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Influence of Rail–Track Structural Irregularities on Train-Induced Ballast Settlement

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Abstract: The long-term performance and safety of high-speed railway infrastructure are strongly governed by the dynamic interaction between trains and the rail–track system, particularly in the presence of structural irregularities. In this study, the influence of rail and sleeper irregularities on train-induced vertical ballast settlement was systematically investigated using advanced three-dimensional finite element simulations implemented in PLAXIS 3D. Nine representative track configurations were established, encompassing ideal conditions as well as isolated and combined rail and sleeper irregularities. Dynamic train loading was simulated at operating speeds of 100, 200, and 300 km/h, while nonlinear constitutive behavior of ballast and substructure materials, together with realistic contact interactions between track components, was explicitly considered. The numerical results indicate that even minor geometric or support irregularities significantly disrupt load transfer mechanisms, leading to localized stress concentrations and accelerated ballast settlement. With increasing train speed, the sensitivity of the rail–track system to such irregularities was markedly amplified, resulting in pronounced dynamic displacements. Track configurations involving concurrent rail and sleeper irregularities exhibited the most severe settlement responses. These findings demonstrate that ballast degradation is governed not only by train speed but also by the interaction and superposition of track irregularities, which can substantially shorten maintenance cycles if left unaddressed. The study underscores the critical importance of early defect identification, preventive maintenance strategies, and high-fidelity numerical modeling in enhancing the resilience, serviceability, and long-term reliability of modern high-speed railway networks.

Keywords: Rail–track irregularities; Ballast vertical settlement; High-speed railway; Finite element modeling; PLAXIS 3D

1 Introduction

Numerous experimental and numerical studies have been conducted in recent decades to assess how railroad system irregularities affect track and ballast settlement caused by trains and how this in turn affects passenger comfort. Sadeghi et al. [1] sought to determine how rail defects affect the comfort of trains running on slab tracks. A numerical model was created to simulate the interaction between the car and the slab track. The model's output was then verified by comparing it with data from field tests conducted throughout the investigation. According to the research, travel comfort on slab tracks is greatly impacted by rail irregularities with short wavelengths. In particular, it was discovered that ride comfort significantly decreases, especially on metro lines, when the wavelength of rail irregularities falls below 0.75 m. A train's critical speed was also calculated as a function of rail irregularity, which is the speed at which ride comfort is at its lowest. Interestingly, it was found that the critical speed of the train is mostly unaffected by the amplitude of rail irregularities.

Fallah Nafari et al. [2] investigated how track stiffness affects the rail. The results showed that variations in track stiffness significantly impact the bending moment of the rail by creating a track model that includes stochastically fluctuating track stiffness. Additionally, it was discovered that these variations in stiffness result in higher wheel–rail contact forces, which in turn cause uneven wear on the rail head and the development of rail corrugation. This demonstrates how important track stiffness is to the overall functionality and maintenance. Yu et al. [3] focused on a similar method for determining the design seismic track irregularity. Amplitude response spectra were proposed for designing seismic track irregularities and the effects of fault distance, site conditions, and seismic intensity were analyzed. A shape correction coefficient was determined for random structures, providing a basis for post-earthquake planning. Results showed that the amplitude of seismic irregularity increases with the number of spans and pier height but eventually stabilizes. A nine-span structure was used for calculations, and train acceleration under design irregularity exceeded post-earthquake measurements, confirming a reasonable safety margin.

Naeimi et al. [4] modeled the coupled vehicle–track system and found that minor left/right rail irregularities cause low roll excitations, while severe unevenness dominates roll deformations and causes dynamic shifts in roll direction. Kouroussis et al. [5] showed that localized defects, such as rail joints, significantly increase vibrations, with larger defects producing stronger effects. Train speed influenced vibrations differently depending on the defect type. Bian et al. [6] integrated track irregularities in a 2.5-dimensional track–ground model and found that amplitude mainly affects low-speed vertical responses, while short-wavelength irregularities increase vibrations in both low- and high-speed trains, with wavelength having little effect on far-field ground vibrations at high speed. Train–ground vibrations change near the system's critical velocity. Short-wavelength irregularities produce high-frequency track vibrations, while long wavelengths are dominated by axle loads, with minimal differences between irregular and smooth tracks [6].

