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Research Article

Investigating the Behaviour of Railway Track Ground Vibrations for Different Track Foundation Conditions Using FEM

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Abstract

High-speed trains are a useful friendly option for ground transportation. Railway-induced ground vibrations can have a severe impact on human health and the communities that surround rail lines. Current research is showing the problem and its solution as technology is advancing steadily, still, there are some misunderstandings. This is because the propagation of railway vibration in urban areas is complex. So, this work focuses on reducing vibration by enhancing the ballast, and sub-ballast qualities of the railway track through the use of insulation technologies. The Finite Element Method (FEM) model offers insight into how vibrations propagate over a railway track's foundation. The FEM model can be used to forecast the frequency of vibrations. The Plaxis 3D model's results show a reduction in vibration propagation. Sylomer is used as a damping material to absorb the vibration and block the propagation path. The application of damping material changes the track-bed system's dynamic response, effectively decreasing vibration transmission to the surrounding soil. Stress on the surrounding soil and structure foundation is reduced by the process of vibration mitigation. Establishing a benchmark reference for soil parameters is crucial for the accurate analysis and prediction of ground behavior. By creating a detailed and standardized set of soil data, engineers and planners can better understand the characteristics and capabilities of the ground on which they intend to build.

Keywords

Railway, PLAXIS 3D, Vibration, FEM Model, Sylomer

1. Introduction

With the recent tendency of trains to operate faster even on soft grounds, vibration studies along train lines are becoming increasingly important. The need for the study stems from concerns about maintaining a better built-up area alongside the track and safe train operation. Thus, with particular attention to critical speed, the geotechnical engineer examined the behavior of ballasted railway track foundations for high-speed trains. Buildings and monuments are frequently damaged by the vibrations brought on by train movement. A technological method is necessary to prevent damage from vibrations and/or earthquakes and this technique becomes more sophisticated the more culturally significant the afflicted structures and monuments are, and the longer the estimated duration of conservation is. For these reasons, a numerical method is proposed here for modeling the rail track components that are directly related to the dynamic study of the soil structure

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interaction caused by external force resulting from train passage. In the case of the numerical simulation, carried out a study about the dynamic stability of railway tracks on soft soils. They have modeled a train railway embankment in PLAXIS 2D and the numerical results have been compared to experimental data [1]. Also accomplished a preliminary study of the comparative suitability of 2D modeling with different numerical tools such as PLAXIS 2D and other finite element software [2]. In recent studies, the effect of the third dimension is considered by some assumptions, for example, Yang and Hung (2001) suggested a so-called 2.5D model for moving loads [12]. The initial findings of numerical modeling in PLAXIS 3D for simulating moving loads on a typical soil embankment which is intended for high-speed railway trains are presented in this work. Several static point loads were applied along the railroad track to achieve this. The load quantity is equivalent to the train's axle load. A dynamic multiplier is assigned as a time-shear force signal for every point load. To calculate shear forces, a beam under unit loads on the elastic basis was modeled. As elements of the dynamic multiplier, the resulting shear forces in the beam were transferred to the 3D model.

Furthermore, some constitutive soil models, including Mohr-Coulomb (MC), Linear Elastic (LE), and Hardening Soil small-strain (HS-small) were used to approximate the dynamic behavior of the soil dam [3]. The battle between different traffic in terms of speed, and carrying the demand for faster and heavier trains has significantly increased due to factors including capacity, comfort, safety, and cost. This request suggests anticipated pressure to build railway tracks that use cutting-edge technologies that are appropriate for heavy axle loads (HALs) and high-speed trains (HSTs). It is anticipated that this tendency will raise the need for railway track foundation design. As a result, a comprehensive analysis of how different design factors affect the overall performance of railway tracks is necessary [4]. For railway geotechnical engineers to develop the best plan possible for track design and ongoing maintenance, this kind of study is essential. This chapter develops advanced finite element (FE) modeling in three dimensions (3D) to better understand the dynamic response of ballasted railway tracks under real train moving loads. Field measurement data published in the literature is used to validate the FE modeling [5].

The impact of several significant parameters on the track performance is then examined through thorough parametric research. These factors include train loading characteristics and the modulus and thickness of the track foundation layers, which are called the ballast, sub-ballast, and subgrade [8]. Further finite element analyses are conducted to examine how train speed affects the behavior of ballasted railway track foundations and to assess the critical speed that is, the train speed at which resonance causes unusually high vibrations under various train-track-ground system conditions. These circumstances include the nonlinearities of the track materials, the train geometry, the amplitude of train loading, the modulus and thickness of the ballast material, and the subgrade soil. A critical analysis and discussions are held regarding the practical implications of the track design results acquired.

2. Modeling Approach

In this thesis, three-dimensional (3D) finite element (FE) numerical modeling is used to simulate the dynamic response of railway track foundations subjected to train movement loads. PLAXIS 3D (2016) is the program used for this purpose. It is used because this software can replicate the actual train movement load. To develop useful design charts as part of the suggested design method for calculating the granular layer thickness required to protect against track failure and vibration, the current study's numerical modeling aims to investigate the dynamic response of railway tracks under various train-track-ground system conditions [7]. As such, it is extremely prudent to confirm that the FE modeling procedure can yield trustworthy results. The initial analysis is performed for case studies, which are well documented in the literature.

