# Multi-scale Numerical Analysis of Bituminous Railway Sub-ballast and Deep Learning Surrogate Model


Department of Civil Engineering

Indian Institute of Technology Kharagpur


MTP-I


Aditya Singh Anand 21CE31001

under the supervision of Dr. Arghya Deb

**DEPARTMENT OF CIVIL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR**

**KHARAGPUR - 721302, INDIA**

## *CERTIFICATE*

This is to certify that the project report entitled "**Multiscale Numerical Analysis of Bituminous Railway Sub-ballast and Deep Learning Surrogate Model**" submitted by Aditya Singh Anand (Roll no. 21CE31001) to Indian Institute of Technology Kharagpur towards partial fulfilment of requirements for the award of degree of Bachelor of Technology and Master of Technology in Civil Engineering is a record of bona fide work carried out by him under my supervision and guidance during the Autumn Semester, 2025-26

Prof. Arghya Deb
Department of Civil Engineering
Indian Institute of Technology Kharagpur
Kharagpur - 721302, India

Date: 25th Nov, 2025

Place: IIT Kharagpur

# DECLARATION

I certify that

(a) The work contained in this report has been done by me under the guidance of my supervisor.

(b) The work has not been submitted to any other Institute for any degree or diploma.

(c) I have conformed to the norms and guidelines given in the Ethical Code of Conduct of the Institute.

(d) Whenever I have used materials (data, theoretical analysis, figures, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references. Further, I have taken permission from the copyright owners of the sources, whenever necessary.

Date: 25th Nov, 2025 Aditya Singh Anand

Place: IIT Kharagpur 21CE31001

# Abstract

This research project addresses an issue that frequently occurs in railway maintenance as in what should be done when there is not sufficient time to properly compact the new bituminous sub-ballast underlayer? Poorly compacted asphalt tends to hold more air pockets, which in turn is believed to weaken the asphalt. In order to estimate the actual effect of this issue, I performed a 3d finite element model analysis for granular sub-ballast and bituminous sub-ballast with experimental values taken from experimental results and inculcated it in our model, after that I conducted runs on it, substituting various types of asphalt in order to observe how the rail would perform. The results were staggering with even the poorly compacted bituminous sub-ballast was identified as a great step forward compared to the conventional crushed stone layer it took place. The impact of the air voids content variation on the complete track performance was trivial.

Nevertheless, a vital issue was disclosed during the study of different computer simulation models. The Linear Elastic model overstated the amount of stretching the bituminous sub-ballast was experiencing, which might cause the engineers to think that it would crack too soon. On the contrary, the more sophisticated Linear Viscoelastic Model indicated that the strains were considerably lesser, thus the asphalt would last much longer that what the simple model indicated.

All in all, this study offers comforting proof to the railway engineers that the asphalt layering is an extremely advantageous option and the worries about the suboptimal compaction during limited construction periods may be exaggerated. The secret lies in the use of the right computer tools that would give an accurate prediction of its long term performance. A surrogate model was later carried out using Neural Networks to imitate fast displacements output in accordance with the needs.

# Introduction

**The Railway Problem: A Multilayered Challenge Simple Explanation:**

The railway track is not just a combination of steel rails and wooden sleepers. It is a huge, multi-layered construction that is directly erected on the original ground or subgrade layer. The critical job of each layer is to transfer the enormous weight of the trains passing by down to the earth below without changing its shape. You can think of it as a mattress system where the soft top layer is the one that comforts you, but it has to have a firm base below to stop you from sinking to the floor. The layered system has become unevenly settled over time due to the continuous heavy train axles pounding on it. This results in a bumpy ride, safety issues, and frequent maintenance that is both costly and disruptive to the railroad companies. Professional Elaboration: The basic structure of a ballasted railway track consists of the superstructure elements (rails and sleepers) and a granular substructure (ballast and sub-ballast) that ultimately transfers the load to the foundation soil (subgrade). The main reason for the deterioration of the track is the continuous accumulation of permanent deformation or differential settlement within these layers, which occurs under repeated cyclic loading. This deterioration is indicated by a deficiency in the vertical alignment of the track, which necessitates the performance of regular geometric corrections through maintenance interventions such as tamping. These activities represent a considerable percentage of the costs associated with the railway life cycle and they also cause operational disruptions resulting from the time needed for the tracks to be temporarily taken out of service. Soft and weak soils in the subgrade make the situation worse as they become the main source of settlement, a phenomenon often called "subgrade failure," which is the degradation of the subgrade.

**The Asphalt Solution: Enhancing Performance with Bituminous Sub-ballast Simple Explanation:**

In order to create a railway that lasts longer and is more stable, engineers came up with an inventive idea: the traditional crushed stone sub-ballast layer would be replaced by a thin but strong asphalt layer, which is also known as Bituminous Sub-ballast (BS). This is similar to swapping a dirt road with a concrete sidewalk. The asphalt layer acts like a hard and steady surface that distributes the train's weight over a broader area of the soil beneath. Therefore, the total settlement is lowered that much and at the same time the track structure is made more uniform and less affected by changes in the ground conditions below. Consequently, the track is smoother, and it keeps its shape for much longer, thus reducing maintenance to a great extent. Professional Elaboration: The use of a bituminous layer as a sub-ballast has become a powerful and effective technology in the enhancement of tracks. The layer adds several essential advantages when compared to unbound granular materials: Structural Enhancement: The overall stiffness (modulus) of the track system is increased significantly, resulting in a decrease in vertical deflections under the applied load. Stress Distribution: The layer serves as a stress-dissipating one, thus the vertical stress transmitted to the susceptible subgrade is reduced significantly, which in turn, plastic deformation is minimized. Homogeneity: It provides an even and continuous platform that lessens the impact of local subgrade inhomogeneities, thus, leading to more predictable track behaviour.

# Literature Review

The application of bituminous materials for railway trackbeds, particularly as a subballast layer, has gained much research attention as a way to improve the structural performance and life time of rail infrastructure. The current chapter is dedicated to the review of prior research related to bituminous sub-ballasts, including their advantages, mechanical behaviour as well as the importance of volumetric properties in that context.

## 1.1) Benefits of Bituminous Sub-ballast in Railway Engineering

Research in various forms such as field observations, numerical simulations, and laboratory testing have all pointed out to the advantages of adding a bituminous sub-ballast layer. Continuous reports from researchers like Rose & Bryson (2009), Albalat et al. (2011), and Cardona et al. (2016) indicated that the maintenance frequency for tracks with bituminous sub-ballasts is far lower than that of conventional all-granular structures. One of the remarkable revelations by the French National Railway Company (SNCF) was the reduction of 40% in the standard deviation of vertical stiffness in sections with bituminous sub-ballast which caused a more uniform track response and less differential settlement (Cardona et al., 2016). Moreover, the layer received credit for preventing mud pumping, managing vibrations and noise, and keeping the subgrade dry even in the case of moisture fluctuations, all thanks to its relatively low permeability (Robinet & Cuccaroni, 2010; Rangel et al., 2015).

## 1.2) Constitutive Behaviour and the Influence of Air Voids

The behaviour of bituminous mixtures is quite complicated and they show a viscous-elastic behaviour that depends on time and temperature. This electric nature of road pavements is known, but its importance in railway sub-ballast applications, where conditions of stress and loading differ, is still being investigated. In trying to capture this phenomenon, various studies have resorted to numerical modelling methods with some using simple linear elastic (LE) models and others opting for more computationally demanding linear viscoelastic (LVE) approaches (Di Mino et al., 2012; Teixeira et al., 2010). One of the main factors that affects the mechanical properties of bituminous mixtures is the air voids content. Strong inverse relationship between air voids content and stiffness has been firmly established. The works of Harvey & Tsai

(1996) and Ma et al. (2016) who did DEM and lab studies showed that less air voids content leads to greater flexural stiffness and longer fatigue life. Ma et al. (2016) further clarified that the air voids' configuration is equally as important as the amount, with their being interconnected at the bottom of a layer being especially bad for the layer. This is in line with the findings of Hofko et al. (2012) and Underwood & Kim (2013), who noted that increasing air void content substantially lowers the dynamic modulus and strength of asphalt mixtures.

### 1.3) Identified Research Gap:

The importance of low air voids (typically <5%) for optimal performance has been very well documented, yet still such conditions are not always met because of the practical challenges during the railway maintenance that, among others, include short work windows and poor platform support. As a result, inadequately compacted areas and higher than designed air voids content in the field may occur (Alves, 2018; Liden & Joborn, 2016). Nowadays, there is great knowledge about the effect of air voids on fundamental material properties, particularly on roads, however, no comprehensive studies exist that would quantify this aspect of construction-induced variability on the overall mechanical response of a railway track system. Most of the existing numerical models are either based on the assumption of perfect compaction, or they do not determine the impact of air voids on the structure by systematically varying air voids. No doubt, the gap exists between the validation of a 3D finite element model with field data to explicitly demonstrate how variations in air voids content (e.g., from 4% to 10%) affect critical track responses such as displacements, stresses on the subgrade, and strains in the bituminous layer under realistic railway loading conditions. Validation of the finite element model is utilized for calibration of the 3D numerical model as the present study tackles this gap by utilizing it to determine the sensitivity of track performance to air voids content in the bituminous sub-ballast, which will lead to more robust design and construction tolerances.

# Goals and Objective

Specific Objectives:

**Numerical Model Development**: To create an accurate and verified three-dimensional (3D) Finite Element Model (FEM) of the railway track using ABAQUS software, which will include the actual geometry, boundary conditions, and loading from a real instrumented railway site.

**Performance Simulation and Analysis**: The conducting of the track's material properties taken from the experiments into the FEM and the study of the track's reaction to static loading for different cases will be done in this regard, the following will be included in the analysis: Vertical displacements at the rail seat.

**Comparative Analysis:** The following comparisons will be made between: The performance of the track subjected to being paved with bituminous sub-ballast and that with traditional granular sub-ballast. Different air void contents of (4%, 8%, 10%) in the bituminous layer. The results achieved with a simplified Linear Elastic (LE) constitutive model versus a more realistic model. Then a Linear Viscoelastic model will be setup using Prony series coefficients to give better accurate results of downward displacements along with a surrogate model made using Neural Networks to yield us displacement results close to our accurate values.

# Material Characterization

## *Material-Source-and-Composition:*

The bituminous mixture utilized in this research came straight from a production haul truck during the overhaul of a heavy-haul freight railway line in Brazil to guarantee its relevance and practical applicability to the study. The mixture comprised granite aggregates mixed with a standard 50/70 penetration grade bitumen. As per the best practices for moisture resistance in pavement layers, 2% of hydrated lime (Type CH-I) was incorporated into the aggregate matrix to function as an anti-stripping agent. The aggregate gradation and binder content conformed to the Brazilian specification DNIT 031/2004 for an intermediate course with a nominal maximum aggregate size of 25 mm. The final job mix formula that was used in the field had a binder content of 4.8% by weight of total mix.

## *Volumetric Compaction Study and Specimen Grouping:*

One of the main aims during the laboratory phase was to imitate the variety of compaction densities that could be reached in the field. In order to achieve this, a single batch of loose mixture was taken, reheated, and compacted into specimens for three different levels of air void content. This method allows one to exclusively study the influence of air voids, because all the other factors (binder content, aggregate gradation, binder type) are kept constant.

Three Groups were established accordingly:

<u>Group I (4% air voids):</u> Representing high quality compaction, inferring an ideal scenario where the compaction is done perfectly.

<u>Group II (8% air voids):</u> Representing average to poor compaction, a likely scenario given short maintenance window and challenging subgrade conditions.

<u>Group III (10% air voids):</u> Represents poorly compacted pavement.

# Resilient Modulus Test

*Principle:*

The Resilient Modulus (Rm) is a primary mechanical property that determines a substance's elastic stiffness during transient loading situations. It is characterized as the proportion of the imposed cyclic deviator stress to the elastic (resilient) axial strain that can be recovered. The Rm is one of the main parameters for mechanistic design and linear-elastic numerical modelling for unbound and bound granular materials in pavement and railway structures since these materials are subjected to countless quick, non-destructive load pulses from traffic. The experiment replicates the quick loading and unloading cycle associated with the passage of a train wheel over a specific point on the track. The material's ability to recover its deformation elastically is the factor that grants the long-term stability of the track's geometric configuration.

*Test Methodology:*

The testing was done according to the ASTM D7369-11 standard "Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension." A cylindrical specimen is subjected to a haversine-shaped compressive load at the centre of its vertical diametrical axis. The load pulse lasted for 0.1 seconds and had a 0.9-second resting phase, thus imitating the stress pulse of a moving wheel load. The resulting deformations in the horizontal and vertical directions across the specimen's diameter were accurately measured by Linear Variable Differential Transformers (LVDTs). The resilient modulus was then determined by applying the theory of elasticity for a diametrically loaded cylinder.

# Resilient Modulus Test Results:

| Group | Air Voids Conter | Average Resilient Modulus (MPa) | |
|---|---|---|---|
| I | 4 | 6655 | |
| II | 8 | 5558 | |
| III | 10 | 4244 | |

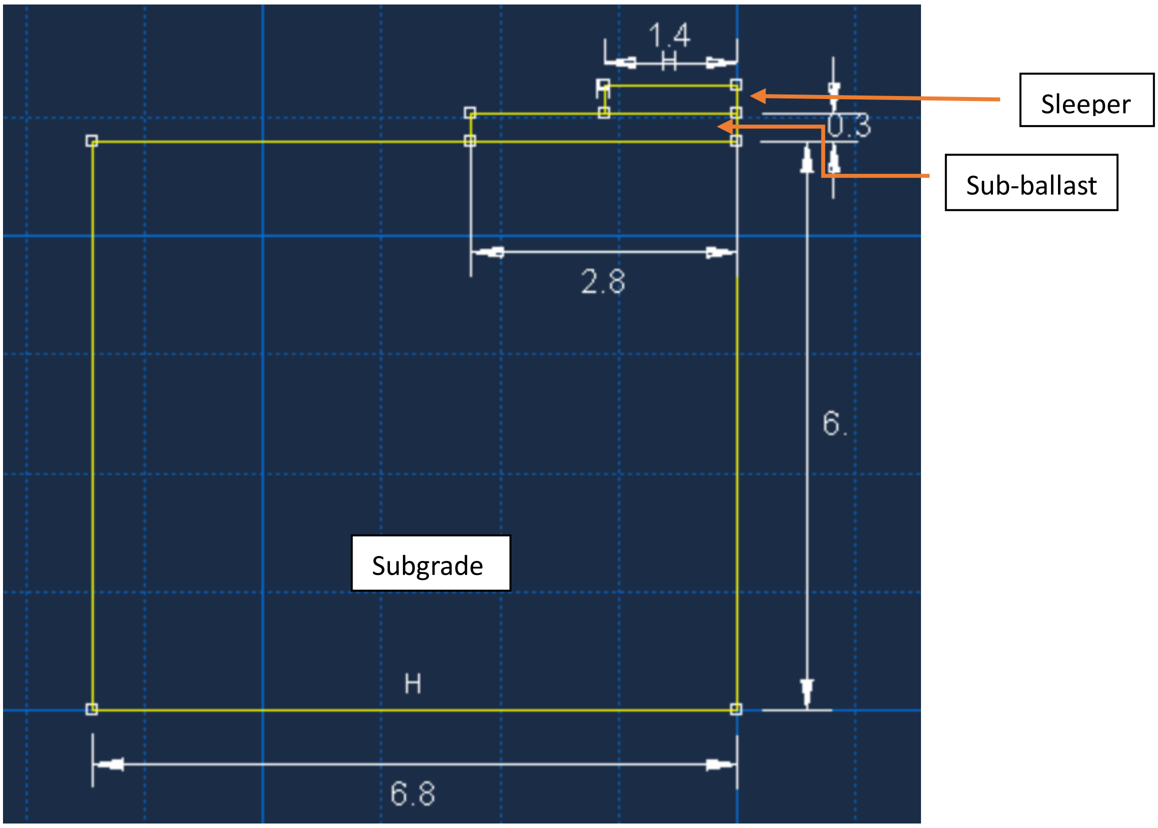
The results indicate that there is a significant inverse correlation between the air void content and the stiffness of the material. Increasing the air void content from 4% to 10% caused the Resilient Modulus to decrease by 36% (i.e., from 6655 MPa to 4244 MPa). This phenomenon is due to the fact that there is less solid mass supporting the load and the internal structure becomes less uniform with the larger air voids. The aggregate skeleton is not as compactly filled and there are more stress concentrations around the air pockets resulting in larger deformations for the same load applied.

