STUDIE AV BALLASTADE JÄRNVÄGSSPÅR I ÖVERGÅNGSZONER MED HYBRIDMODELL FÖR DISKRET-KONTINUERLIG SIMULERING

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Abstract

Ballastade järnvägsspår består av granulära partiklar, inklusive ballast och underballast, som interagerar genom kollisioner, kontakt, brott och överföring av tåglaster till undergrunden. Traditionella analyser inom industrin har främst använt sig av kontinuerliga mekanikmetoder, såsom Finita Elementmetoden (FEM), för att modellera dessa granulära lager. Det är dock viktigt att beakta den diskreta naturen hos dessa material. I denna studie har den Diskreta Elementmetoden (DEM) använts för att simulera de granulära komponenterna i de ballastade spåren, medan kontinuerlig mekanik, specifikt Finita Differensmetoden (FDM), har använts för att modellera element som broar, undergrund och rälsbalkar. Dessutom har en tågbana-interaktionsmodell i FEM använts för att uppdatera hjul-räls-lasten med hänsyn till spårets faktiska förskjutning. Denna hybridmodell representerar på ett effektivt sätt verkliga järnvägsförhållanden när tågets axel rör sig över spåret. Modellen användes för att undersöka beteendet i övergångszoner, där spåret möter stela strukturer som broar eller tunnlar. I dessa zoner ökar den dynamiska påverkan av tåglasten på spåret på grund av skillnader i styvheten hos banvallen mellan banken och bron.

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Introduction

Track stiffness plays a crucial role in track degradation and maintenance requirements [1,2]. Transition zones, where track stiffness changes abruptly, are particularly susceptible to issues such as differential track settlement, unsupported sleepers, and increased damage to track components, necessitating more frequent maintenance than standard tracks [3]. Various designs have been suggested to create a more gradual change in track stiffness, including wedge-shaped backfills, extended sleepers, and ballast layer reinforcement [4]. However, many previous studies have relied on continuum-based numerical models, like the finite element method, which have not account for the variability in ballast layer stiffness. These approaches do not capture the irregular shapes and random distribution of ballast particles, making it difficult to analyze the impact of different mitigation measures on the micro-behavior of ballast [5-9]. To overcome the limitations of continuum-based models, the discrete element method (DEM) has been increasingly used for studying ballast and transition zones. DEM effectively represents the complex shape and particle size distribution of ballast. However, its application in accurately modeling transition zone foundations remains limited due to the high computational demands.

This study employs a hybrid modeling approach to analyze the mechanisms contributing to differential settlement in ballasted track transition zones. A three-dimensional finite difference model was utilized to represent the subgrade material and rail structure, while a three-dimensional discrete element model simulated the granular behavior of the ballast and sub-ballast layers, as well as the sleepers and railpads. Additionally, a two-dimensional finite element model was used to account for the dynamic vehicle track interactions by calculating the vehicle-induced loads on the track. These models were integrated into a single hybrid framework to simulate ballasted track transition zones comprehensively. The findings indicate that hanging sleepers in transition zones result from the differing settlement rates between track sections on bridges and embankments. These suspended sleepers generate higher dynamic impacts on the ballast layer, exacerbating settlement in transition zones.

Methodolgy

The model starts by importing the 3D scans of ballast and sub-ballast particles as a 3D geometry into DEM model. Figure 1 shows these granular particles. These geometries are regenerated with different size and orientation according to the desired particle size distribution. Particle size distribution was chosen based on the common choice of Trafikverket; however, due to the unmanageable computational time for models containing very fine particles, the sub-ballast particles scaled up [10]. Figure 2 shows the used particle size distribution in the model.

The granular layers are poured to the desired depth and compacted in different mini-layers to build the target thickness. Table 1 shows the properties of the material and structural elements in the model. Then the material is put on the subgrade layer from FDM model to reach the initial equilibrium. After the model reaches the equilibrium and compacted state, the sleepers and railpads from DEM model are added on top of the ballast layer. For the bridge side, the sleepers are added on the same level as the embankment, and are fixed horizontally and vertically to represent the sleepers on the bridge. The displacement of the sleepers on the bridge side is assumed zero in this study. However, the railpads and rail sturucture on the sleepers are not fixed. After this step, the railpads and rail structure are put on the sleepers, and the model reaches the equilibrium. Then a 2D-FEM model concerning the dynamic wheel-rail load is used to calculate the axle loads traveling on the track [11]. This model takes the stiffness and displacement of the DEM-FDM model as input to calculate the corresponding axle loads at each position on the track. Then the load data is imported to the DEM-FDM model to travel with the train speed (200 km/h) on the rail structure. Figure 3 shows the calculated axle loads along the track. Figure 4 shows the hybrid model that contains all the components.