2.1. Model Geometry

Figure 1 (Degrande and Schillemans, 2001) shows the geometry and subgrade profile of the Thalys HST track at the Ath site, while Figure shows the corresponding 3D FE model created to simulate the problem. This model comprises layers of ballast and sub-ballast and a capping layer based on the soil's natural subgrade. The longitudinal, horizontal, and vertical dimensions of the FE model are 80 m, 36 m, and 12 m, respectively. One-dimensional (1D) I-beam sections that span the entire length of the simulated track are used to model the rail [6].

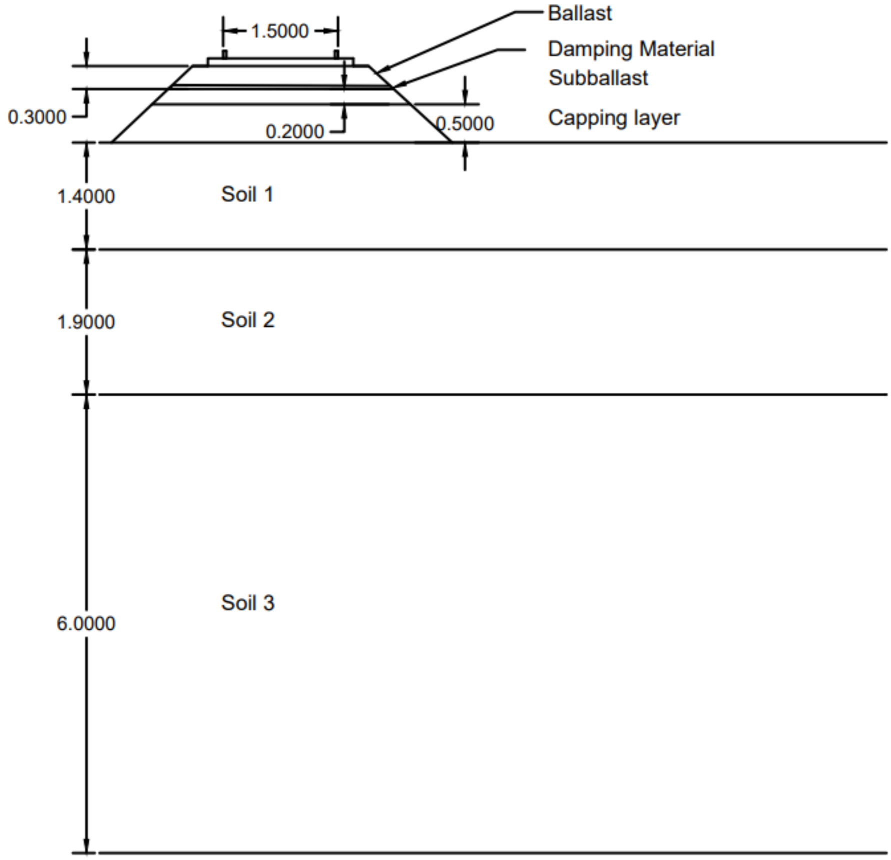

Figure 1. *The Thalys HST Railway Track (Track Geometry and Soil Profile).*

A UIC-60 section is assumed for the rail, which is fixed to the sleepers by rail pads characterized by an elastic link (spring-like) element of stiffness equal to 100 MN/m. All other track components (i.e. sleeper, ballast, interface, and subgrade) are modeled using 3D solid elements. For model geometry, a total of 133 sleepers are placed along the rail at 0.6 m intervals. The rail and sleepers are considered linear elastic (LE) materials, whereas the ballast and interface layer are modeled using elastoplastic Mohr-Coulomb (MC) materials. The rail, linked to the sleepers by rail pads with an elastic link (spring-like) element of stiffness equal to 100 MN/m, is considered to have a UIC-60 section. 3D solid elements are used to model the sleeper, ballast, interface, and subgrade, among other track components [11]. To create the model geometry, 133 sleepers in total are spaced 0.6 meters apart along the rail. While the ballast and interface layer are modeled using elastoplastic Mohr-Coulomb (MC) materials, the rail and sleepers are thought of as 11 linear elastic (LE) materials. Since nothing is known about the subgrade soil's plasticity properties, it is taken for granted that it is elastic [10]. This assumption makes sense because the granular media's thickness (ballast and sub-ballast, for example) is often chosen to minimize the amount of stress on the track subgrade soil. As a result, little to no plastic yielding can occur.

2.2. Material Properties

Soil parameters are essential for modeling geotechnical phenomena in PLAXIS 3D. To accurately predict soil behavior, parameters such as cohesion, friction angle, and soil stiffness are established. Furthermore, anisotropy, non-linear behavior, and time-dependent characteristics can all be taken into account with PLAXIS 3D, facilitating thorough assessments of soil-structure interaction and geotechnical engineering projects By incorporating cutting-edge materials into railway infrastructure, high-stiffness damping materials help mitigate railway vibrations by minimizing the number of vibrations that pass from trains to surrounding environments and buildings. These materials usually include damping qualities that disperse vibrational energy in addition to high stiffness, which means they resist deformation under load. The table provides an overview of the material characteristics of every track component [9].