Train speed, building distance, and track irregularities have been shown to significantly affect building vibrations and ground settlement [7]. Train–track–ballast models indicate that higher train speeds and larger settlement amplitudes increase the dynamic responses of both train and track [8]. Ballast settlement control considers both train safety and passenger comfort, with ride comfort dominating except for uneven settlements shorter than 10 m. The deflection ratio is used to simplify settlement criteria. Charoenwong et al. [9] developed a numerical method to predict track irregularities, combining empirical settlement rules with finite element analysis. The model updates train–track interaction after each load, accounts for three-dimensional stresses, and shows that subgrade properties strongly affect track settlement. Shan et al. [10] developed an iterative method to predict track differential settlement in transition zones, showing that heavy axle loads require reinforcement and maintenance.

Bian et al. [11] created a vehicle–track–foundation dynamic model using thin-layer elements and a 2.5-dimensional finite element approach, validated against field data, effectively capturing track irregularities and vibration responses. Vehicle characteristics mainly influence track vibrations, with short-wavelength irregularities causing high-frequency responses and long wavelengths causing low-frequency, far-reaching vibrations. Track irregularities dominate below the critical velocity, while wheel loads dominate above it. Charoenwong [12] modeled track irregularity progression using multi-body train–track interaction and 2.5-dimensional finite element analysis. Zhu et al. [13] detected track degradation via vehicle-mounted accelerometers and a Winkler spring–mass model, identifying stiffness loss from settlement, loose fasteners, or ballast issues. Hu and Bian [14] developed a 2.5-dimensional finite element model to study stress distribution in track substructures and underlying soil, particularly near critical train speeds. Validation with field data from a ballasted high-speed railway showed close agreement with measurements. Results indicate that the substructure, including ballast and foundation, effectively dissipates loads, reducing stress transmitted to the soil. Simplified models like the Boussinesq approximation were insufficient, as they cannot capture the multi-layered substructure or dynamic train effects. The study highlights that both track irregularities and train speed increase subgrade stress and failure risk and that high-speed rail design must account for dynamic amplification from track imperfections, unlike low-speed rail where simplified smooth-track models suffice.

Gan et al. [15] analyzed the dynamic responses of multilayered soft-saturated ground under rough tracks, modeling the train as a multi-rigid-body system. The ground was treated as a poroelastic medium using Biot's theory, capturing soil–fluid interactions and stress wave propagation under dynamic loading. Gan et al. [15] modeled the train–track–ground system as a composite structure of rails, sleepers, and ballast, with a fully coupled multilayered poroelastic ground. Using Fourier transforms and transmission–reflection matrices, the model accounts for dynamic wave propagation and enforces the compatibility of displacement and stress at interfaces. Track irregularities were shown to affect dynamic loads, displacements, accelerations, stresses, and pore pressures. The study provides analytical insights for designing high-speed rail systems on soft, saturated soils.

Mhanna and Hussein [16] developed a three-dimensional numerical model with a subroutine to discretize moving loads based on train speed and track irregularities. The model, validated with in-situ data, was used to study the effects of soil stiffness, rail defects, and train speed on vibrations. Faster trains on high-quality tracks generate vibrations above human thresholds even 15 m away, while poor tracks cause excessive ground vibrations at larger distances. Increasing soil stiffness tenfold reduces vibration amplitude by approximately 40%. Kedia et al. [17] showed that short-wavelength track irregularities dominate vibration and noise, exceeding Indian Railways limits, and that stiffer rail pads reduce both. Long-wavelength irregularities have less impact, so track modifications should focus on short wavelengths. Farsi and Asgari [18] studied contaminated ballast under bridges using a Train–Track–Bridge Interaction (TTBI) model, showing that higher ballast stiffness improves stability and reduces deflection, while fouling significantly increases acceleration and vibration, highlighting the need for proper maintenance. Milne et al. [19] found that track-level changes and large subgrade differential settlements greatly affect vehicle dynamic loads and track geometry, creating additional stress in monolithic track beds.

Sayeed and Shahin [20] developed an advanced three-dimensional finite element model to simulate realistic moving train loads and analyze the dynamic response of ballasted tracks. By examining factors such as substructure stiffness and thickness, load amplitude, and train speed, the study provides practical insights to help engineers optimize track design and maintenance strategies. Auersch [21] used a multi–beam–on–soil model coupled with a vehicle model to study vehicle–track interaction and track filtering effects. The research showed how varying support stiffness converts into equivalent rail irregularities and generates ground vibrations through the scatter of axle pulses. Field measurements validated the approach, highlighting that moving static loads over uneven support is the main source of mid-frequency ground vibrations. Lei and Wang [22] developed a spatial nonlinear vehicle–track coupled dynamics model based on the finite element method (FEM), consisting of a vehicle system with 31 degrees of freedom (DOFs) and a three-dimensional slab track linked through the wheel–rail interface. By incorporating realistic wheel and rail profiles and using efficient contact–search methods, the coupled system was solved with improved computational performance. The analyses of V-shaped and torsional track irregularities demonstrated that such defects significantly affect both vehicle and track dynamic responses.