This quantified reduction in (Rm) offers the main input parameter for the Linear Elastic (LE) constitutive model employed in the subsequent numerical simulations, thus permitting a direct evaluation of the impact of construction-induced density variations on the macro-scale stiffness of the sub-ballast layer.

# Numerical Modelling- The Granular Baseline

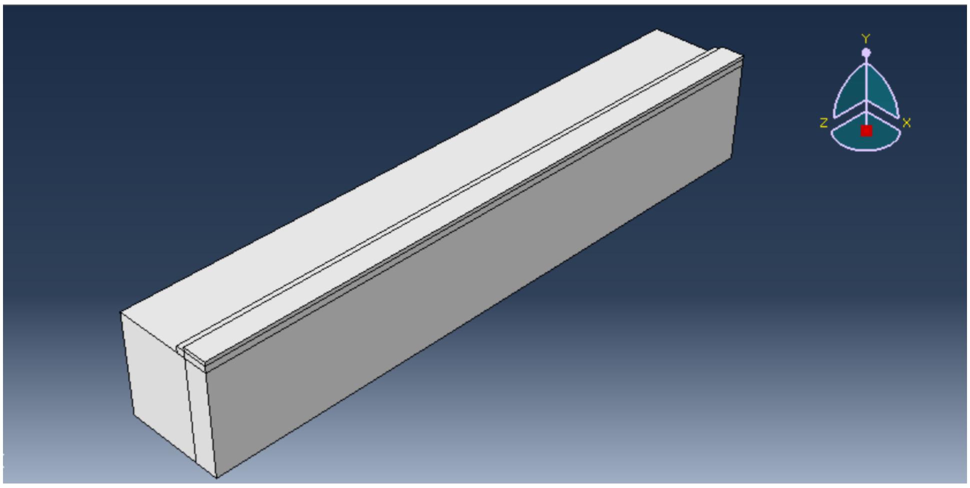
The Granular Ballast Only model is the conventional railway track design. The track system of this design is composed only of loose granular materials under the sleeper level. This model plays the role of the critical reference or control case for measuring the performance of the creative bituminous sub-ballast solutions. It quantifies the "status quo" in terms of displacements, stresses, and strains that are typical for a standard track and gives a reference point for the future trials of any alternative design to wrongly or rightly claim the advantages.

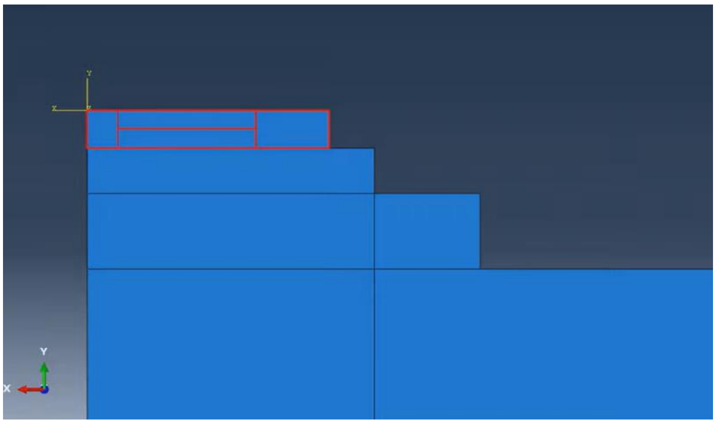
## Model Geometry:



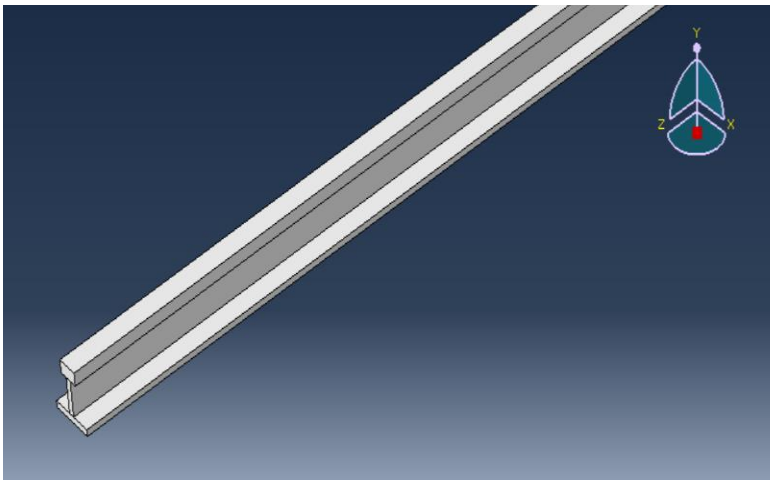
# Components

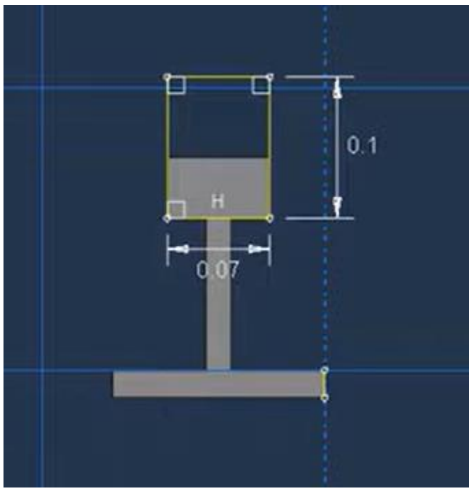
1) Structure:



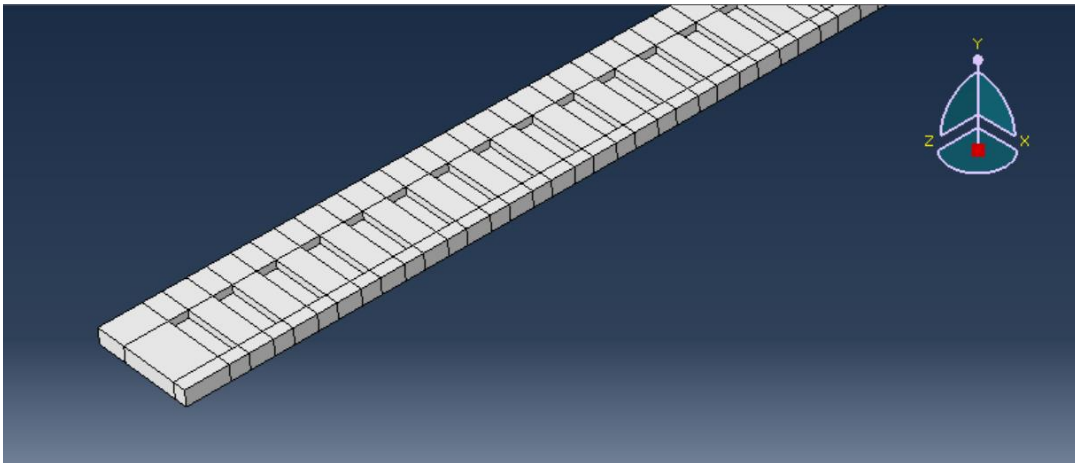




2) Rail (115RE):

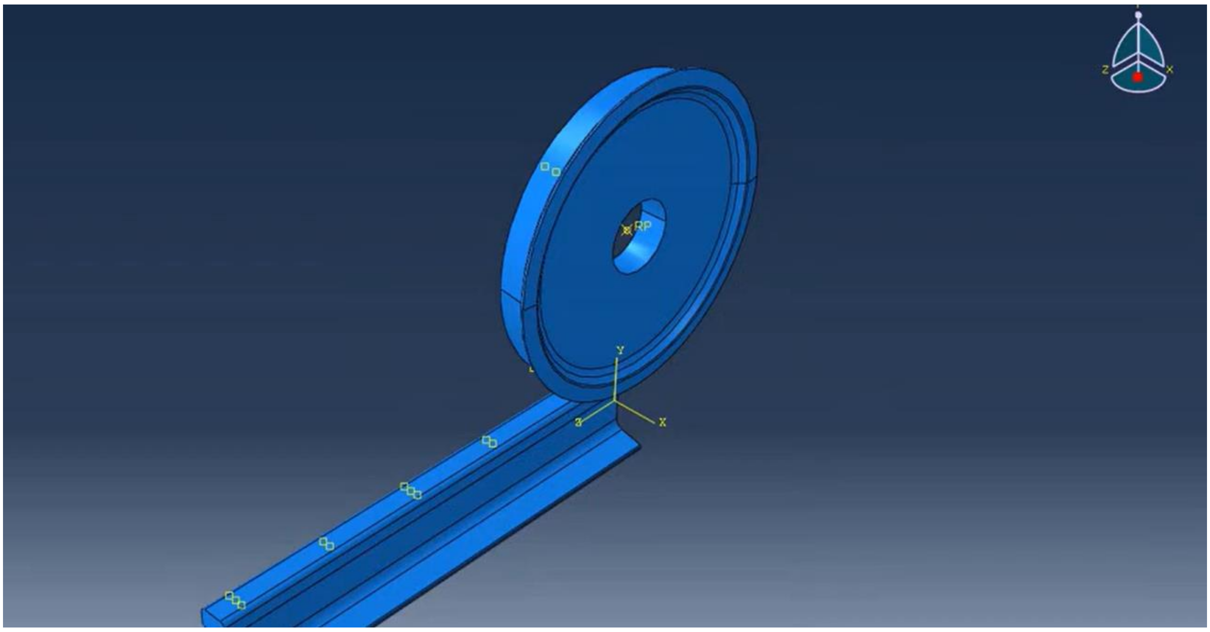


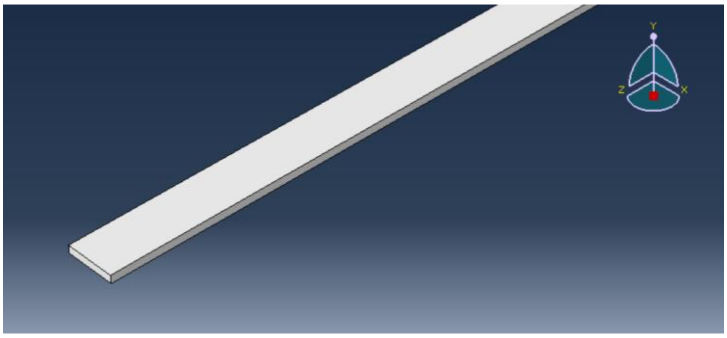
3) Sleepers:




4) Wheel Load:




5) Granular Sub-ballast:



# Material Properties

## Rail 115RE:

Data

| | Mass Density |
|---|---|
| 1 | 7850 |

Data

| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 205000000000 | 0.30 |

## Sleeper:

Data

| | Mass Density |
|---|---|
| 1 | 700 |

Data

| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 13000000000 | 0.3 |

## Granular Sub-ballast:

Data

| | Mass Density |
|---|---|
| 1 | 2100 |

Data

| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 1.5e8 | 0.35 |

## Subgrade:

Data

| | Mass Density |
|---|---|
| 1 | 1900 |

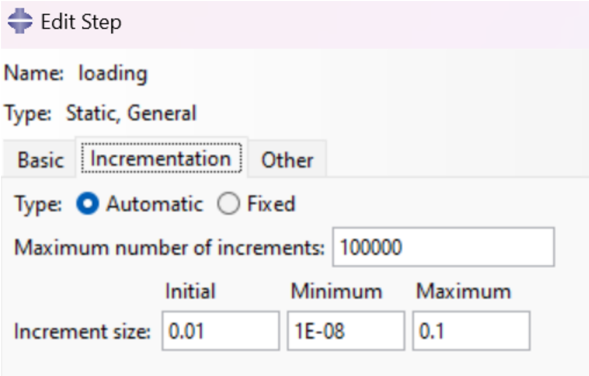
Data

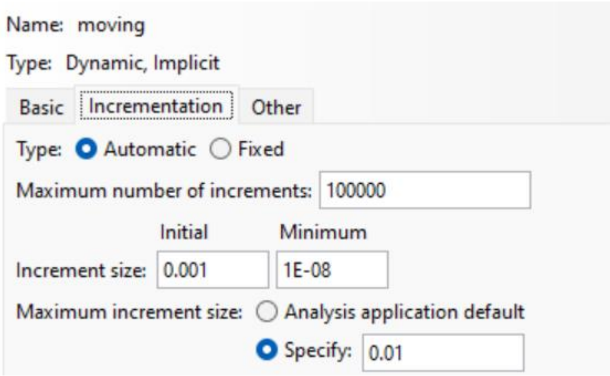
| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 2e7 | 0.40 |