Table 1. *Material Properties.*

Parameters	Ballast	Sub-Ballast	Capping Layer	Soil 1	Soil 2	Soil 3	Damping material
Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Linear Elastic	Hardening-soil	Linear Elastic
Unit weight, ɣ (kN/m^3)	17.7	21.6	21.6	16	20	17	17
Dynamic Modulus of Elasticity, E (MPa)	135	165	165	10	50	-	200
Cohesion, c	30	0	10	5	-	10	-
Friction Angle, θ	50	40	28	25	-	33	-
Poisson's Ratio, v	0.1	0.1	0.2	0.3	0.3	-	0.4
m	-	-	-	-	-	0.5	-
E_{oed}^{ref}	-	-	-	-	-	35 X 10^3	-
E_{50}^{ref}	-	-	-	-	-	35 X 10^3	-
E_{ur}^{ref}	-	-	-	-	-	105 X 10^3	-

Installing elastomeric bearings or pads under railroad tracks and other infrastructure is one frequent use. In addition to offering damping to absorb and disperse vibrations, these materials provide a high degree of rigidity to withstand the weight of trains. To improve vibration isolation, high-stiffness damping materials can also be employed to build under-ballast mats or railway sleepers. By incorporating these materials into railway infrastructure, the transmission of vibrations to nearby buildings, residences, and sensitive equipment can be significantly reduced. This is particularly important in urban areas where railway noise and vibrations can negatively impact the quality of life for residents. Sylomer is a special PU elastomer manufactured by Getzner, which features a celled, compact form and is used in a wide range of applications in the construction and mechanical engineering industries.

In most cases, the Sylomer is used as a compression-loaded elastic support element. The characteristics of the elastic support can be adjusted to the structure, construction method, and load requirements by selecting the specific type of Sylomer, the load-bearing area, and the thickness. Sylomer materials are available as a continuous roll and are particularly well suited as flat, elastic layers. Above and beyond this, engineered molded parts made of Sylomer are also available.

3. Calculation Phases and Result

In this model, calculation consists of three phases. The first phase is common for generating the initial stresses with an active groundwater table. A plastic drained calculation type is chosen in phase two. In this phase, all elements of the railway track (sleepers, rails, and rail clips) should be active. The dynamic option should be selected in phase three to consider stress waves and vibrations in the soil. In this phase, all dynamic point loads on the rail are active. The dynamic boundary conditions are chosen as viscous to limit the calculation. Dynamic time interval is assigned as 2.4 s for the model to run all the points load through the length of the model. In the last phase, which calculates the dynamic condition the movement function is assigned. Lines, which are indicated as rail are selected as a movement path of the point load.

3.1. Dynamic Load Multiplier

A key component of dynamic analysis in PLAXIS 3D is the dynamic load multiplier, which is used to show how different dynamic loads affect soil behavior over time. It is a scaling factor that is used with dynamic loads to help engineers more realistically mimic intricate interactions between soil and structure.

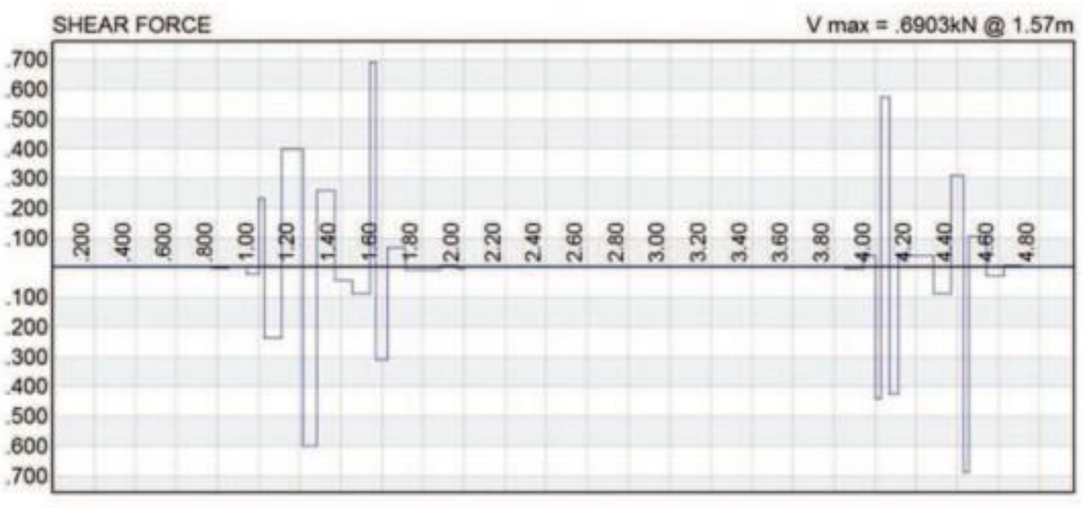

Figure 2*. Shear Force on the Beam Using PROKON.*

Each point load in the described scenario is allocated a dynamic multiplier corresponding to the time shear force signal. These load multipliers signify the shear forces induced in the beam by the static load along the rail at specific times. Estimating these shear forces involves a static analysis conducted through PROKON, employing the theory of beam on elastic foundation. This analysis aids in determining the shear forces acting on the rail, facilitating an understanding of how the static load influences the structural integrity of the rail system.