Most previous numerical studies have simplified the rail–track system by modeling rails as ideal line elements without considering key structural details such as sleepers and fasteners. Additionally, research that addresses track irregularities is limited, and studies that investigate combined irregularities affecting both the rail and structural components (e.g., sleepers and fasteners) are particularly scarce. Since such combined defects frequently occur in aged or deteriorated rail networks, studying their impact is practically relevant and technically important in railway engineering. To fill this gap, three-dimensional train–track models were developed in this study to examine the effects of track irregularities on ground vibrations and ballast settlement, considering various types of irregularities and train speeds. The findings aim to help engineers identify and mitigate track irregularities, improve design and maintenance, and enhance the performance, durability, and sustainability of rail systems.

2 Methodology

In this section, the methodology for numerically modeling the influence of train–track irregularities on ballast deformation under varying train velocities is presented. The simulations were conducted in PLAXIS 3D, an advanced geotechnical tool capable of capturing the complex interactions between moving loads and rail infrastructure. To systematically examine the effects of irregularities and speed, three three-dimensional models were developed–one representing an ideal track and two incorporating common irregularity scenarios (irregularities in the rail only and in both the rail and sleepers). Train speeds of 100, 200, and 300 km/h were simulated to evaluate their dynamic impact on ballast behavior. First, the model of an ideal track without any irregularities was constructed and validated against a previously published study. Then, irregularities were introduced. Each model accounted for nonlinear material properties and transient dynamic loading as trains passed over the track. The main output analyzed was the vertical settlement of the ballast, a key parameter for assessing long-term track performance and ride quality.

2.1 Description of the Finite Element Model

As noted earlier, a three-dimensional finite element model of a rail–track system under moving train loads was developed and validated using a reference study [23]. Accordingly, all input parameters and train load conditions were adopted from that study. The analysis was conducted in two phases: static and dynamic. In the static phase, the boundary conditions and stability of the soil–track model were verified in the absence of moving train loads. In the dynamic phase, the influence of soil mass inertia forces on the interaction between moving train loads and the subgrade soil was considered. The governing dynamic equilibrium equation is presented in Eq. (1) [24]:

$$\mathrm{M}\ddot{u} + \mathrm{C}\dot{u} + \mathrm{Ku} = \mathrm{F} \tag{1}$$

where, M denotes the mass matrix, C is the damping matrix, K denotes the stiffness matrix, F is the load vector, and $u, \dot{u}$, and $\ddot{u}$ represent the displacement, velocity, and acceleration vectors, respectively. The damping matrix C is calculated using Eq. (2) [25]:

$$C = \alpha\mathrm{M} + \beta\mathrm{K} \tag{2}$$

An initial time step of 0.01 s was chosen for the investigation, and the Rayleigh damping coefficients, α and β, were given values of 0.2454 and 0.0016, respectively. According to Figure 1, the subgrade soil model was 180 m × 100 m in plan and reached a depth of 30 m. Boundary conditions in line with earlier research [7] were used during the static phase: the bottom boundary was completely set to stop motion, the lateral boundaries could only move vertically, and horizontal displacements were fixed. In order to reduce spurious wave reflections during the dynamic phase, absorbent boundaries [7, 26] were added at the bottom and lateral sides.

10-node solid elements were used to discretize the track system and subgrade soil. With a coarse mesh density, the mesh has 99,264 nodes and 54,543 elements. The moving point loads option in PLAXIS 3D, a simple and commonly used technique for simulating railway traffic-induced loading, was used to simulate train loading [7]. Figure 1 provides further information on the subgrade soil and track system model. In this study, the loading configuration and wheel loads of the power and passenger cars of the X-2000 passenger train [27] were adopted for the simulation, and the corresponding details are presented in Figure 2. The mid-span of the rail track served as the measurement point for comparison with the reference study.