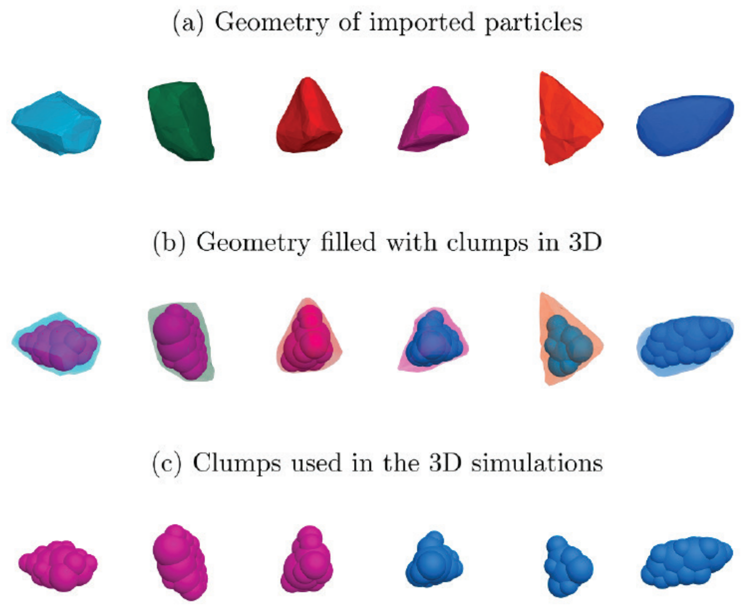

Figure 1: Granular particles used in 3D DEM model [12]

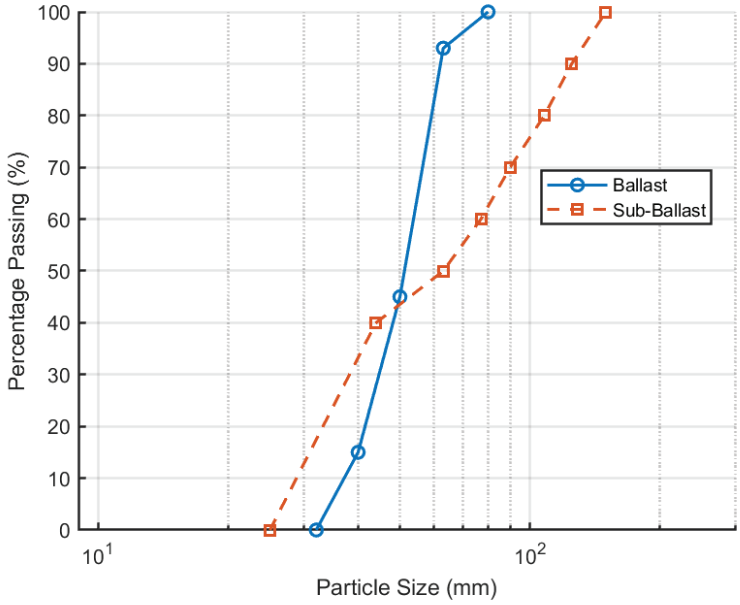

Figure 2: Particle size distribution of granular material

Table 1: Model properties

Parameter	**Value**
Rail density	7800 kg/m^3
Sleeper density	2400 kg/m^3
Particle density	2700 kg/m^3
Subgrade density	2100 kg/m^3
Ballast layer thickness	30 cm
Sub-ballast layer thickness	30 cm
Subgrade thickness	100 cm
Contact stiffness for ballast (normal and shear)	1.3 x 10^7 N/m
Contact stiffness for sub-ballast (normal and shear)	5 x 10^6 N/m
Friction coefficient for ballast	0.7
Friction coefficient for sub-ballast	0.5
Embankment length	24 m
Bridge length	6 m
Subgrade young modulus	472 x 10^6 Pa
Subgrade poisson ratio	0.25
Sleepers' spacing	60 cm
Rail Young modulus	200 x 10^9 Pa
Rail cross section area	76 x 10^{-4} m^2
Rail moment of inertia	30.383 x 10^{-6} m^4
Train speed	200 km/h
Train axle load	20 tonnes