3.2. Result After Calculation

To comprehend the dynamic changes, the peak value on the graph can be compared. The vertical acceleration at the same nodal point is much lower after applying the damping material. The standard ballast exhibits a vertical acceleration range of $+0.5\ m/s^2$ to $-0.5\ m/s^2$. The value varies between +0.3 and $-0.35\ m/s^2$ depending on the ballast and damping material conditions. There is a noticeable decrease in the vertical acceleration shown in Figure 3 and Figure 4.

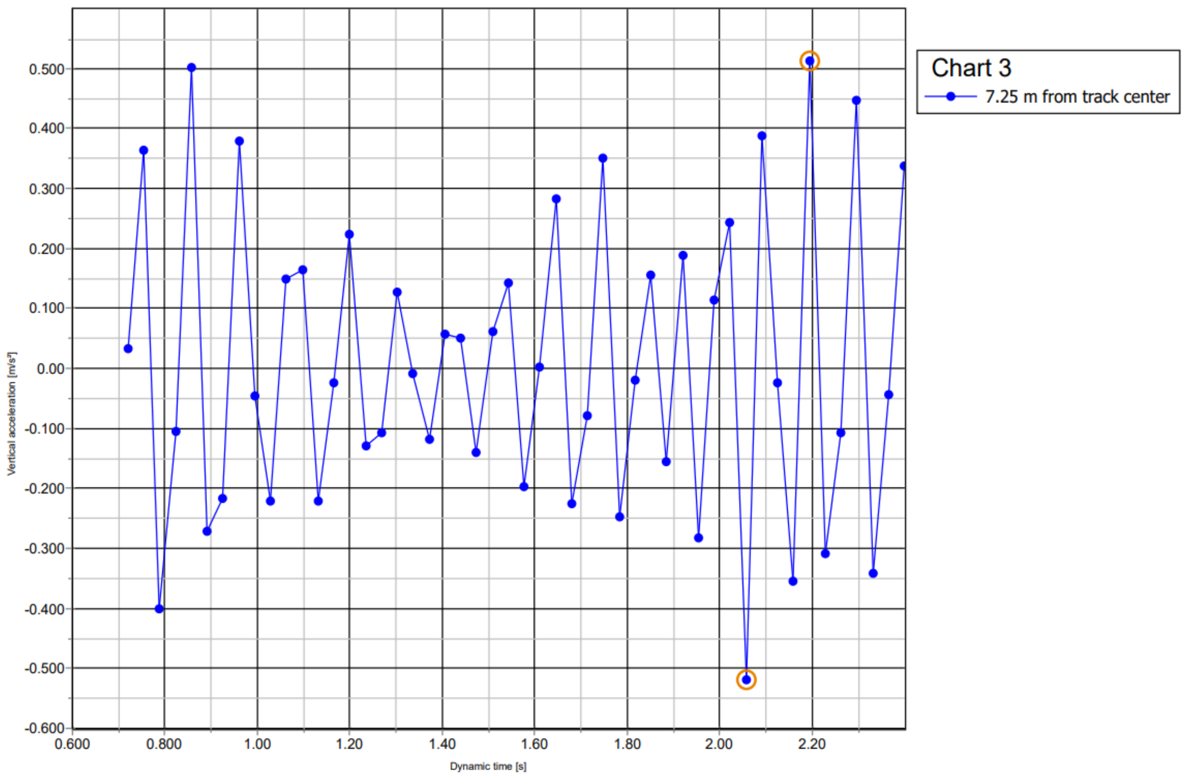

Figure 3*. Vertical Acceleration Vs Dynamic Time Graph in Normal Conditions.*

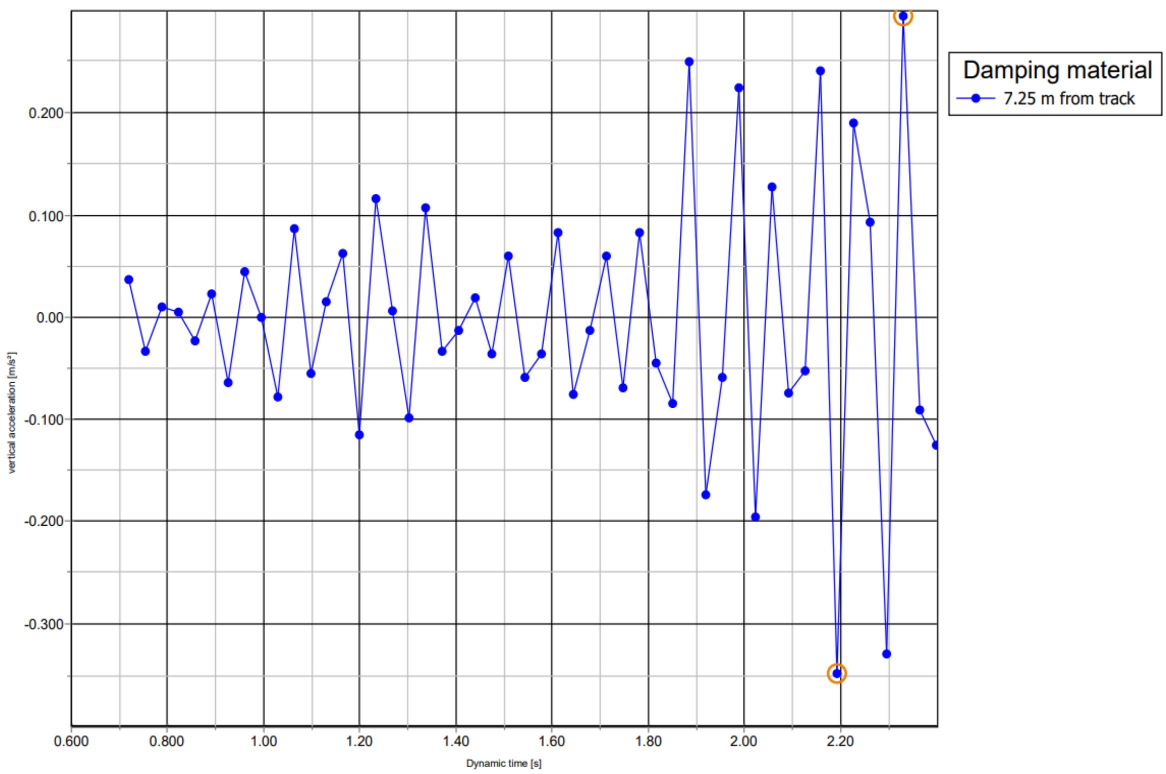

Figure 4*. Vertical Acceleration Vs Dynamic Time Graph using Damper.*

From the graph, the peak value can be compared to understand the dynamic changes. Clearly after using the damping material the vertical velocity is reduced significantly in the same nodal point. Vertical velocity in the normal ballast is ranging from 0.042 m/s^2 to -0.045 m/s^2. In damping material and ballast conditions, the value ranges from +0.025 m/s^2 to -0.025 m/s^2. The vertical velocity is reduced significantly.

