy and reliability of the numerical analysis.

## 3 Numerical simulations to investigate the impact of elastic modulus of track subgrade layers

In this section, a parametric study is performed to investigate the effect of elastic modulus on the rail vertical deflection. For this, the same numerical model discussed in the previous section is used (Table 1). However, to investigate a specific parameter, only the concerned parameter is changed as given in Table 2. The effect of elastic modulus on the rail vertical deflection is presented in Figure 6. It can be seen that the elastic modulus of each track-subgrade layer has effects on the rail vertical deflection. The major variation observed is due to the change of elastic modulus of subgrade.

Table 2. Track properties used for the parametric study

| Parameter | Nominal Value of Dynamic Young's modulus, $E$ (GPa) | Value Used at parametric study $E$ (GPa) |
|---|---|---|
| Track Slab, $E_{ts}$ | 35 | 30, 40 |
| Concrete Base, $E_{cb}$ | 30 | 25, 35 |
| Road Bed, $E_{rb}$ | 0.4 | 0.2, 0.6 |
| Subgrade, $E_s$ | 0.18 | 0.06, 0.3 |

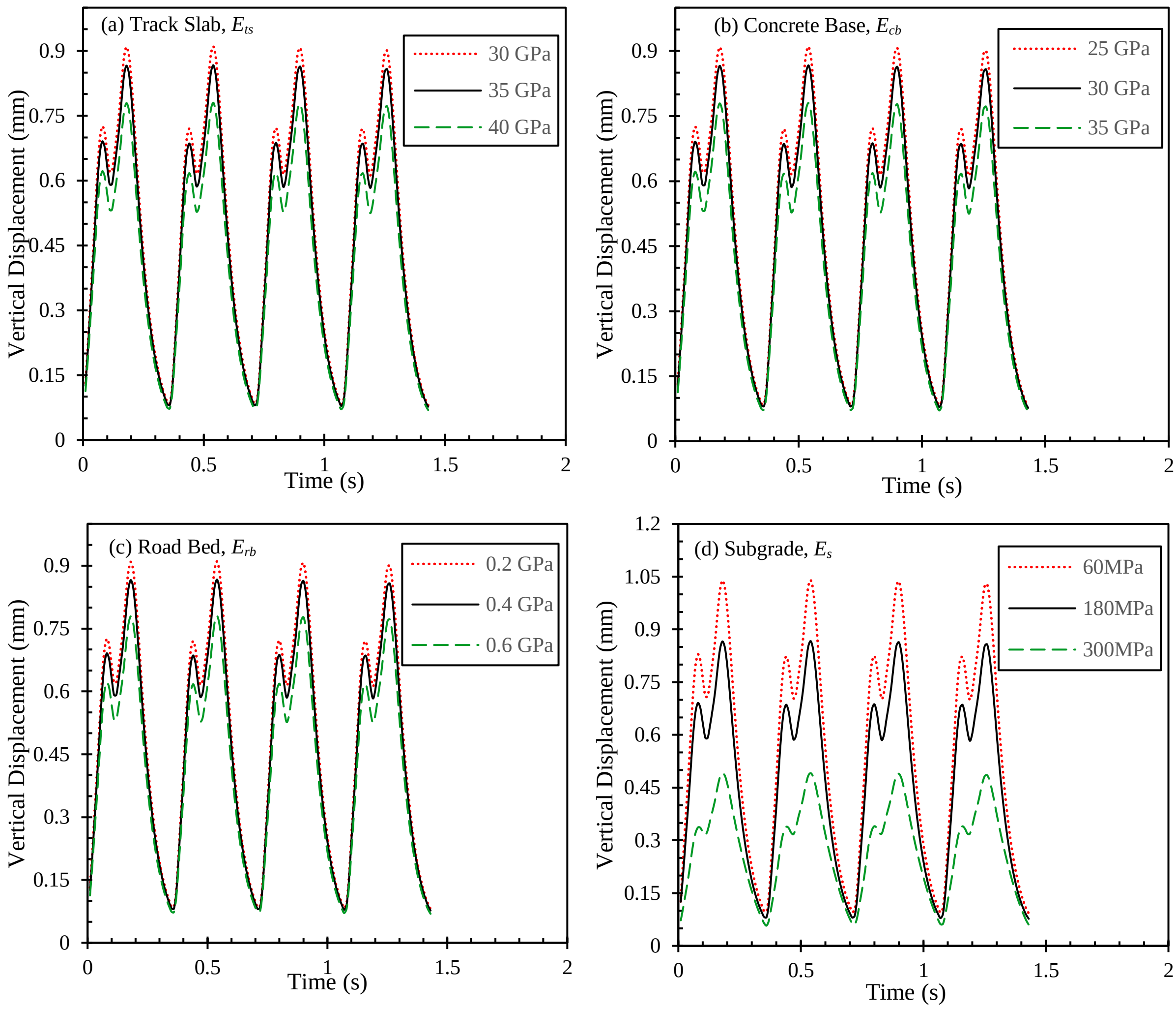



Figure 6. Vertical displacement at rail surface for different elastic modulus of (a) Track Slab (b) Concrete bed (c) Road Bed (d) Subgrade

Figure 7 shows a comparison of the effect of elastic modulus of different track-subgrade layers. It can be noted that due to the change of elastic modulus of road bed and subgrade layers there is a significant effect on the rail vertical deflection. It is very important to notify that with the increase of elastic modulus of road bed and subgrade layer the rail deflection decreases considerably. Therefore, to reduce the rail track deflection and improve the riding comfort the subgrade soil characteristics should be improved by ground improvement technics.