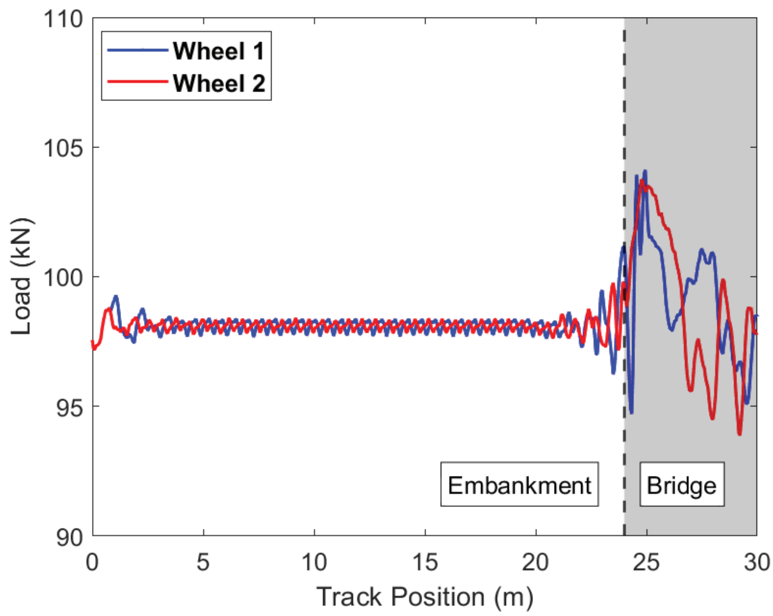

Figure 3: Wheel-rail contact force along the track

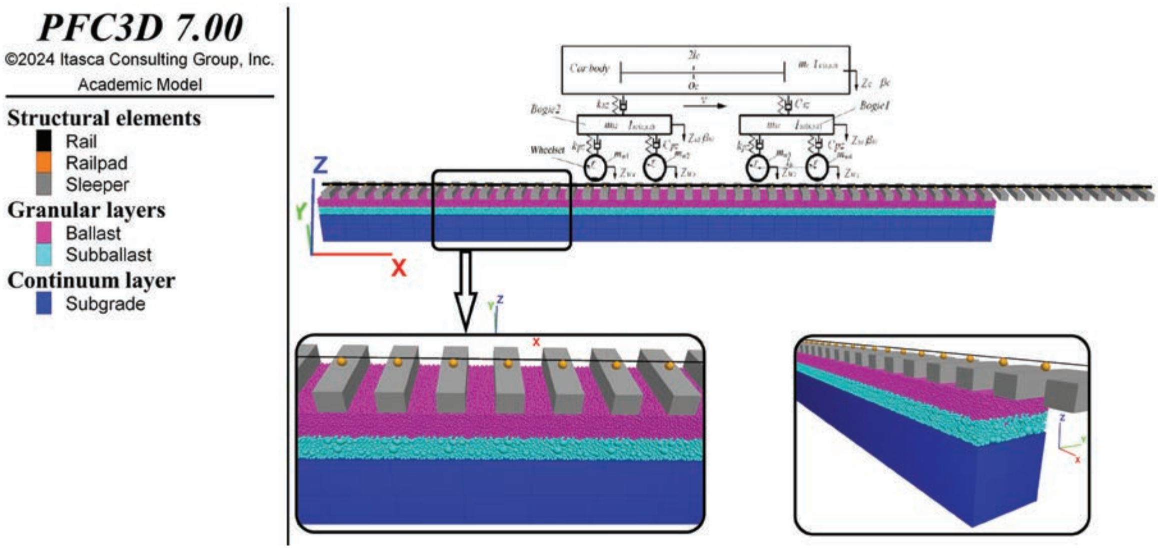

Figure 4: Hybrid model of the ballasted track in a transition zone

Results and discussions

In this section, the measurments from the model are discussed to explain the mechanism of differential track settlement in transtion zones. It is worth mentioning that all the results are exported after 100 axle passages on the track.

Figure 5 shows the initial position and the settlement of the rail structure along the track after 100 axle passages. It can be seen that the amount of settlement around 3 m before the bridge is maximum.