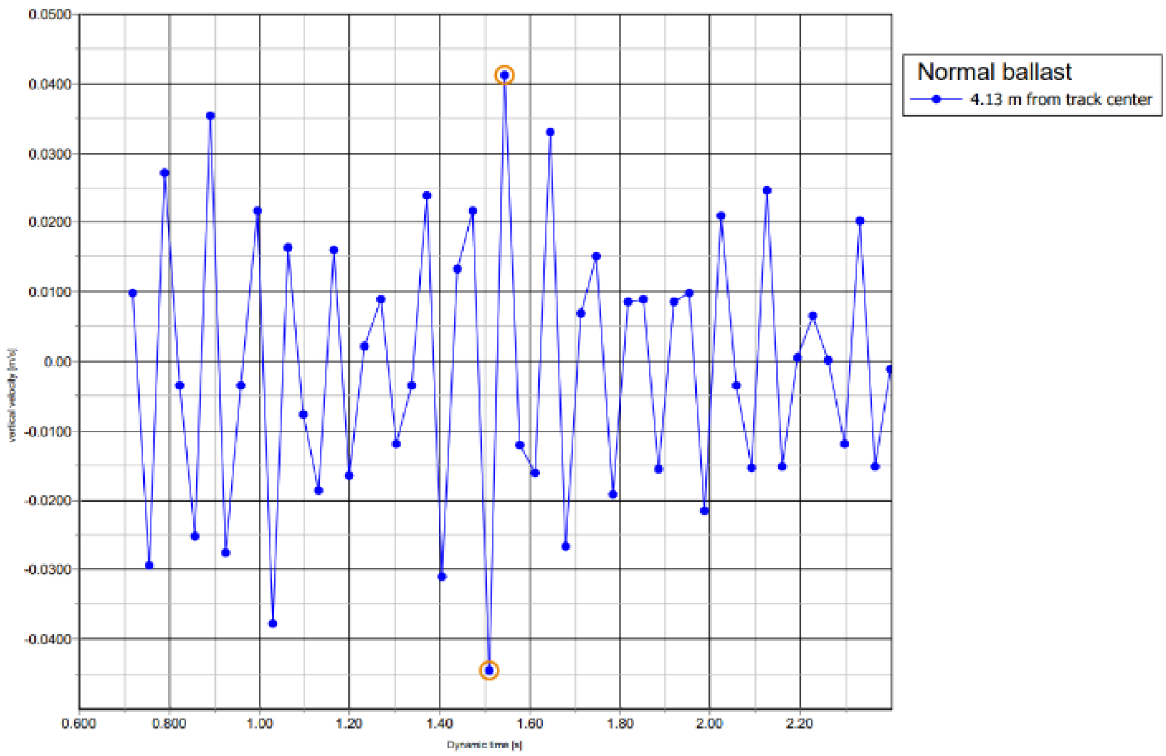

Figure 5*. Vertical Velocity Vs Dynamic Time Graph in normal condition.*

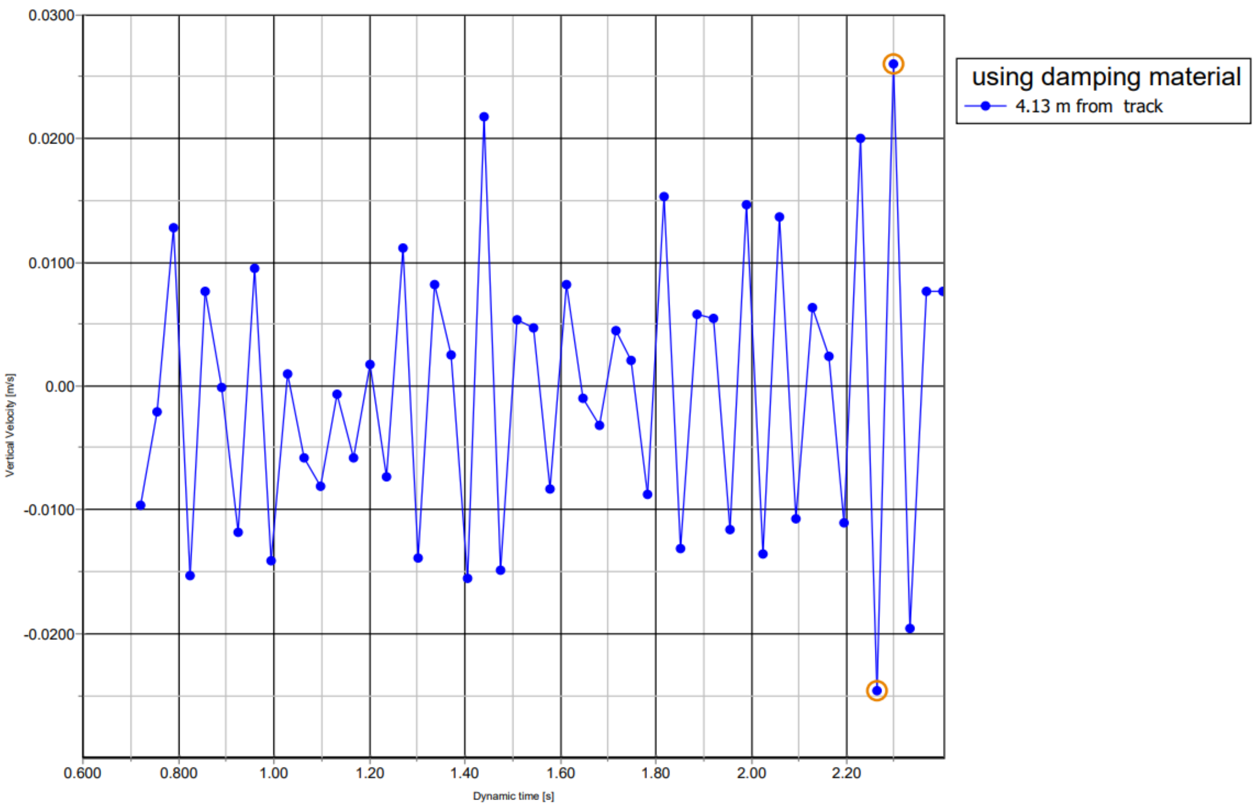

Figure 6. Vertical Velocity Vs Dynamic Time Graph using Damper.

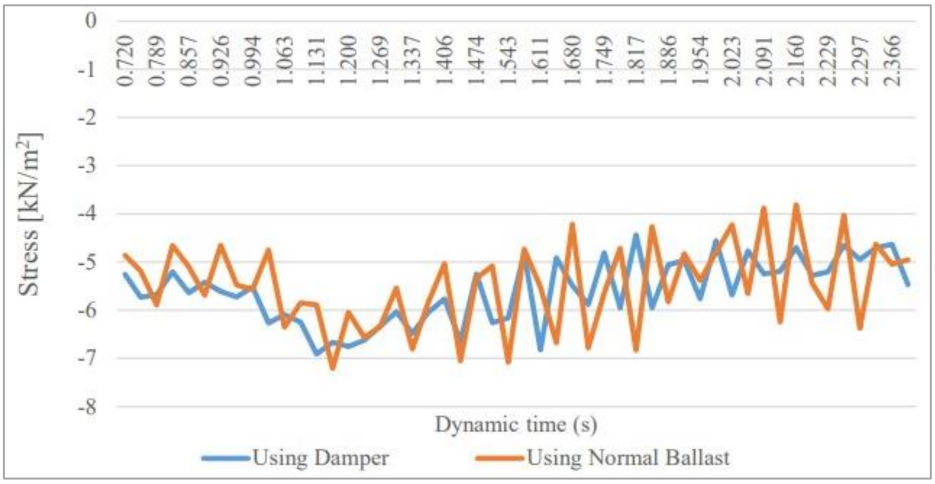

Figure 7. Time Histories of Stress at Stress Point 4.13 m from the Track.

From Figure 7, the stress variation under different circumstances can be observed. In the damping condition, the stress variation is less than in the normal ballast condition. A material's stiffness is a key factor in determining the stress it experiences when subjected to external forcing. The force per unit area pressing on a material is known as stress, and it is directly impacted by the material's stiffness.

4. Analysis of the Data

When it comes to comprehending and reducing vibrations in railway track systems, the link between material modulus, vertical acceleration, and velocity is crucial. The dynamic response of the track to passing trains is directly influenced by modulus, a measurement of a material's stiffness. Velocity and vertical acceleration both decrease with increasing modulus. Vibrations are lessened when the ballast, or the material that supports the railroad tracks is stiffened. Several techniques, including inserting dampening materials beneath the sleepers and swapping out the ballast for materials with greater stiffness, can be used to achieve this stiffening. Because stiffer materials are more resistant to deformation and can withstand dynamic loading forces, there is a drop in vertical acceleration and velocity as modulus increases. As a result, vibrations are decreased since the track system absorbs less energy. This phenomenon is illustrated for different ballast moduli by time histories of vertical acceleration and velocity at a specific point along the track center. Engineers can evaluate the success of stiffening techniques in reducing vibrations and adjusting track design by comparing these histories for various modulus.