Table 4.1: Material Properties for the Granular Baseline Model

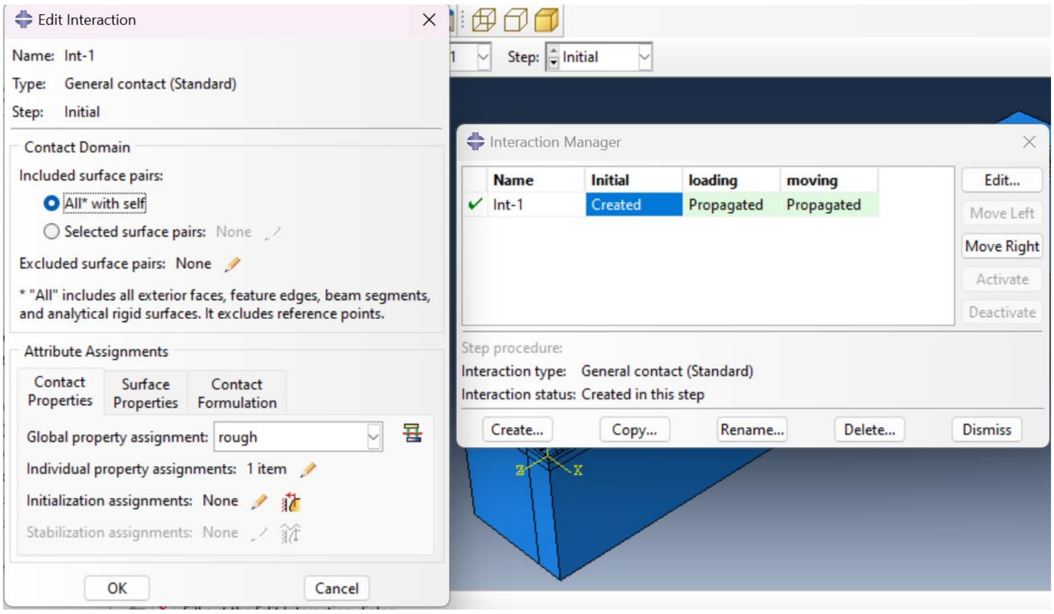
| Component/Layer | Model | E | v | Density | Element |
|---|---|---|---|---|---|
| Rail (115RE) | Linear Elastic | 205 GPa | 0.3 | 7850 kg/m³ | C3D8R |
| Sleeper (Wood) | Linear Elastic | 13 GPa | 0.3 | 700 kg/m³ | C3D8R |
| Granular Subballast | Linear Elastic | 150 MPa | 0.35 | 2100 kg/m³ | C3D8R |
| Subgrade | Linear Elastic | 20 MPa | 0.4 | 1900 kg/m³ | C3D6 |

## Step: Static and Dynamic

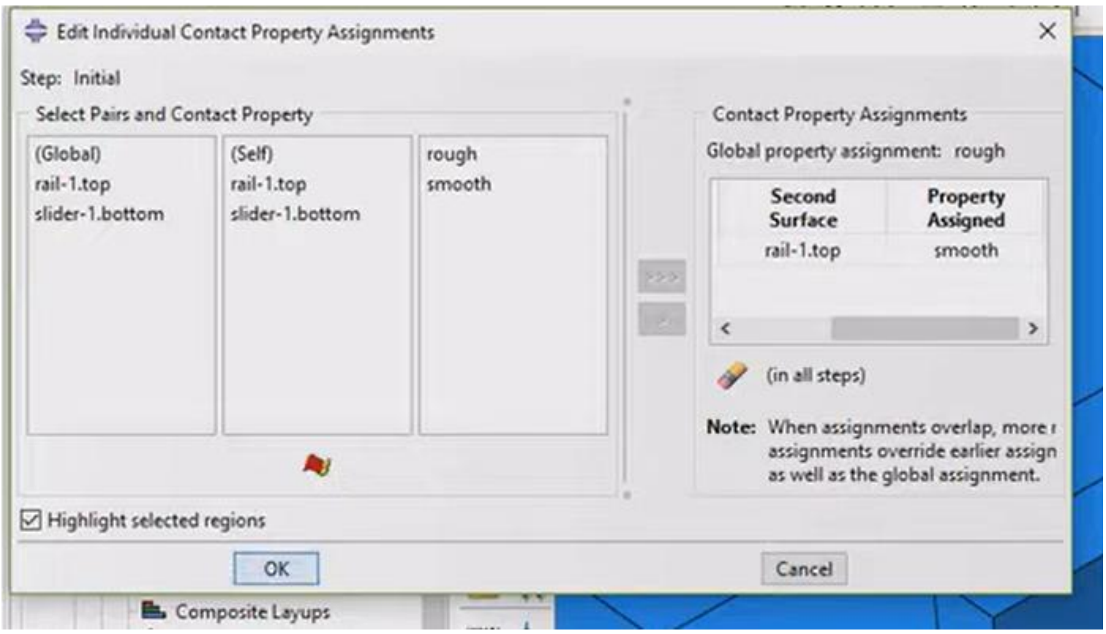


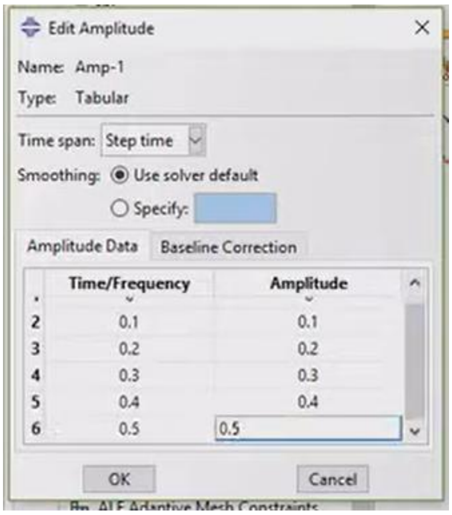

## Interaction:



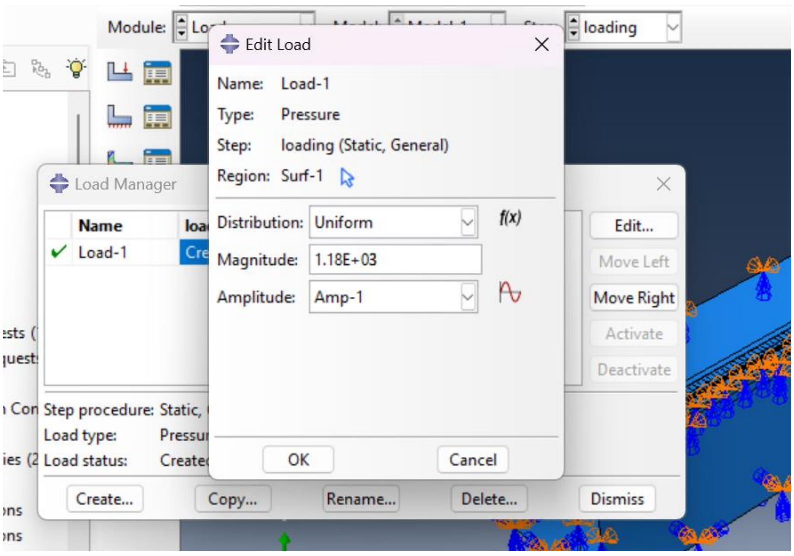

The interaction was applied to two surfaces rail_top and slider_bottom



# Loading:

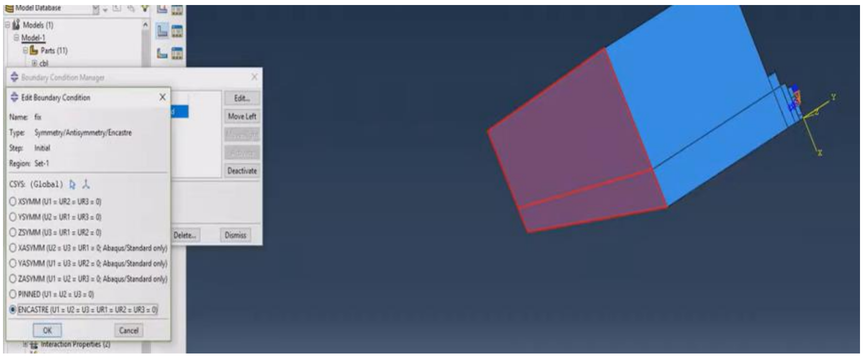


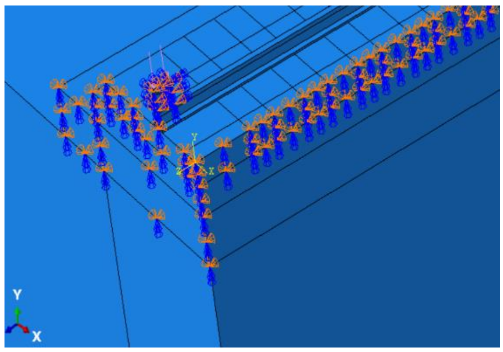

This is a time-dependent load amplitude definition that controls how a load is applied during the simulation. Load of 118kN being applied on top of the wheel.



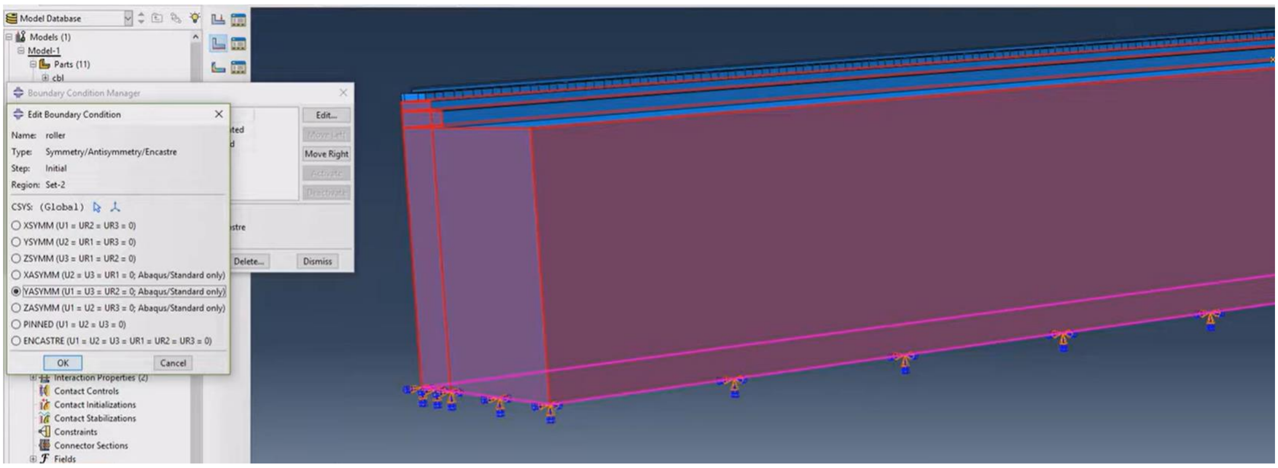

## Boundary Conditions:

ENCASTRE: Fully fixed



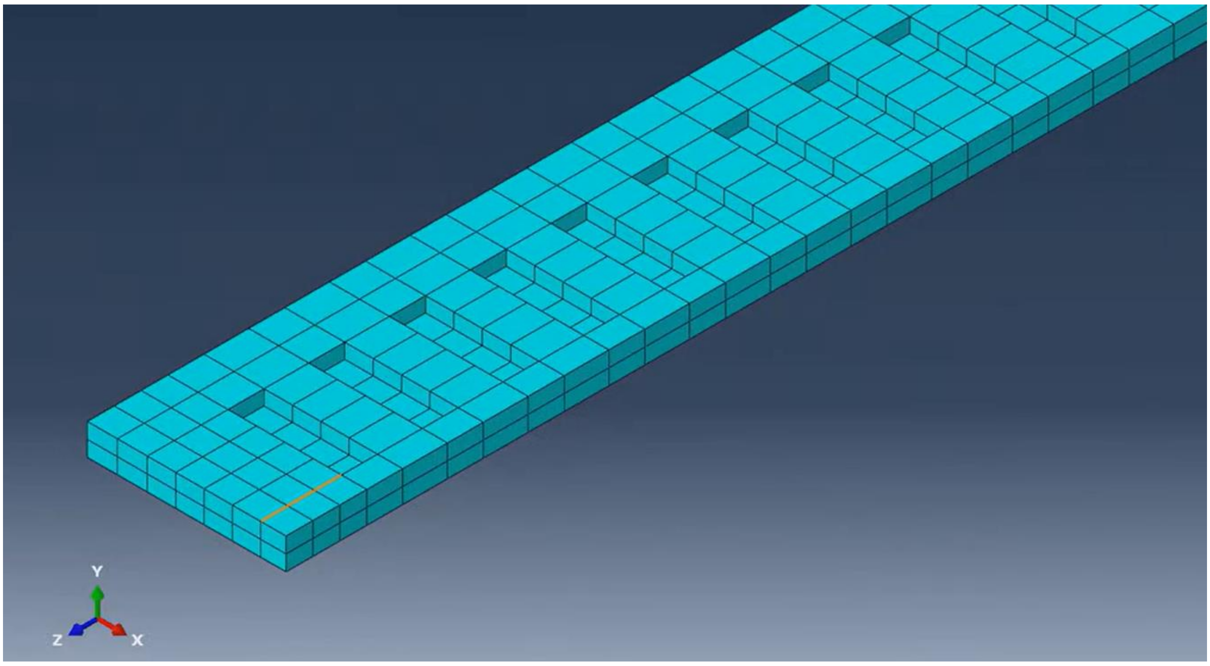


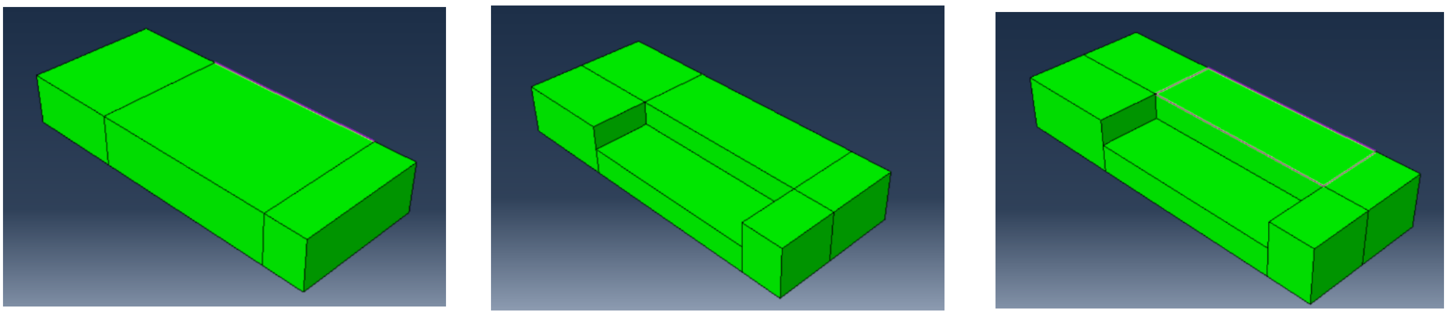
YASYMM (u1=u2=0)



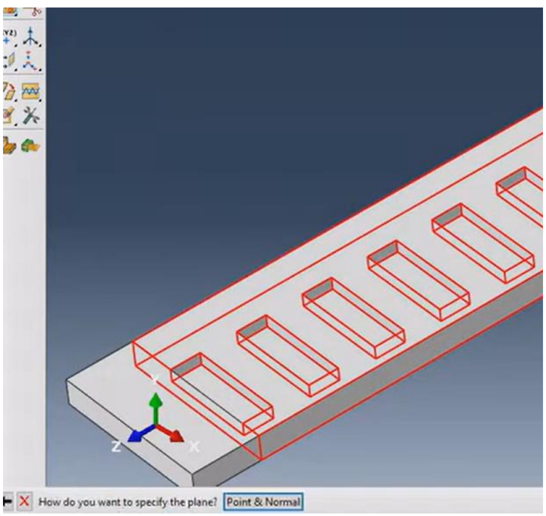
# Meshing and Convergence

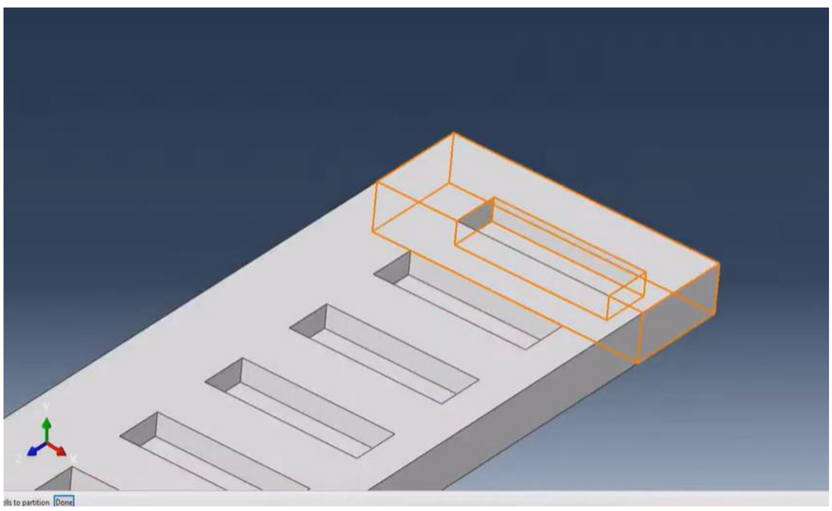
A mesh sensitivity study was conducted prior to the final analysis. The mesh was progressively refined until the key output parameters (vertical displacement under the rail, vertical stress on the subgrade) changed by less than 2% between subsequent refinements. The final mesh consisted primarily of 8-node linear brick elements (C3D8R) for the track layers and 6-node linear triangular prism elements (C3D6) for the subgrade.