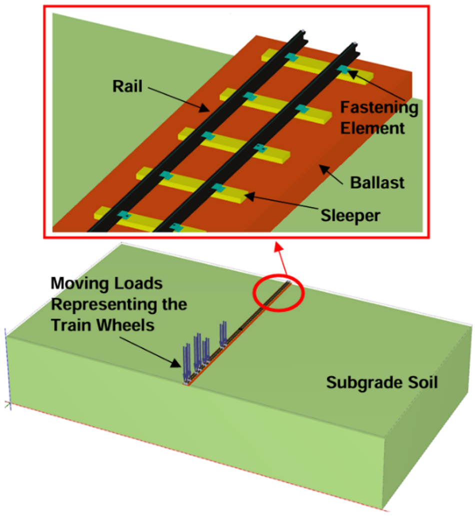

Figure 1. Details of the model for subgrade soil and rail–track system

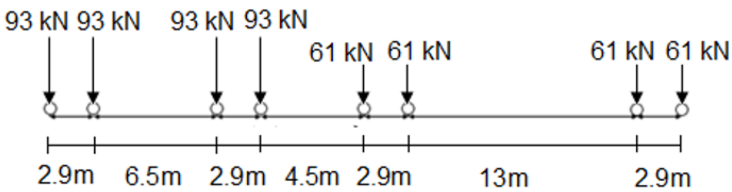

Figure 2. Loading configuration of the X-2000 train

The properties of materials used in the models are given in Table 1.

Table 1. Parameters of the subgrade soil, ballast and sleepers [7]

Material	γ (kN/m^3)	Young's Modulus E (MPa)	Cohesion (kPa)	Friction Angle φ (°)	Poisson Ratio v
Subgrade soil	18.5	16	–	–	0.25
Ballast	17	134	20	48	0.3
Sleepers	23.5	25,500	–	–	0.2

The subgrade soil, ballast and sleepers were modeled as volume elements using bilinear elastic–plastic material following the Mohr-Coulomb failure criterion to achieve higher accuracy in the analysis. It should be noted that the rail was modeled as a linear elastic material with a Young's modulus of E = 206,000 MPa and a unit weight of γ = 78.5 $\mathrm{kN/m^3}$. Additionally, the plate element with a thickness of 1 cm and the same properties as the rail was used to simulate the rail–foot fastening parts and then added to the model.

2.2 Validation of the Numerical Model

Before examining the effect of train speed on ballast settlement considering rail–track irregularities, an ideal model without irregularities (Figure 1) was first developed and validated against the numerical model proposed by Hadi et al. [23]. They conducted a series of three-dimensional analyses to examine the influence of variation of train speed on ballast settlement. Three dynamic analyses involving train passages at different velocities—100, 200, and 300 km/h—through the soil–rail track system were selected as reference cases to validate the model. Their results indicated that train speed has a significant effect on the maximum settlement of the railway track. The findings indicated that the settlement increases as the train speed rises from 100 to 200 km/h, then decreases as the speed further increases to 300 km/h. Hence, the critical speed can be identified as 200 km/h. The comparison of train-induced ballast settlements between the present study and the reference is presented in Figure 3. The figure indicates that increasing the train speed leads to a slight increase in the vertical settlement of the rail track. The numerical results from this study show that the settlement rises from 4.5 mm to 4.7 mm as the train speed increases from 100 to 200 km/h, and then decreases to 4.6 mm as the speed further increases to 300 km/h. Therefore, the critical speed can be identified as 200 km/h, which is consistent with the reference study. This agreement confirms that the model has been correctly developed and validated.

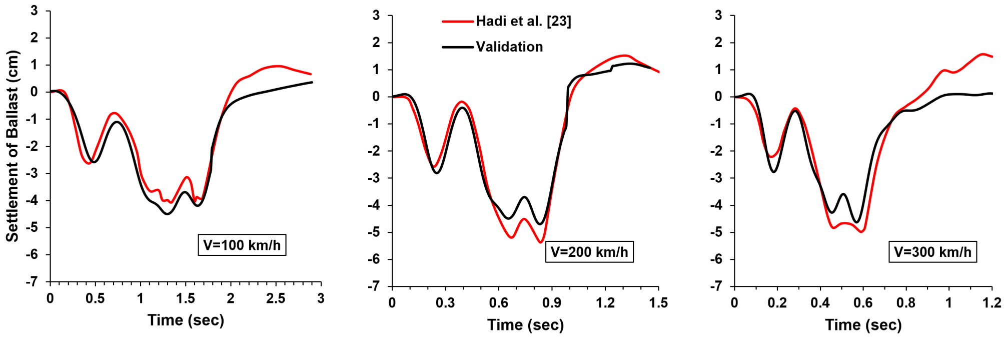

Figure 3. Comparison of the ballast settlement for validation of the numerical model