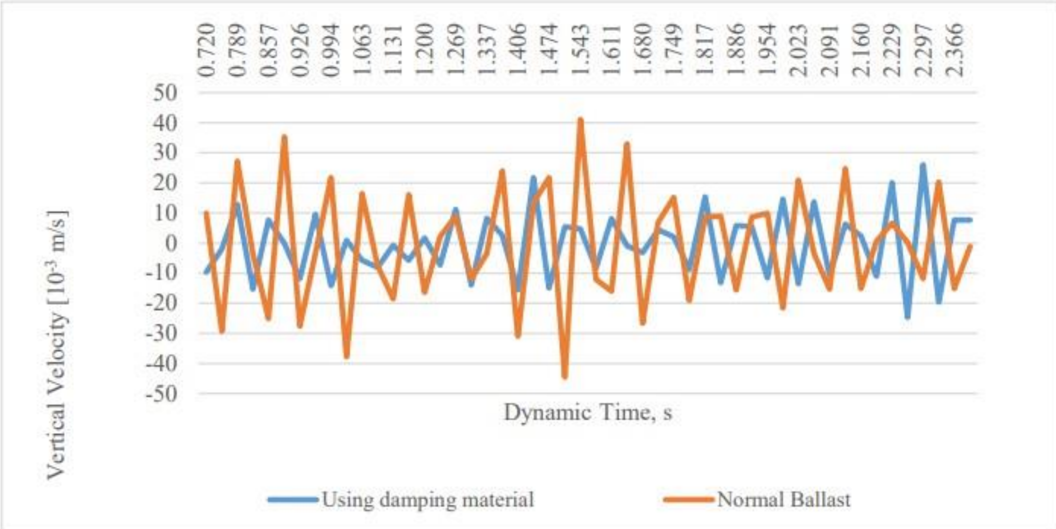

Figure 8. *Vertical Velocity Comparison with Normal Ballast and Ballast with Damping Material.*

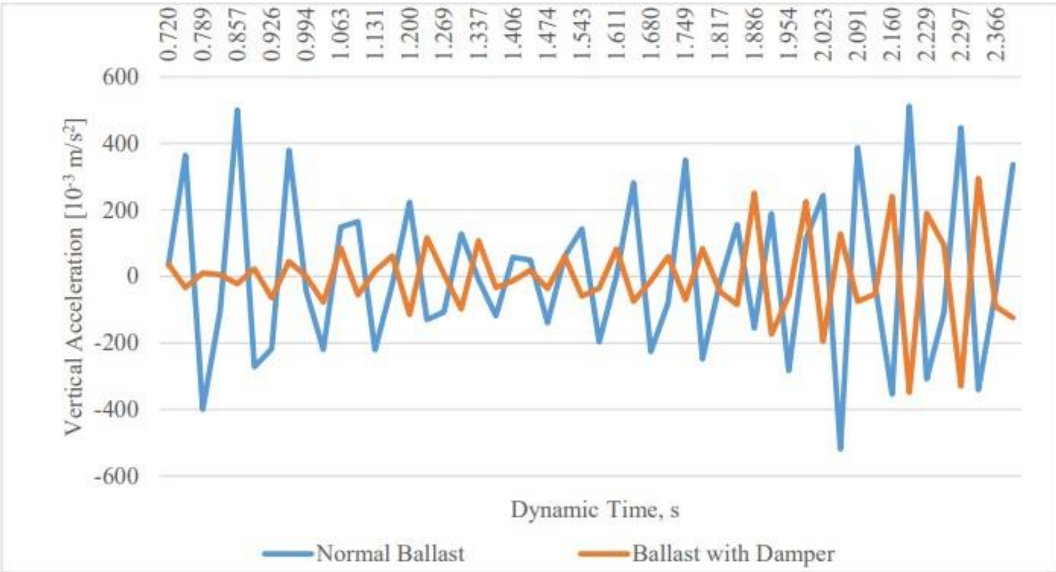

Figure 9. *Vertical Acceleration Comparison with Normal Ballast and Ballast with Damping Material.*

From the decreasing value of the vertical velocity and acceleration, the decision can be made that ground vibration is less after using the damping material in the ballast layer. When damping materials are added to the ballast layer of railroad tracks, the values of vertical velocity and acceleration decrease, indicating a decrease in ground vibration. This discovery implies that vibrations caused by the passing of trains are effectively attenuated by the damping material.