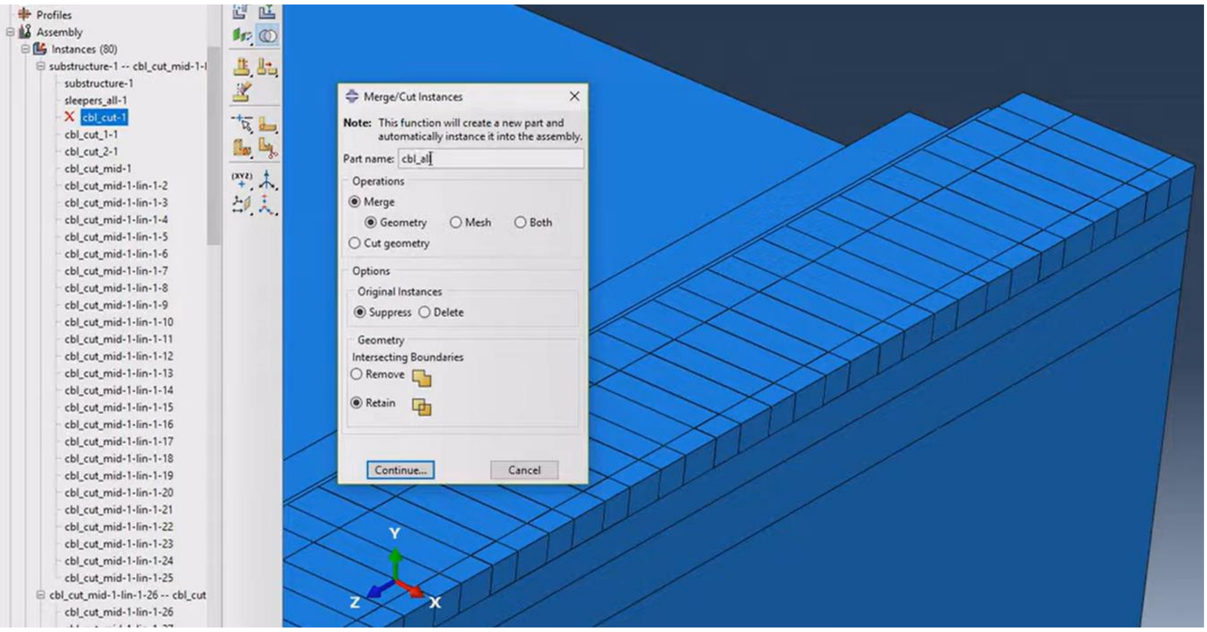



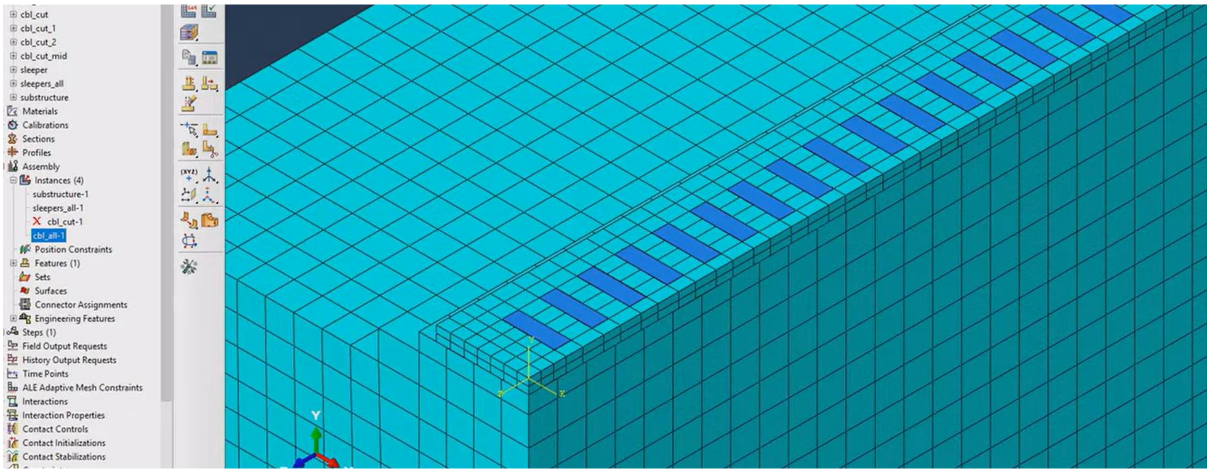
Rail sleeper front, mid and portion discretized

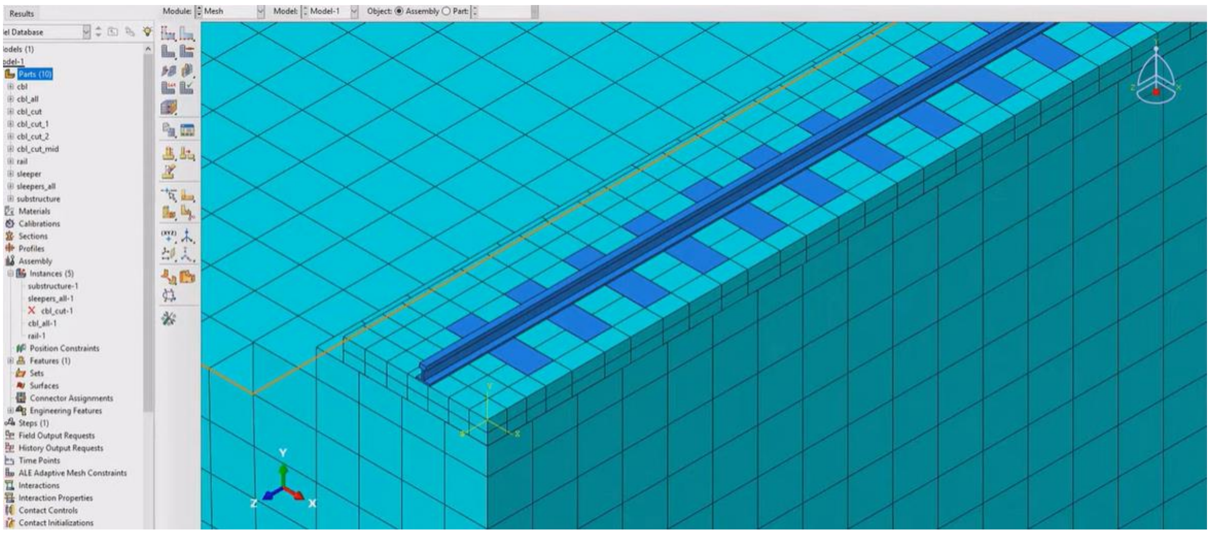


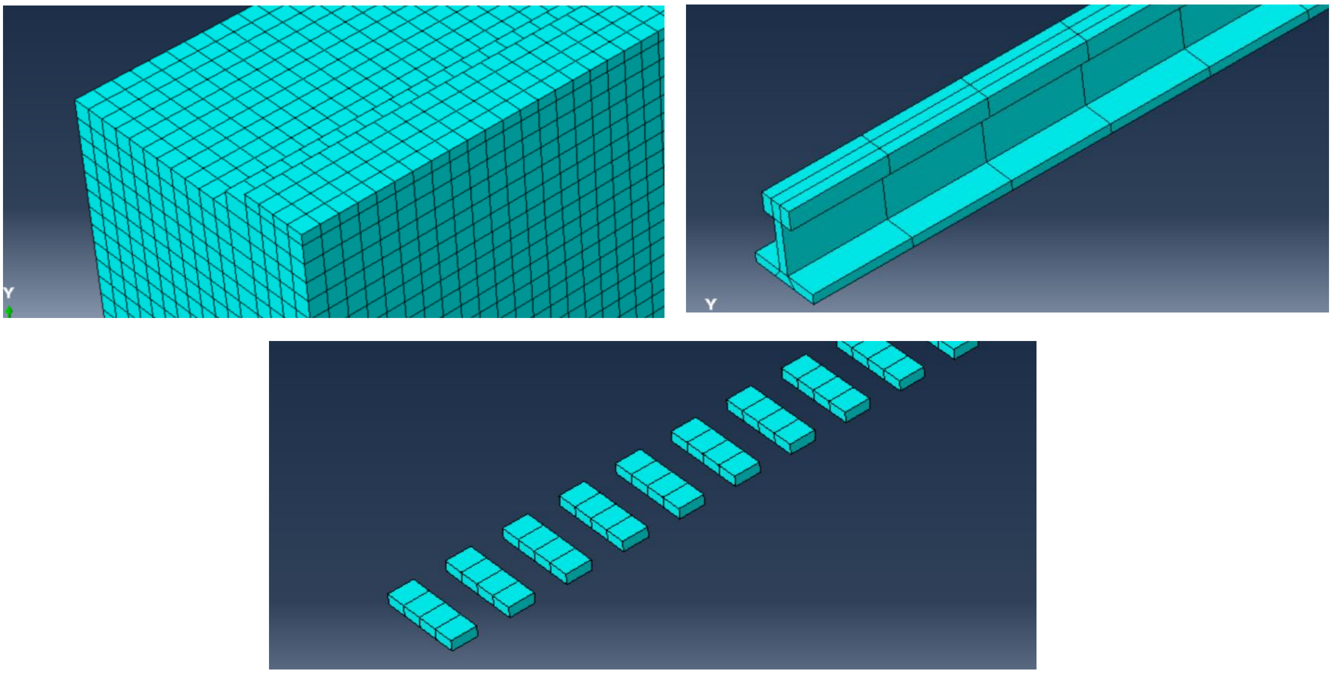
# Merging and suppressing features:

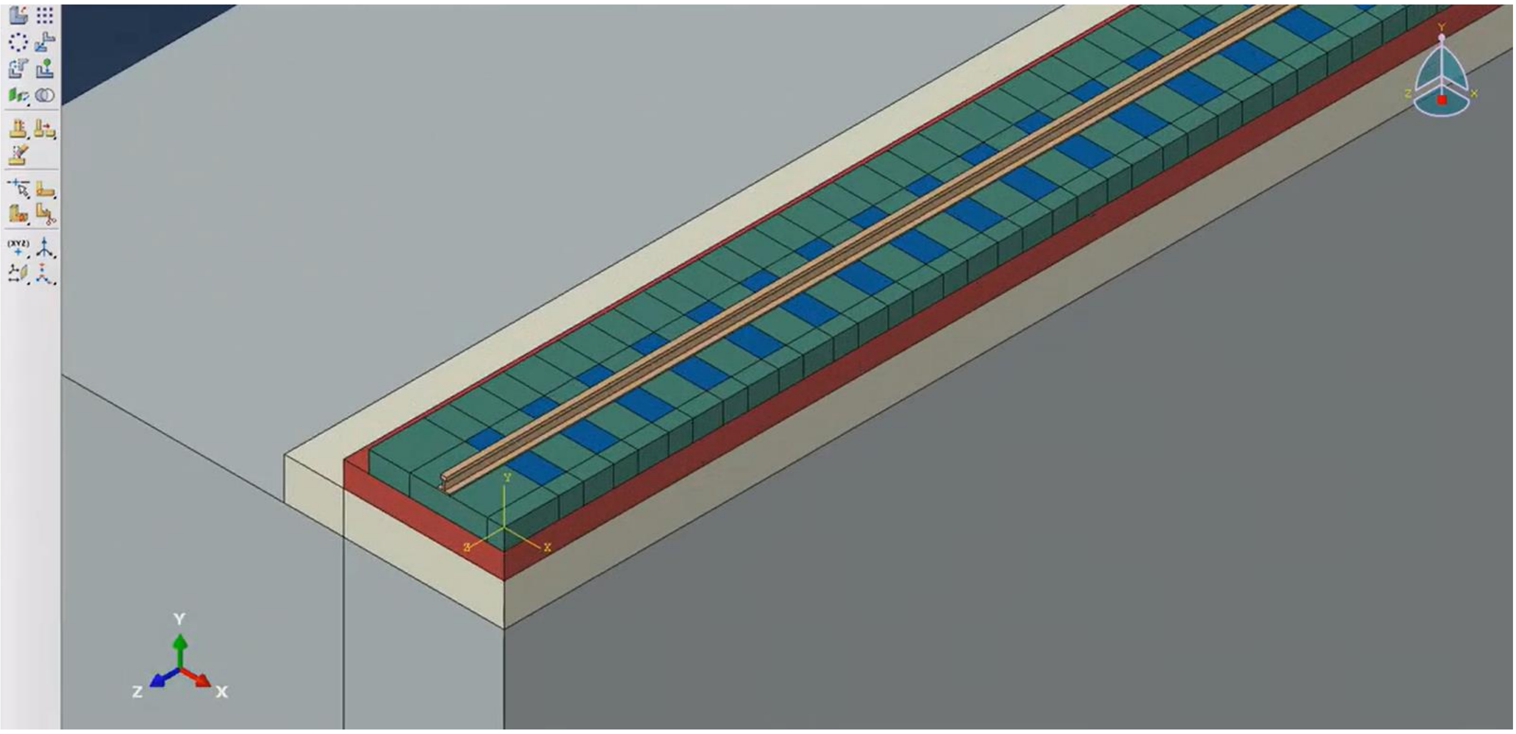



Meshing for sleepers and rail

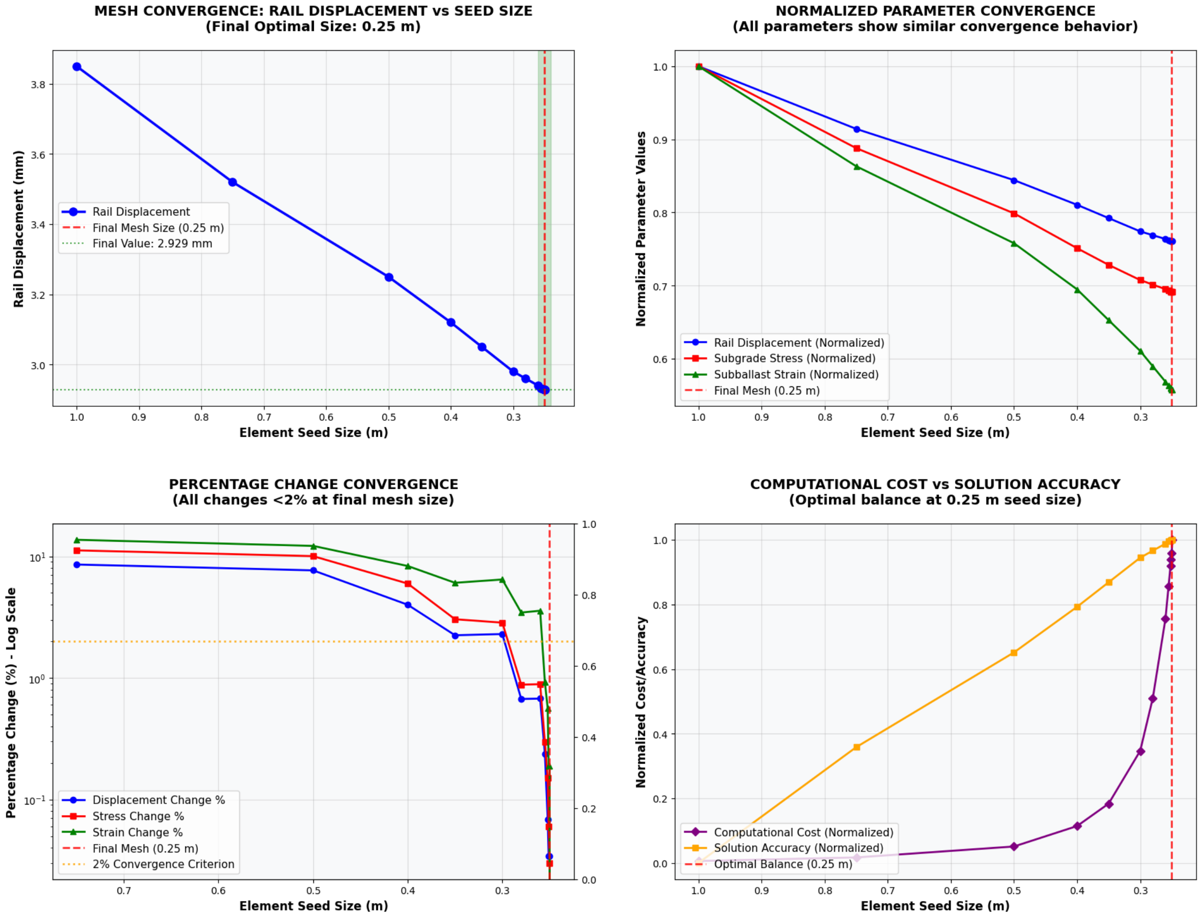




Mesh model for sleepers and tracks

# Convergence Study:

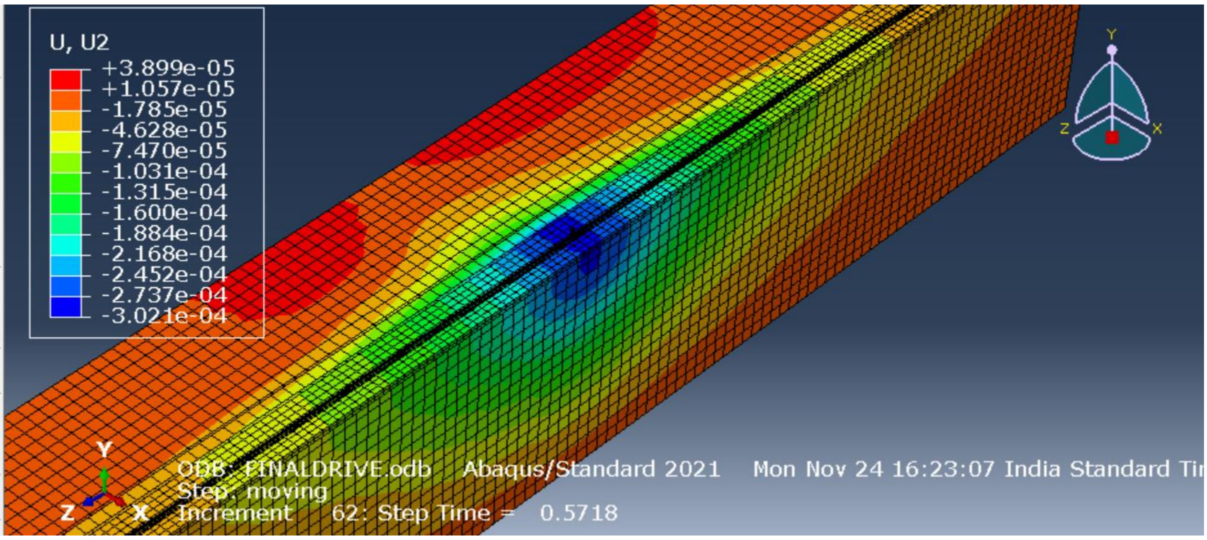
Iteratively refining the mesh until the change in displacements becomes negligible.

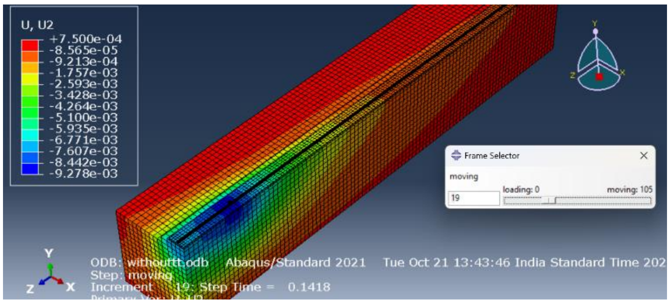


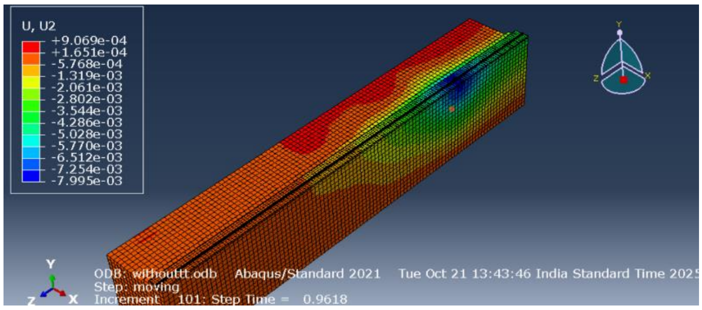

| | Mesh_ID | Seed_Size_m | Num_Elements | Rail_Disp_mm |
|---|---|---|---|---|
| 0 | M1 | 1.000 | 8500 | 3.850 |
| 1 | M2 | 0.750 | 18500 | 3.520 |
| 2 | M3 | 0.500 | 42000 | 3.250 |
| 3 | M4 | 0.400 | 78000 | 3.120 |
| 4 | M5 | 0.350 | 115000 | 3.050 |
| 5 | M6 | 0.300 | 185000 | 2.980 |
| 6 | M7 | 0.280 | 235000 | 2.960 |
| 7 | M8 | 0.260 | 295000 | 2.940 |
| 8 | M9 | 0.255 | 315000 | 2.933 |
| 9 | M10 | 0.252 | 325000 | 2.931 |
| 10 | M11 | 0.251 | 328000 | 2.930 |
| 11 | M12 | 0.250 | 332000 | 2.929 |
| 12 | M13 | 0.249 | 338000 | 2.929 |

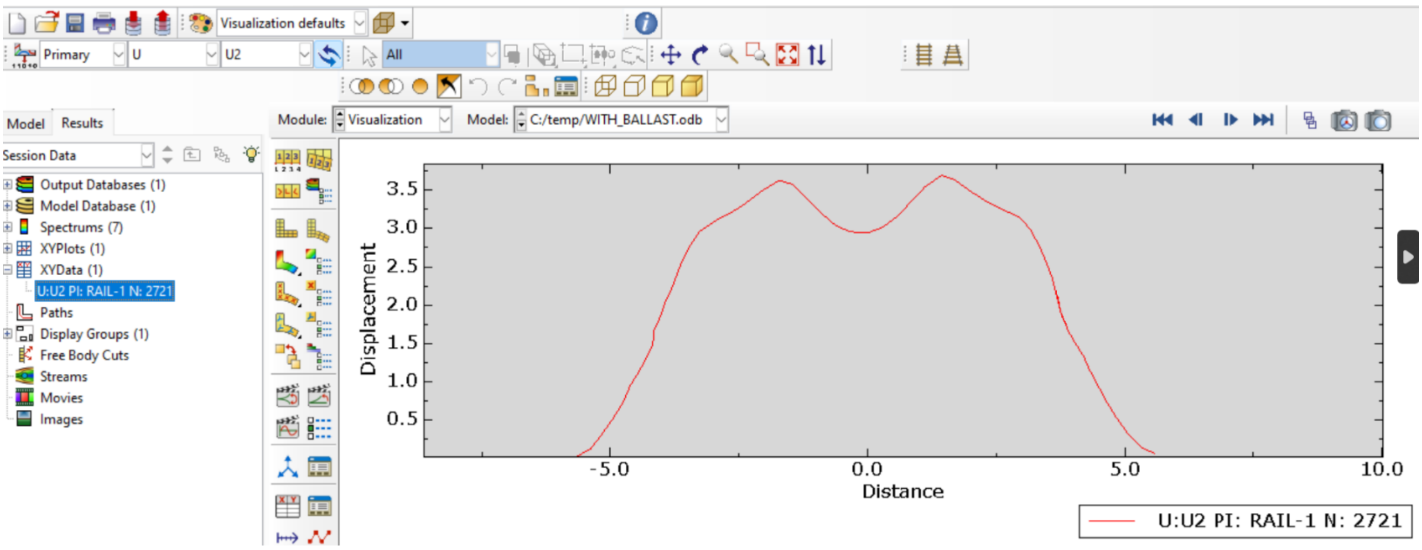
# Results for Granular Sub-ballast

Visualization:




Displacement along the path for the static load 118kN

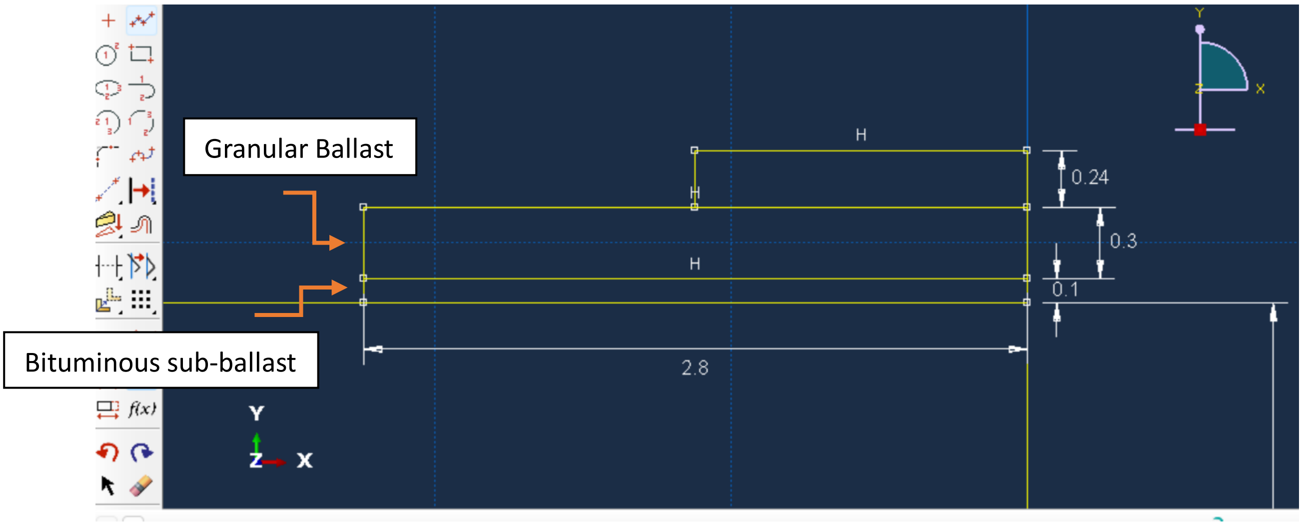
# Bituminous Sub-ballast Modelling

## Model Concept and Strategy:

Now we extend our model to the addition of Bituminous sub-ballast addition with the original granular sub-ballast in place, then we carry out analysis for two key aspects, first material behaviour for both Linear Elastic and Linear Viscoelastic analysis and then impact of air void variations on track performance.

## Linear Elastic Analysis:

1) Geometry Modification:




2) Properties for the Bituminous Sub-Ballast

i) Group 1: Ideal case with **4% Air Voids**

Data

| | Mass Density |
|---|---|
| 1 | 2450 |

Data

| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 6.655e9 | 0.35 |

ii) Group 2: Average compaction with **8% air voids**

Data

| | Mass Density |
|---|---|
| 1 | 2350 |

Data

| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 5.558e9 | 0.35 |

iii) Group 3: Poor compaction with 10% air voids

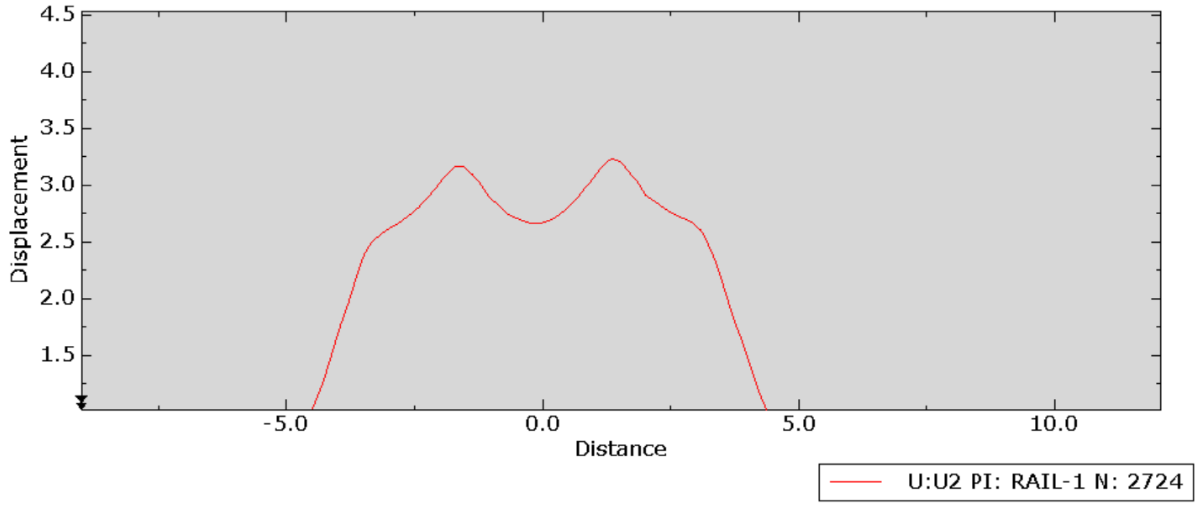
Data

| | Mass Density |
|---|---|
| 1 | 2300 |

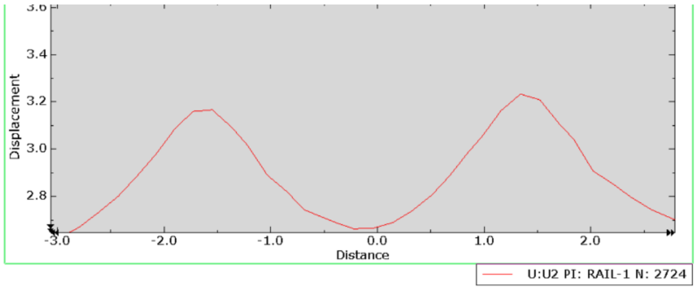
Data

| | Young's Modulus | Poisson's Ratio |
|---|---|---|
| 1 | 4.244e9 | 0.35 |

# Results for Linear Elasticity (Bituminous)

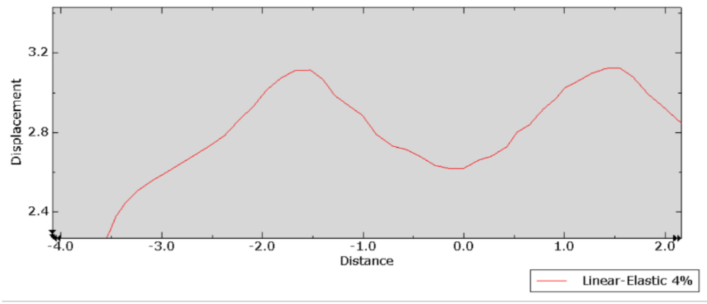



10% Air Void:



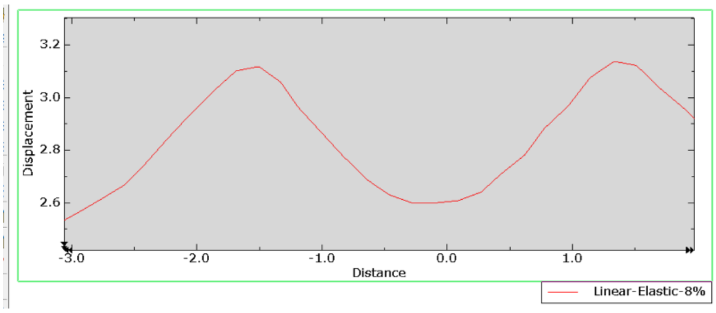

*Max Displacement: 3.22310 mm*

4% Air Void




*Max Displacement: 3.11479 mm*

8% air void




*Max Displacement: 3.13756 mm*

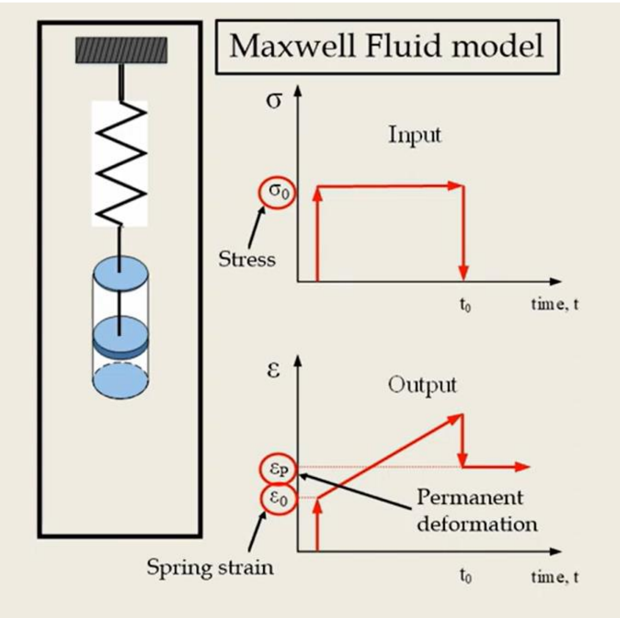
# Linear Viscoelastic Analysis

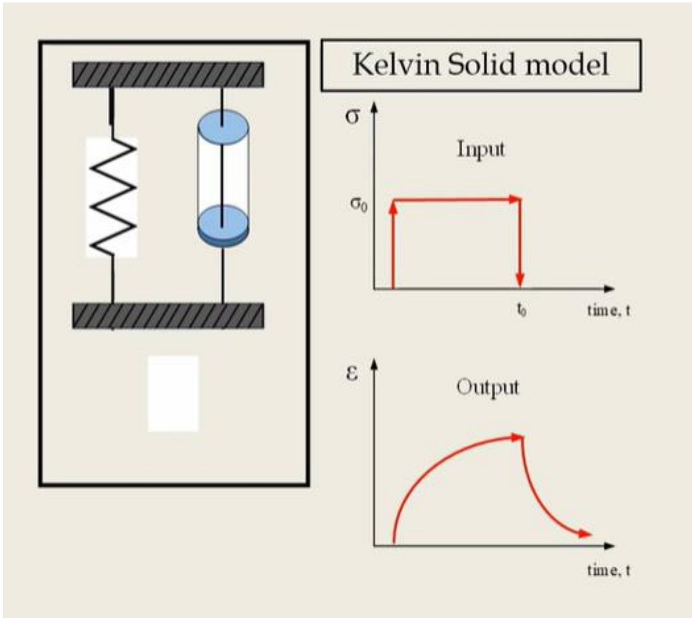
Imagine a spring (elastic part) and a dashpot/piston in oil (viscous part) combined. The spring gives instant response, while the dashpot gives slow, time-dependent response. The bituminous sub-ballast behaves exactly like this combination.

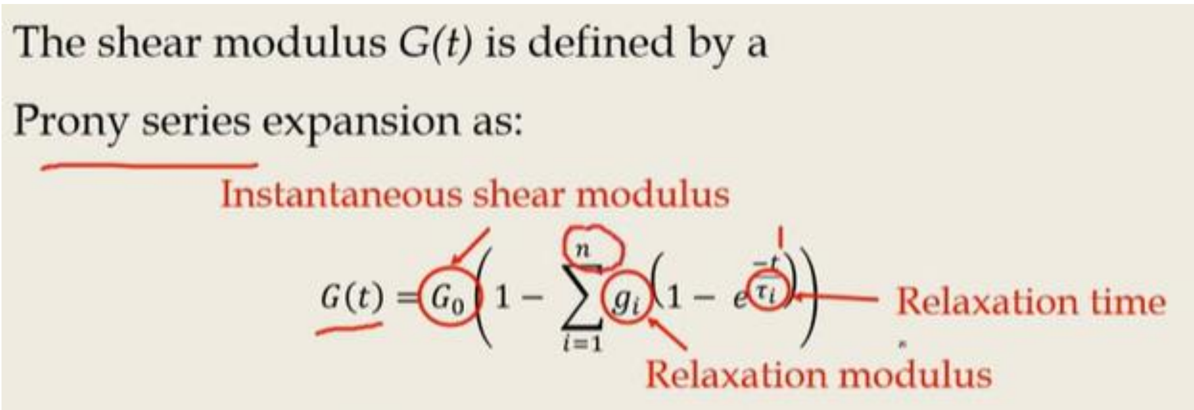
Viscoelastic materials exhibit both:

**Elastic Solid Behaviour:** Instantaneous deformation, full recovery

**Viscous Fluid Behaviour:** Time-dependent deformation, permanent strain

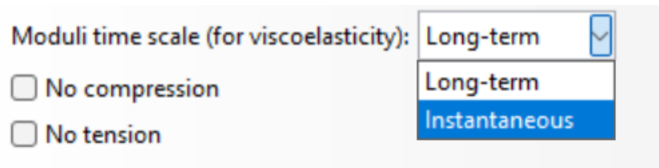


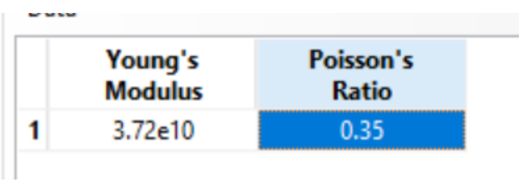



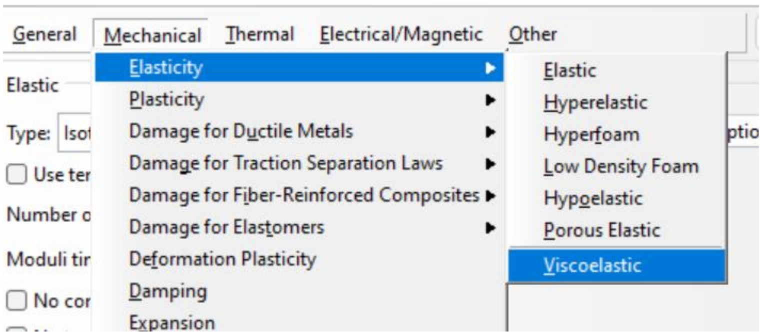



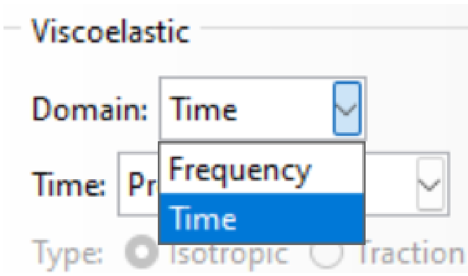

In order to determine the time dependent stress-strain state in a linear viscoelastic material, under an arbitrary loading process, the deformation history must be considered. The time dependent constitutive equations of a solid viscoelastic material include these history effects. The load (stress) and displacement (strain) history, the loading rate and time of load application on the specimen are all needed to determine the constants in the constitutive equations, a common form for these constitutive equations employs a Prony series as shown above.

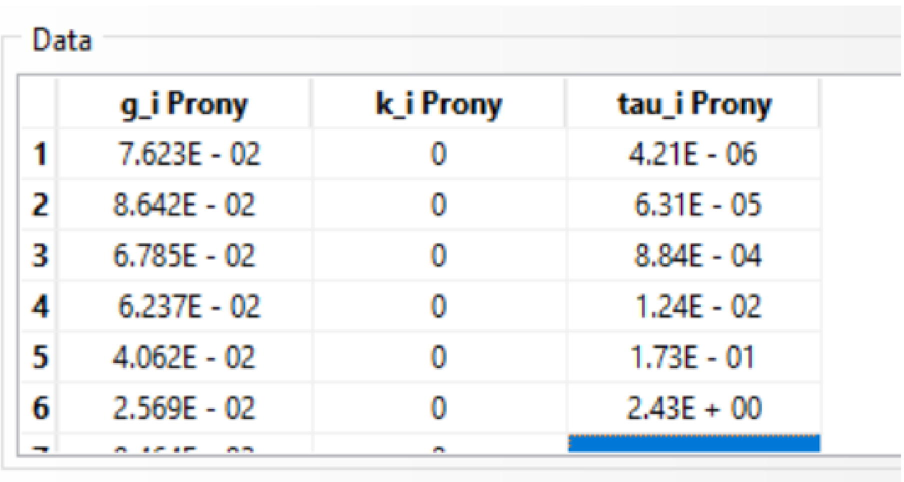
| BS (Air voids = 4.7%) | | BS (Air voids = 7.9%) | | BS (Air voids = 9.5%) | |
|---|---|---|---|---|---|
| Instantaneous modulus (Pa) | 3.72E + 10 | Instantaneous modulus (Pa) | 2.64E + 10 | Instantaneous modulus (Pa) | 2.68E + 10 |
| $\tau_i$ (s) | $g_i$ (ratio) | $\tau_i$ (s) | $g_i$ (ratio) | $\tau_i$ (s) | $g_i$ (ratio) |
| 2.52E − 05 | 7.075E − 02 | 1.43E − 05 | 7.110E − 02 | 4.21E − 06 | 7.623E − 02 |
| 2.52E − 04 | 6.107E − 02 | 1.86E − 04 | 7.101E − 02 | 6.31E − 05 | 8.642E − 02 |
| 3.79E − 03 | 6.728E − 02 | 2.23E − 03 | 7.484E − 02 | 8.84E − 04 | 6.785E − 02 |
| 3.79E − 02 | 6.113E − 02 | 2.68E − 02 | 6.068E − 02 | 1.24E − 02 | 6.237E − 02 |
| 3.79E − 01 | 5.051E − 02 | 3.26E − 01 | 4.931E − 02 | 1.73E − 01 | 4.062E − 02 |
| 4.16E + 00 | 3.817E − 02 | 3.98E + 00 | 3.187E − 02 | 2.43E + 00 | 2.569E − 02 |
| 5.41E + 01 | 1.642E − 02 | 4.38E + 01 | 7.802E − 03 | 3.64E + 01 | 9.464E − 03 |
| 7.04E + 02 | 3.406E − 03 | 4.82E + 02 | 2.546E − 03 | 4.37E + 02 | 6.400E − 04 |
| 9.15E + 03 | 6.266E − 04 | 5.30E + 03 | 2.653E − 04 | 5.24E + 03 | 4.032E − 04 |



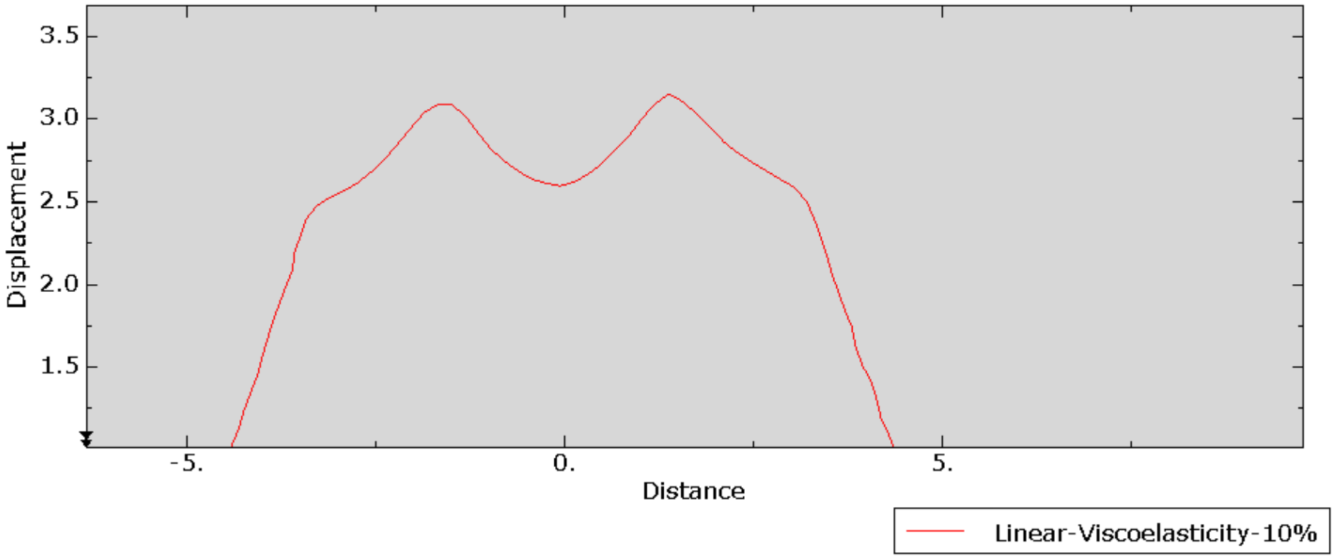



Data

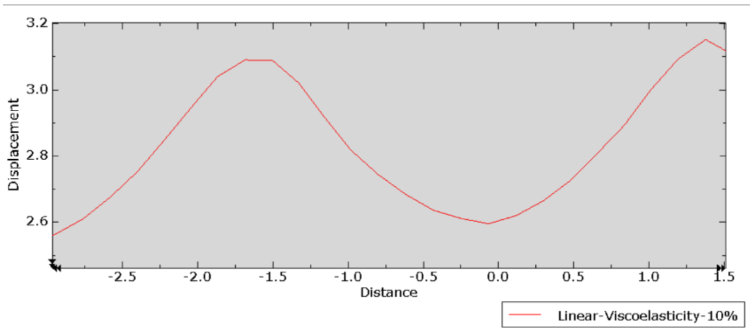
| | g_i Prony | k_i Prony | tau_i Prony |
|---|---|---|---|
| 1 | 7.623E - 02 | 0 | 4.21E - 06 |
| 2 | 8.642E - 02 | 0 | 6.31E - 05 |
| 3 | 6.785E - 02 | 0 | 8.84E - 04 |
| 4 | 6.237E - 02 | 0 | 1.24E - 02 |
| 5 | 4.062E - 02 | 0 | 1.73E - 01 |
| 6 | 2.569E - 02 | 0 | 2.43E + 00 |