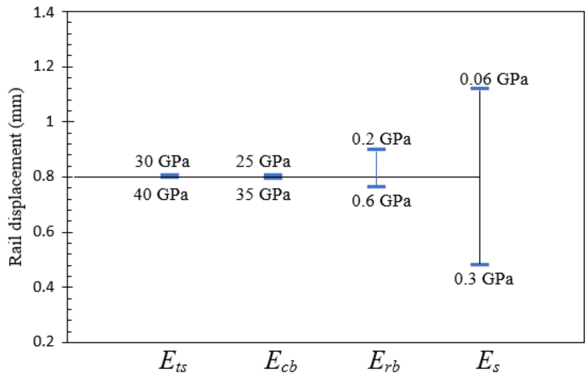



Figure 7. Comparison of the effect of elastic modulus of different track-subgrade layers

**4. Summary and Conclusions**

In this research paper, a comprehensive three-dimensional numerical study of the dynamic response of a ballastless railway track-subgrade system is conducted. The validation with a full-scale physical model test shows that the 3D FE model can accurately predict the dynamic response of the track-subgrade system under HST moving conditions. Based on the findings of this study, it is evident that the elastic modulus of the track-subgrade layer plays an important role on the total displacement of the track-subgrade system. It is evident that by increasing the elastic modulus of the road bed and subgrade layer, the rail displacement decreases dramatically, leading to a more smooth and more comfortable journey by trains.

## References

Balendra, T., Chua, K. H., Lo, K. W. (1989). Steady-state vibration of subway-soil-building system. Journal of engineering mechanics.115(1), 145–62.

Bian, X., Jiang, H., Chang, C. Hu, J., Chen, Y. (2015). Track and ground vibrations generated by highspeed train running on ballastless railway with excitation of vertical track irregularities. Soil Dynamics and Earthquake Engineering. 76, 29–43.

Castanheira, P. A., Costa, P. A., Godinho, L., Mendes, P. A. (2018). On the application of continuous buried periodic inclusions on the filtering of traffic vibrations: a numerical study. Soil Dynamics and Earthquake Engineering. 113, 391–405.

Cheng, J., Zhou, Y. (2018). Dynamic responses of subgrade under double-line high-speed railway. Soil Dynamics and Earthquake Engineering. 110, 1–12.

Connolly, D., Giannopoulos, A., Forde, M. C. (2013). Numerical modelling of ground borne vibrations from high speed rail lines on embankments. Soil Dynamics and Earthquake Engineering. 46, 139.

Connolly, D. P., Kouroussis, G., Woodward, P. K., Giannopoulos, A., Verlinden, O., Forde, M. C. (2014). Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils. Soil Dynamics and Earthquake Engineering. 66, 78–88.

El Kacimi, A., Woodward, P. K., Laghrouche, O., Medero, G. (2013). Time domain 3D finite element modelling of train-induced vibration at high speed. Computers & Structures. 118, 66–73.

Galvín, P., Mendoza, D. L., Connolly, D. P., Degrande, G., Lombaert, G., Ramero, A. (2018). Scoping assessment of free-field vibrations due to railway traffic. Soil Dynamics and Earthquake Engineering. 114, 598–614.

Jiang, H., Bian, X., Cheng, C., Chen, Y., Chen, R. (2014). Simulating train moving loads in physical model testing of railway infrastructure and its numerical calibration. Acta Geotechnica. 1-12.

MIDAS IT. Co. Ltd. Manual of GTS-NX 2013 v1.2: new experience of geotechnical analysis system. South Korea: MIDAS Company Limited; 2013.

Shan, Y., Shu, Y., Zhou, S. (2017). Finite-infinite element coupled analysis on the influence of material parameters on the dynamic properties of transition zones. Construction and Building Materials. 148, 548–58.

Van, H. C., Schevenels, M., Lombaert, G. (2017). Double wall barriers for the reduction of ground vibration transmission. Soil Dynamics and Earthquake Engineering. 97, 1–13.

Yang, L. A., Powrie, W., Priest, J. A. (2009). Dynamic stress analysis of a ballasted railway track bed during train passage. Journal of Geotechnical and Geoenvironmental Engineering. 135(5),680–9.

Yang, Y. B., Ge, P., Li, Q., Liang, X., Wu, Y. (2018). 2.5D vibration of railway-side buildings mitigated by open or infilled trenches considering rail irregularity. Soil Dynamics and Earthquake Engineering. 106, 204–14.

Zhang, X., Zhao, C., Zhai, W. (2019). Importance of load frequency in applying cyclic loads to investigate ballast deformation under high-speed train loads. Soil Dynamics and Earthquake Engineering.120, 28–38.

Zhou, S., He, C., Guo, P., Yu, F., (2019). Dynamic response of a segmented tunnel in saturated soil using a 2.5-D FE-BE methodology. Soil Dynamics and Earthquake Engineering.120, 386–97