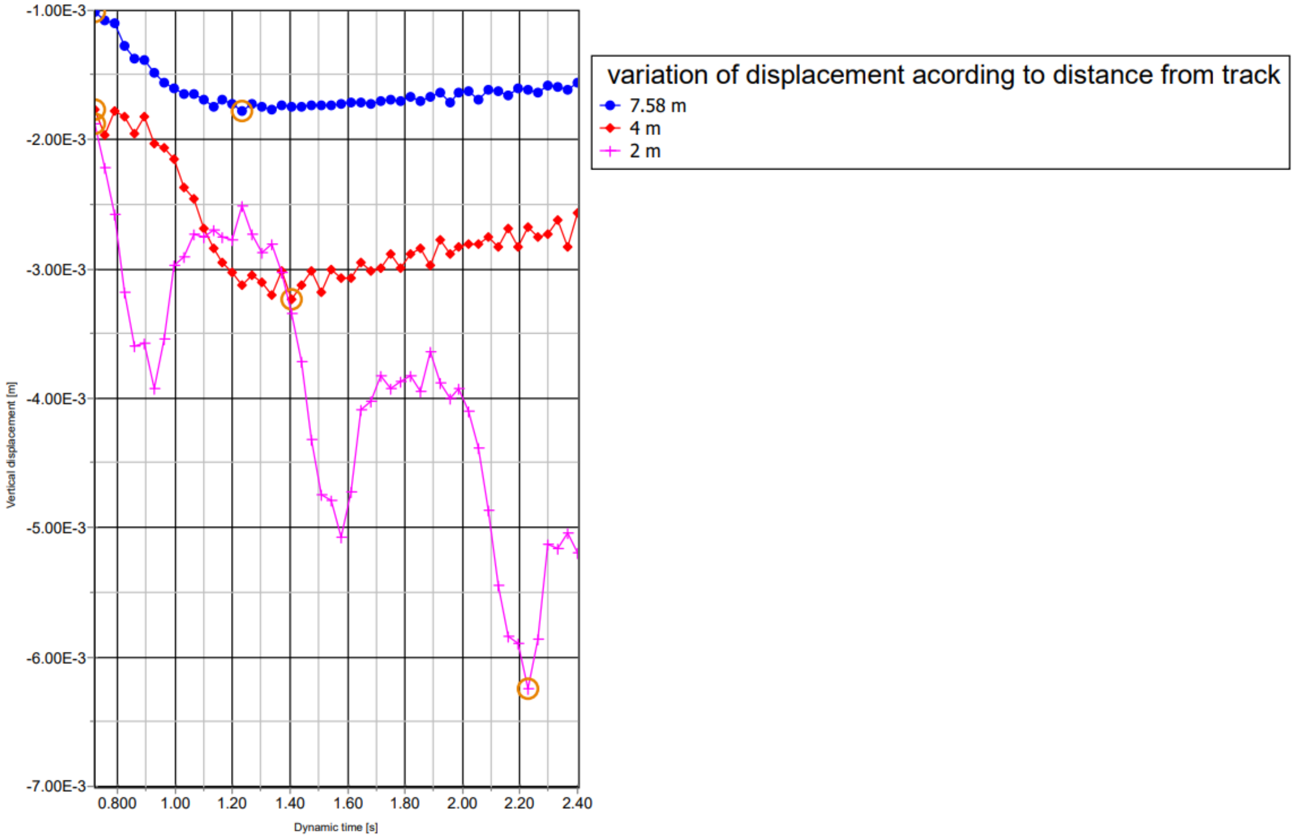

Figure 10. *Change in Displacement Based on the Distance from the Track Center.*

Because of the variance in soil stiffness and damping qualities at different sites, the displacement value in soil fluctuates with the distance from the track center under dynamic load. 37 Vibrations are caused in the soil by a dynamic load, such as a passing train, and these vibrations spread throughout the earth. The dirt is more stressed and deformed close to the track center, where the dynamic force is concentrated. Displacements therefore usually have a greater impact near the track center. On the other hand, dynamic load disperses across a greater region as you move away from the track center, reducing soil stresses and deformations. As a result, displacements get less the farther they are from the track center.

5. Conclusion

The result from the FEM model shows how vibration propagates along the track foundation of the railway path. The Damping material (Sylomer) has been introduced, which integrates with the ballast material. By using the Damping material there are effective changes in the results gathered from the FEM model of PLAXIS 3D. The Finite Element Method (FEM) model sheds light on the propagation of vibrations along the track foundation of the railway path. Significant increases in vibration reduction can be achieved by incorporating dampening material, such as Sylomer, into the ballast material. Damping material affects the track-bed system's dynamic response, effectively minimizing vibration transmission to the surrounding soil and structures. The results from PLAXIS 3D's FEM model demonstrate this reduction in vibration propagation. Specifically, damping material alters the stress and displacement distribution inside the soil, indicating a more uniform and controlled reaction to dynamic loading from passing trains. Based on the experimental results of this investigation the following calculations can be drawn:

1) The effective implementation of vibration reduction measures dramatically reduces vibrations along the railway track, improving comfort and safety for neighboring households and structures.
2) Establishing a benchmark reference for soil parameters allows for exact analysis and prediction of ground behavior, supporting informed decision-making for future infrastructure projects.
3) The successful mitigation of railway vibrations results in a significant drop in stress levels encountered by surrounding structures, assuring long-term stability and integrity.

Abbreviations

LE	Linear Elastic
HSTs	High-Speed Trains
HALs	Heavy Axle Loads
FEM	Finite Element Method

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Author Contributions

Abu Sayeed: Conceptualization, Formal Analysis, Project administration, Supervision

Sudipta Saha: Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft

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Data Availability Statement

The data available from the corresponding author can be provided for verification purposes.

The data supporting the outcome of this research has also been mentioned in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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