10% Void input params for the Prony series

# Results for Linear-Viscoelasticity

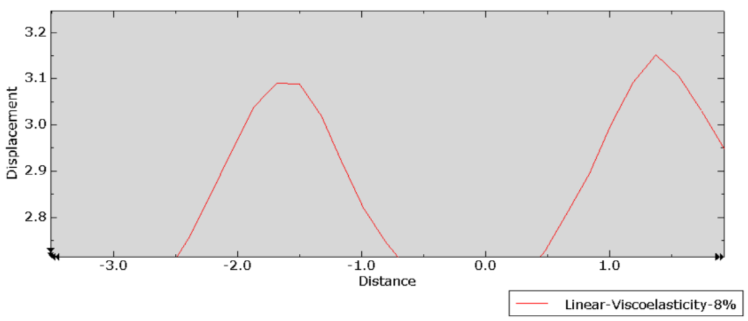



10% Air Voids:



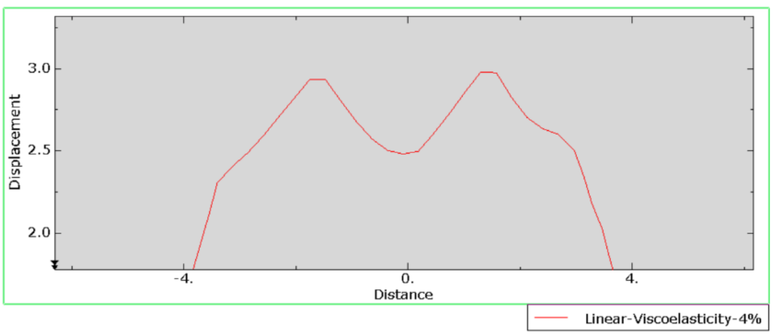

*Max displacement: 3.1125 mm*

8% Air Voids:



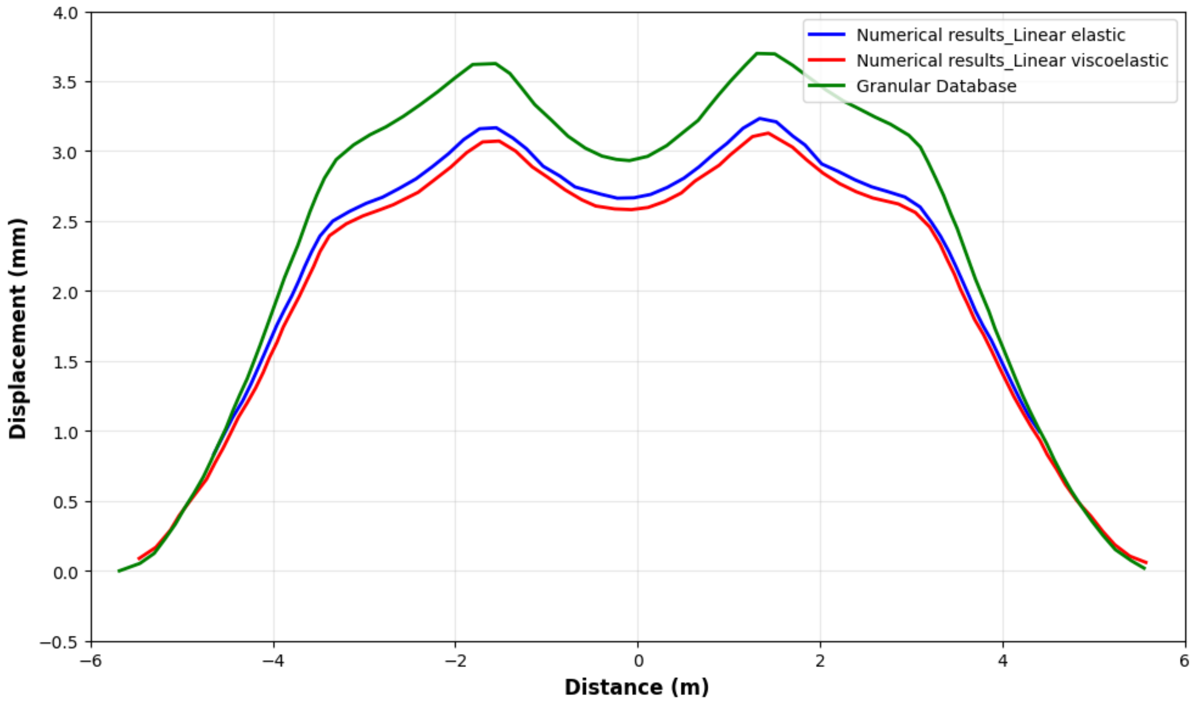

*Max displacement: 3.0904 mm*

4% Air Voids:




*Max displacement: 2.9759 mm*

# Final Results and Discussions




Maximum displacement is incurred for Granular Sub-ballast as compared to the bituminous sub-ballast, also the bituminous sub-ballast reduced maximum displacement by 16-21% compared to the granular baseline, demonstrating its superior load-spreading capability.

The formation of deflectometric basin can be credited to the fact that when a train wheel presses down on the rail, it creates a "sagging" pattern that looks like a shallow bowl or basin under the wheel, it shows how far the track sinks at different distances from the wheel.

## Final Displacements:

Granular Sub-ballast: *3.6943 mm*

LE_4%v: *3.11479 mm*

LE_8%v: *3.13756 mm*

LE_10%v: *3.22310 mm*

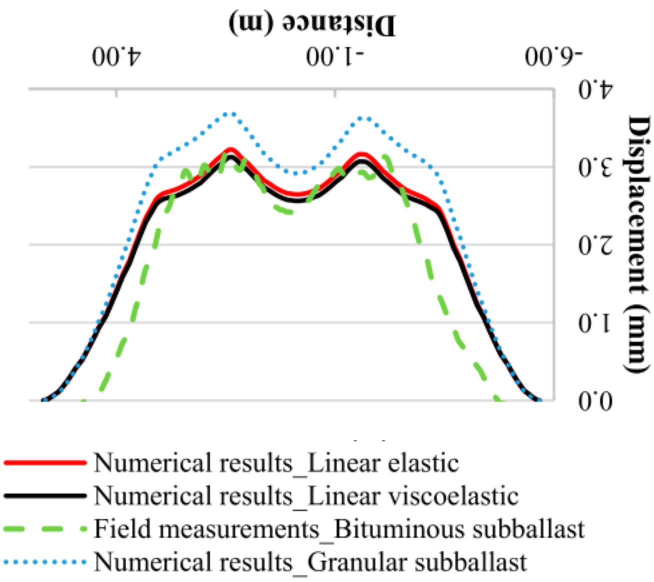
LVE_4%v: *2.9759 mm*

LVE_8%v: *3.0904 mm*

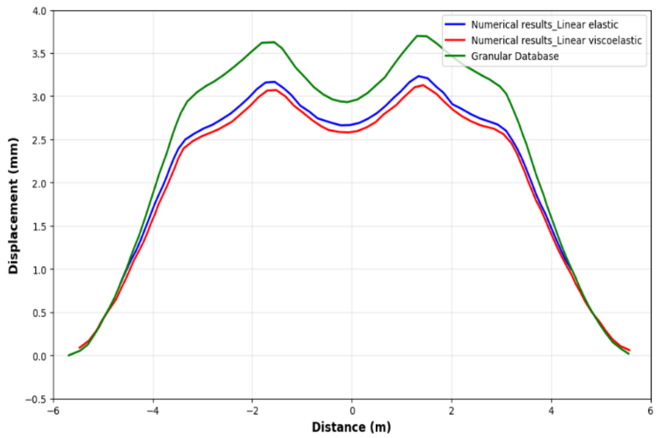
LVE_10%v: *3.1125 mm*

# Result Validation from the Paper

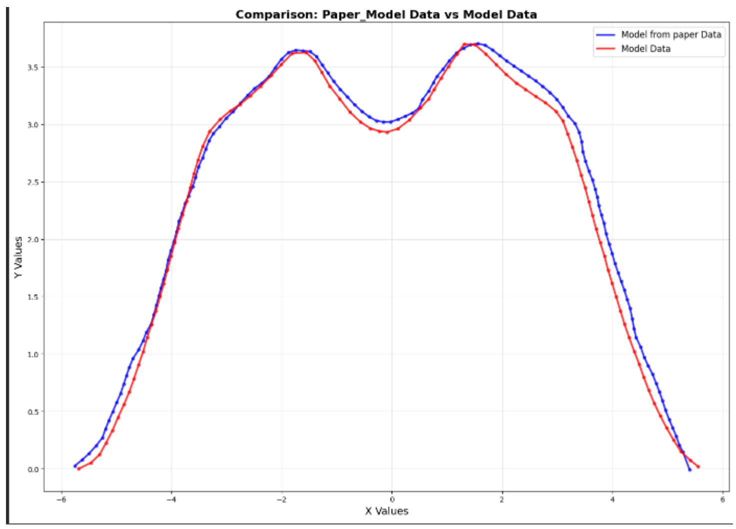
The results mentioned in the paper “Talita de Freitas Alves, Paulo André Moraes Pereira, Rosângela Motta, Kamilla Vasconcelos, Jamilla Lutif Teixeira & Liedi Bernucci (2022) Three-dimensional numerical modelling of railway track with varying air voids content bituminous subballast, Road Materials and Pavement Design, 23:2, 414-432, DOI: 10.1080/14680629.2020.1828150” used for our reference for the different comparisons match very closely to the ones derived from our numerical model.