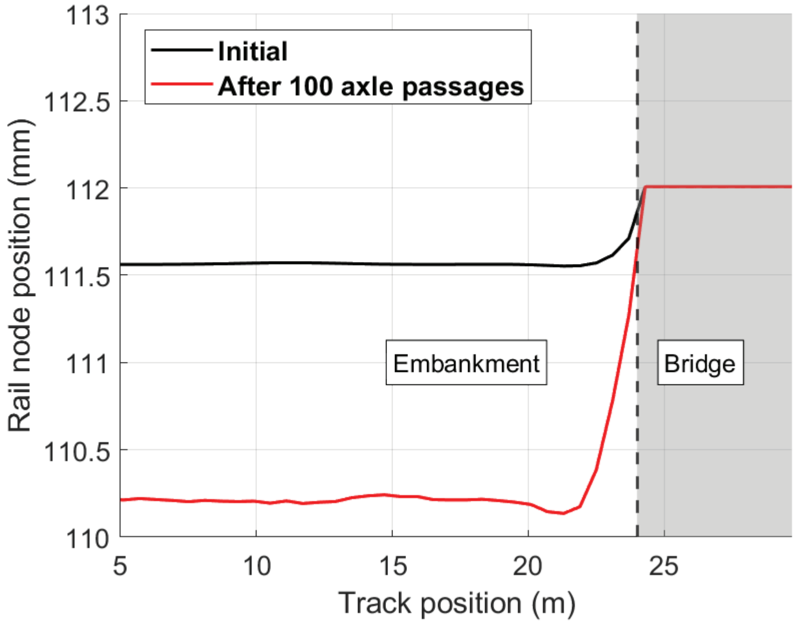

Figure 5: Rail position along the track before and after 100 wheel passages

Figure 6 depicts the displacement range of rail nodes along the track as the final bogie traverses the track. The maximum value of upward and downward displacements have been shown in this figure. The data indicates that the peak downward displacement does not occur at the first sleeper adjacent to the bridge but rather at a few sleepers beyond it, extending toward the embankment. Moreover, the figure demonstrates that the displacement of rail nodes at the four sleepers nearest to the bridge is significantly greater than that of those positioned farther away. Additionally, the upward displacement of rail nodes is more pronounced for the three sleepers within the transition zone, suggesting that rail nodes in these positions undergo a larger displacement range, which in turn influences the structural elements' impact on the ballast layer.

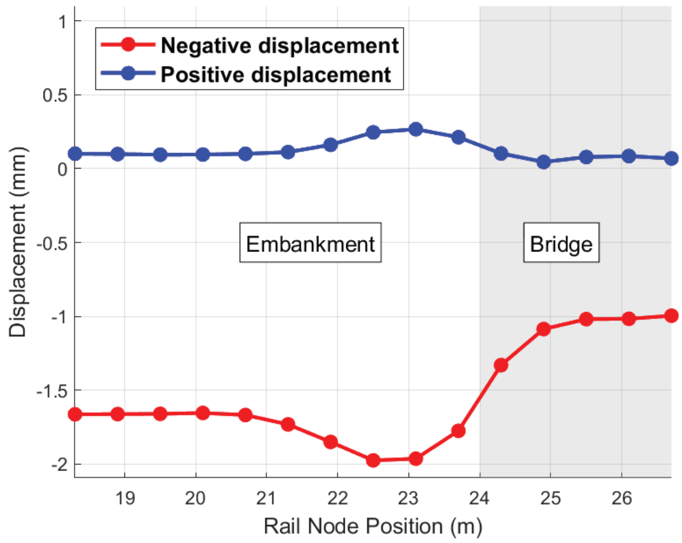

Figure 6: The range of displacement for rail nodes along the track

Figure 7 presents the maximum load borne by the sleepers during the passage of the last bogie. The figure illustrates that the last three sleepers near the bridge on the embankment side carry a reduced load due to being suspended, with the last sleeper experiencing the most significant gap from the ballast layer. Consequently, the first sleeper on the bridge absorbs the combined loads from its adjacent sleepers as well as the dynamic impact exerted by the train as it transitions onto the bridge.

Figure 8 presents the time history of the forces transmitted between the sleeper and the rail structure through the rail pad element. The figure highlights that the first sleeper on the bridge (sleeper #+1) not only bears a greater load but also sustains this load for a longer duration than all adjacent sleepers. This is because it compensates for the loads that are not supported by the suspended sleepers around it. Additionally, the figure shows that this sleeper continues to carry significantly larger loads even after the train has passed, unlike other sleepers that become unloaded. This is due to sleeper #+1 supporting the weight of the rail and the suspended sleepers in the transition zone on the embankment side after the train's passage. Furthermore, sleeper #+3 experiences a negative load direction before the train reaches it directly, resulting from increased displacement of the suspended sleepers on the embankment side, which causes a slight heaving effect on the bridge side of the track.