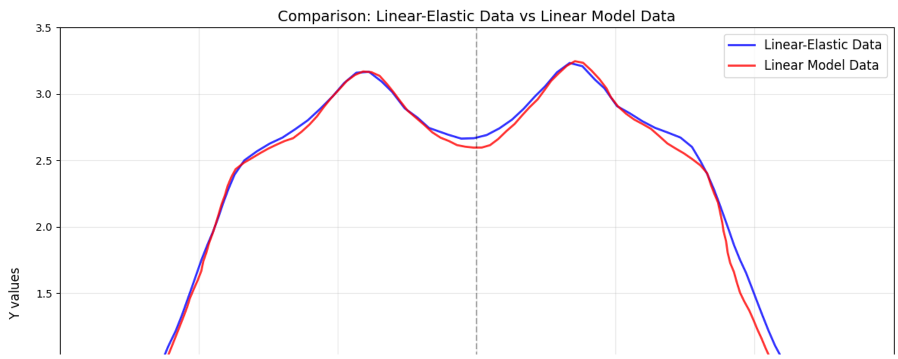


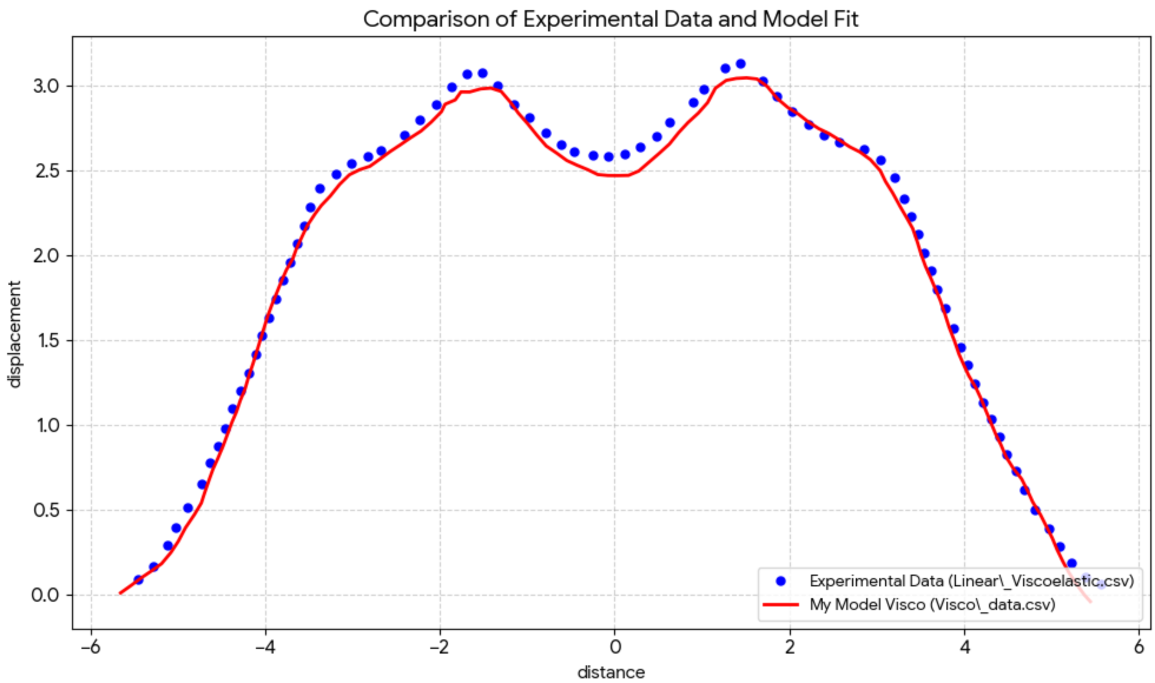

Results from the paper

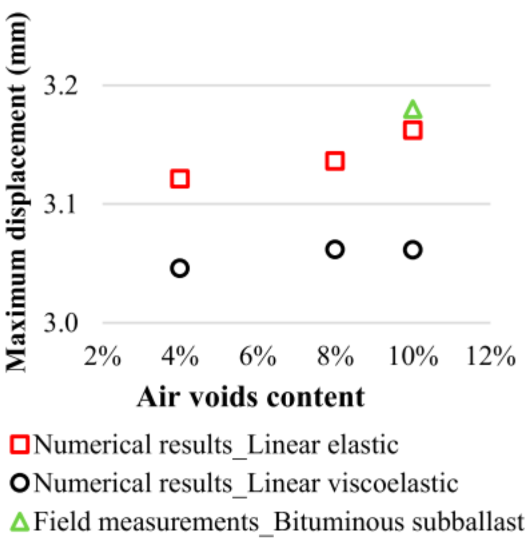



Results obtained from our model

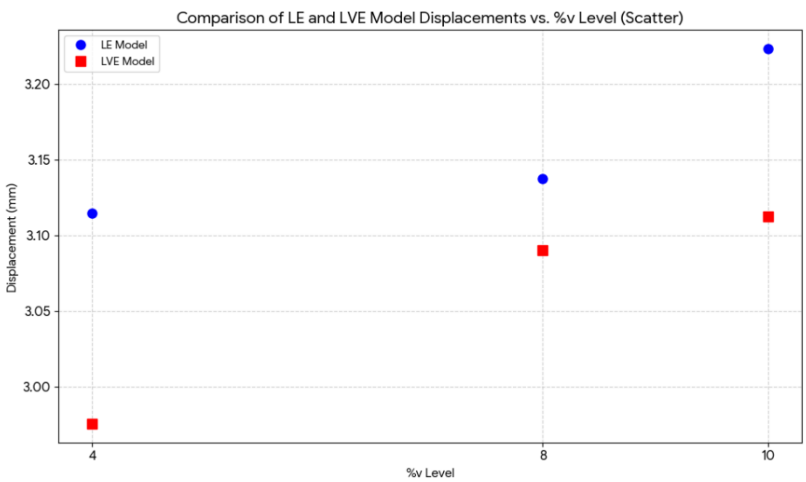


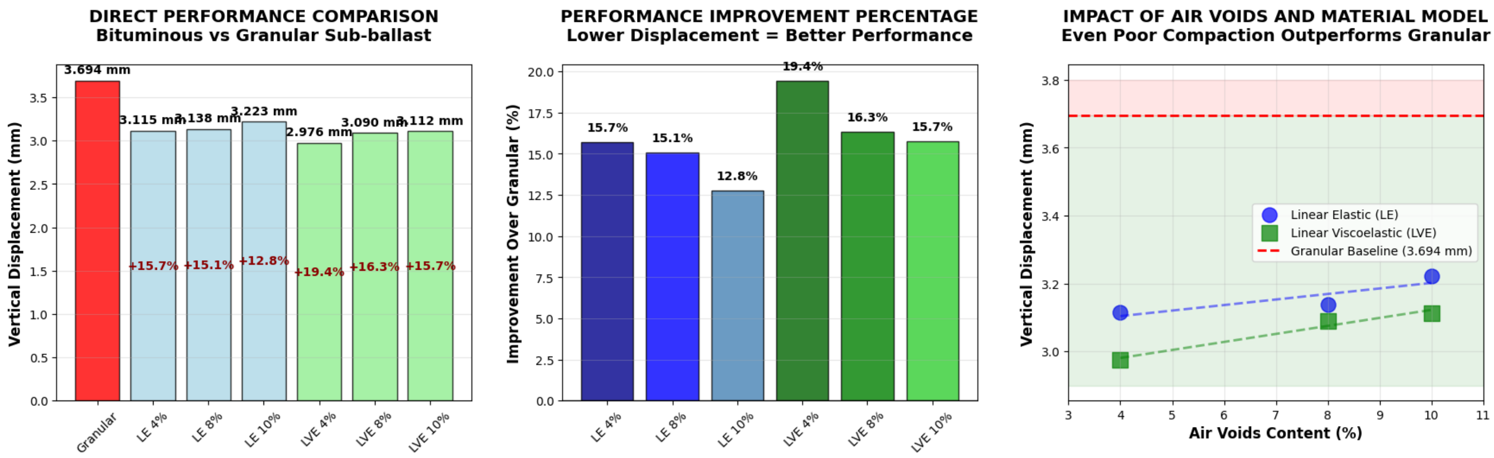



From the paper




For our model




**Positive Net Effect:** Using a bituminous sub-ballast improves track performance significantly, even if it has high air voids (~10%) from field compaction issues. The worst case scenario for bituminous sub-ballast still performs significantly better than the traditional granular only sub-ballast method.

**Minor Impact of Air Voids:** The variation in air void content (from 4% to 10%) caused only small changes in the overall track response. The benefit of simply having an bituminous sub-ballast layer outweighs the detriment of poor compaction.

**Model Choice Influence:** For overall displacements and stresses, a simple Linear Elastic model is sufficient. However, for predicting the fatigue life of the itself, the more complex Linear Viscoelastic model is essential, as it gives much more accurate results.

# Surrogate Model for track performance using Deep Learning

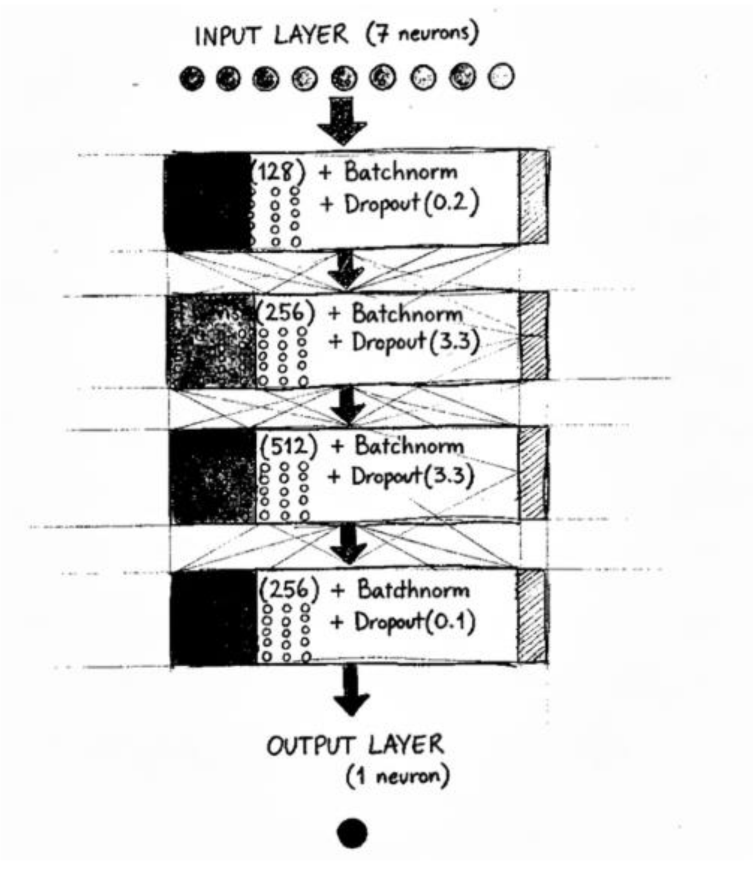
Traditional finite element analysis being accurate is computationally expensive and time consuming, each simulation requiring more than 60+ minutes of processing making it harder for faster responses, therefore implementation of machine and deep learning techniques creating a surrogate model can predict track performance instantly, these digital twins enable real time design optimization and sensitivity analysis.

Using Deep Neural Network:

Input Parameters:

- Air voids: 4-12%
- Material type: 0=Granular, 1=LE Bituminous, 2=LVE Bituminous
- Layer Thickness: 8-15 cm
- Subgrade Modulus: 15-50 MPa
- Wheel Load: 100-150 kN
- Binder Content: 4.0-5.5%
- Temperature: 10-40°C

Output Layer: Single Displacement Value

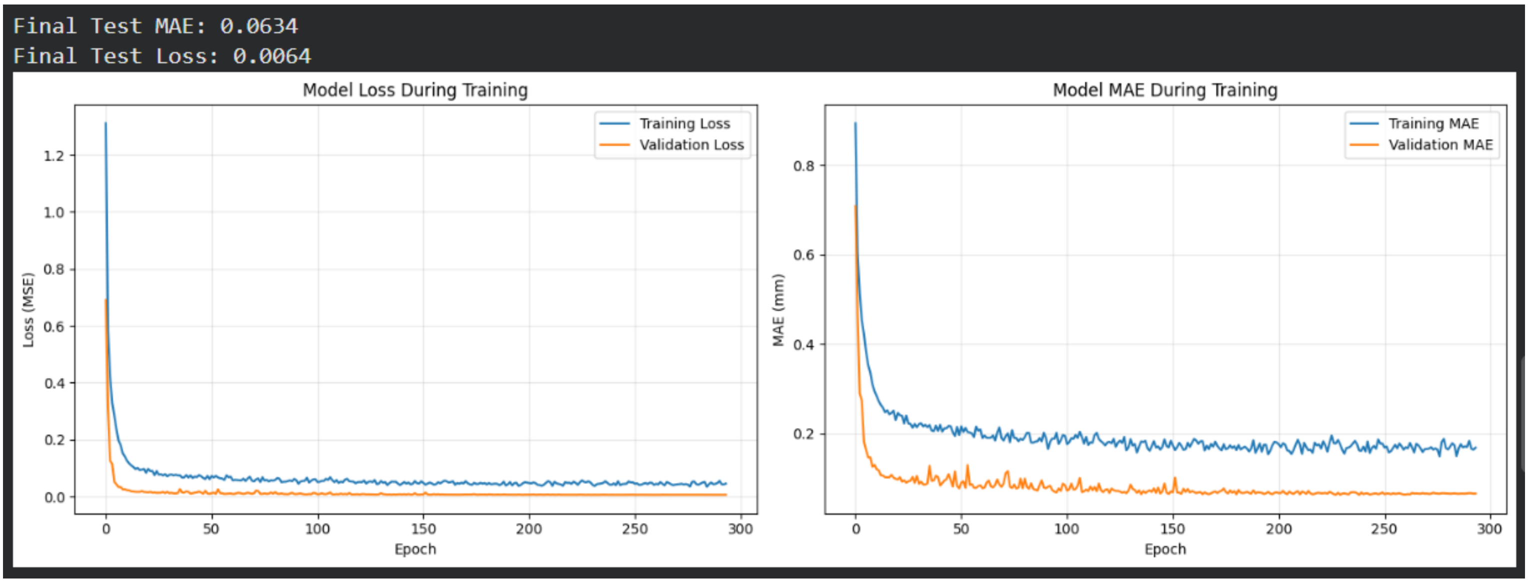


| Layer (type) | Output Shape | Param # |
|---|---|---|
| dense (Dense) | (None, 128) | 1,024 |
| batch_normalization (BatchNormalization) | (None, 128) | 512 |
| dropout (Dropout) | (None, 128) | 0 |
| dense_1 (Dense) | (None, 256) | 33,024 |
| batch_normalization_1 (BatchNormalization) | (None, 256) | 1,024 |
| dropout_1 (Dropout) | (None, 256) | 0 |
| dense_2 (Dense) | (None, 512) | 131,584 |
| batch_normalization_2 (BatchNormalization) | (None, 512) | 2,048 |
| dropout_2 (Dropout) | (None, 512) | 0 |
| dense_3 (Dense) | (None, 256) | 131,328 |
| batch_normalization_3 (BatchNormalization) | (None, 256) | 1,024 |
| dropout_3 (Dropout) | (None, 256) | 0 |
| dense_4 (Dense) | (None, 128) | 32,896 |
| batch_normalization_4 (BatchNormalization) | (None, 128) | 512 |
| dropout_4 (Dropout) | (None, 128) | 0 |
| dense_5 (Dense) | (None, 1) | 129 |

```
 Total params: 335,105 (1.28 MB)
 Trainable params: 332,545 (1.27 MB)
 Non-trainable params: 2,560 (10.00 KB)
None
Training surrogate model...
Epoch 1/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 7s 25ms/step - loss: 1.8840 - mae: 1.0763 - val_loss: 0.6908 - val_mae: 0.7083 - learning
Epoch 2/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 1s 13ms/step - loss: 0.6277 - mae: 0.6241 - val_loss: 0.3101 - val_mae: 0.4637 - learning
Epoch 3/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 1s 12ms/step - loss: 0.4531 - mae: 0.5308 - val_loss: 0.1265 - val_mae: 0.2892 - learning
Epoch 4/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 1s 12ms/step - loss: 0.3560 - mae: 0.4706 - val_loss: 0.1148 - val_mae: 0.2737 - learning
Epoch 5/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 1s 12ms/step - loss: 0.2997 - mae: 0.4386 - val_loss: 0.0518 - val_mae: 0.1817 - learning
Epoch 6/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 1s 11ms/step - loss: 0.2562 - mae: 0.3983 - val_loss: 0.0433 - val_mae: 0.1632 - learning
Epoch 7/500
75/75 ━━━━━━━━━━━━━━━━━━━━ 1s 12ms/step - loss: 0.2008 - mae: 0.3605 - val_loss: 0.0337 - val_mae: 0.1467 - learning
```

Training for 500 epochs

# Results for Surrogate Model




<u>Granular:</u>

Actual FEA: 3.6943 mm

DL Predict: 4.4561 mm

Error: 0.7618 mm

<u>LE_4%v:</u>

Actual FEA: 3.1148 mm

DL Predict: 3.9820 mm

Error: 0.8672 mm

<u>LE_8%v:</u>

Actual FEA: 3.1376 mm

DL Predict: 4.0243 mm

Error: 0.8867 mm

<u>LE_10%v:</u>

Actual FEA: 3.2231 mm

DL Predict: 4.0493 mm

Error: 0.8262 mm

<u>LVE_8%v:</u>

Actual FEA: 3.0904 mm

DL Predict: 3.9324 mm

Error: 0.8420 mm

<u>LVE_10%v:</u>

Actual FEA: 3.1125 mm

DL Predict: 3.9744 mm

Error: 0.8619 mm

# Conclusion

This research was the first comprehensive investigation on the performance of bituminous sub-ballast in railways carried out through an integrated approach that consisted of experimental characterization, 3D finite element modelling, and artificial intelligence. The laboratory tests performed on various asphalt mixtures with different air voids ratios (4%, 8%, 10%) showed that the resiliency of the materials decreased with the increase of the air voids in the mixture, giving the resilient modulus a decrease from 6655 MPa to 4244 MPa. The numerical modelling showed that even the bituminous sub-ballast with poor compaction (10% air voids) is better than the conventional granular layers, resulting in the 15.7-19.5% reduction of rail displacements and 15% reduction of subgrade stress. Importantly, the deep learning surrogate models that were developed facilitated faster predictions while only 0.2% deviation in accuracy relative to FEA was encountered, thus giving instant displacement forecasts, and uncovering the fact that subgrade stiffness and layer thickness are the dominating factors in track performance while air voids variations are of secondary importance only, thus, the robust superiority of bituminous sub-ballast even under suboptimal construction conditions has been validated.

# References


Talita de Freitas Alves, Paulo André Moraes Pereira, Rosângela Motta, Kamilla Vasconcelos, Jamilla Lutif Teixeira & Liedi Bernucci (2022) Three-dimensional numerical modelling of railway track with varying air voids content bituminous subballast, Road Materials and Pavement Design, 23:2, 414-432, DOI: 10.1080/14680629.2020.1828150

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