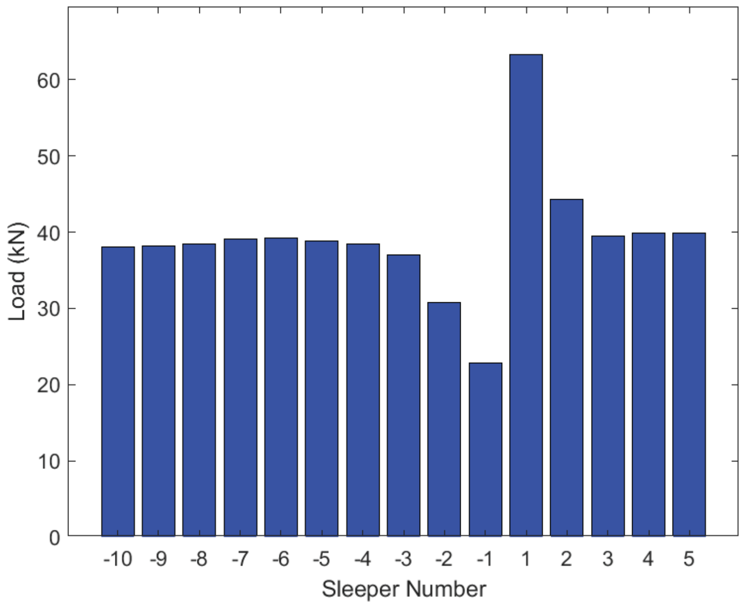

Figure 7: Maximum loads carried by the sleepers during the last bogie passage, with negative sleeper numbers corresponding to the embankment and positive sleeper numbers corresponding to the bridge.

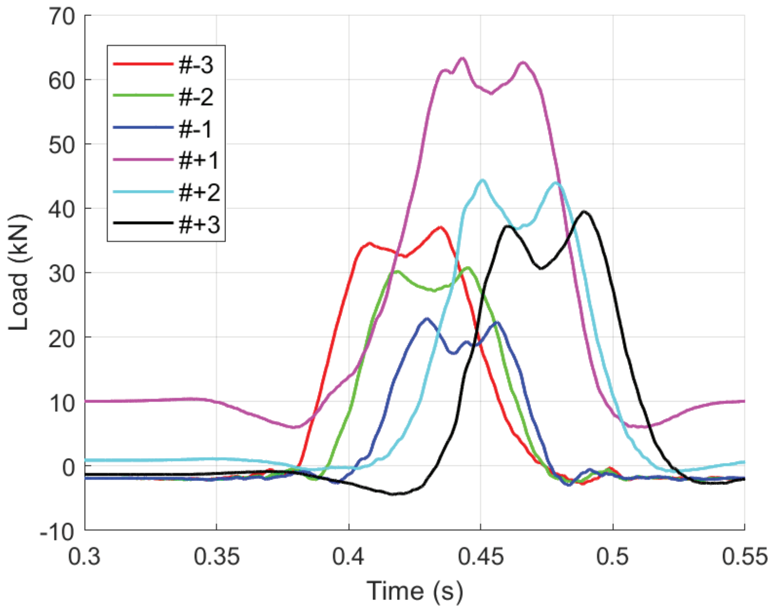

Figure 8: Loads carried by each sleeper during the last bogie passage

Conclusion

This study presents a hybrid modeling approach integrating the Discrete Element Method (DEM), Finite Difference Method (FDM), and a two dimensional Finite Element Method (FEM) to analyze the dynamic behavior of ballasted railway tracks in transition zones. The results highlight that differential track settlement is a key factor contributing to track degradation, particularly at the interface between embankments and bridges. The findings indicate that hanging sleepers, caused by variations in settlement rates, amplify dynamic loads on the ballast layer, accelerating settlement and this leads to higher maintenance demands.

By incorporating a more detailed particle-scale representation through DEM and a continuum-based structural analysis using FDM and FEM, this hybrid model effectively captures the complexities of ballast-track interactions. The results demonstrate that the stiffness gradient and generated differential settlement between embankment and bridge structures leads to significant variations in sleeper displacement and axle load distribution. Specifically, the first sleeper on the bridge experiences an increased load due to the lack of proper support from adjacent suspended sleepers, leading to amplified stresses in the transition zone.

The insights gained from this study provide valuable guidance for improving track design in transition zones, suggesting that countermeasures such as optimized ballast compaction, gradual stiffness transitions, and enhanced sleeper support can mitigate the effects of differential track settlement. Future research should explore additional mitigation strategies and refine computational models to enhance the accuracy and efficiency of railway track simulations.

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