2.3 Introduction of Irregularities in the Rail–track System

It should be noted that the results presented by Hadi et al. [23] differ considerably from real-world conditions because the effects of the rail fastening system and rail–track irregularities were not taken into account. In practice, wear, plastic deformation, and fatigue induced by repetitive train loads are the primary causes of rail irregularities. Variations in rail geometry may also arise from improper installation, uneven sleeper support, or thermal expansion effects. Likewise, cracking, settlement, and deterioration of sleepers due to heavy loads, aging, or insufficient maintenance can introduce additional irregularities. The stability and alignment of the rail system can be further compromised by uneven ballast support or loosened fasteners. Under such conditions, the affected sleepers lose their structural functionality, effectively behaving as if they were absent.

Rail fastening systems and track irregularities play a significant role in influencing ground vibrations and are key factors governing ballast settlement [7]. Neglecting these components may lead to an inaccurate assessment of vibration mitigation measures, potentially resulting in suboptimal design solutions. To enhance the reliability and realism of the present study, both the fastening system along the track and rail irregularities were explicitly modeled and analyzed.

To better reflect real-world issues in railway systems and to address the limitations of previous numerical models–which have often idealized the rail–track system without considering such detailed irregularities–two common types of irregularities were simulated in this study. In the first case, an irregularity was introduced only in the rail, representing a common defect observed in aging railway networks, as illustrated in Figure 4. To model this condition, the height of the mid-10 m section of the rail was deliberately reduced by 1 cm relative to adjacent segments, achieved by cutting and moving it down using the “Move Tool.” In the second case, both rail irregularity and sleeper removal were simulated at the same location to represent another frequently encountered field condition, as shown in Figure 5.

Figure 4. Rail failure induced by repetitive train loads [28]

(a)

(b)

Figure 5. Damage in different types of sleepers: (a) Crack in pre-stressed concrete sleeper [29]; (b) Failure of timber sleeper due to fungal decay [30]

Figure 6 shows the location of the irregularities simulated in this study.

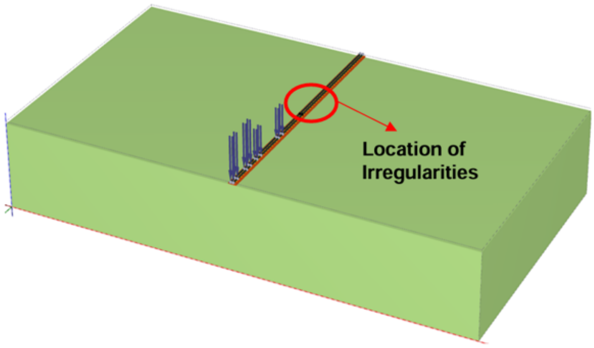

Figure 6. Location of irregularities in the rail–track system

Both types of irregularities described earlier and modeled in this study are illustrated in Figure 7.

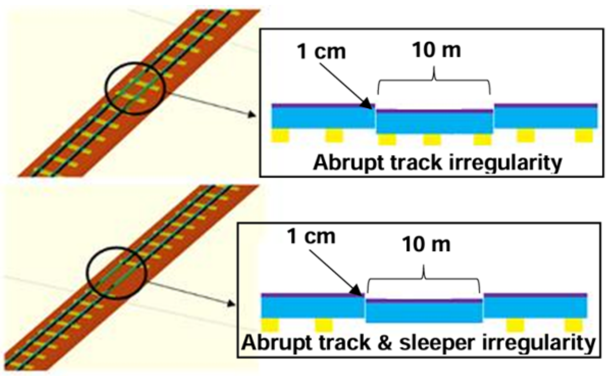

Figure 7. Simulated irregularities in the rail–track system: irregularity only in the rail (top) and irregularity in the rail and sleepers (bottom)

3 Results and Discussion

This section presents the results of the numerical investigation and interprets them into the effects of irregularities in rails and sleepers on ballast settlement. Three different rail–track configurations were analyzed: (a) an ideal track without irregularities, (b) a track with irregularities only in the rail, and (c) a track with irregularities in both the rail and sleepers. Each configuration was subjected to train speeds of 100, 200, and 300 km/h to capture a representative range of realistic operating conditions. The resulting ballast settlements are presented in Figure 8 and Figure 9. Figure 8 clearly shows the significant influence of rail irregularities on the deformation behavior of the track system. These irregularities disrupt the uniform load distribution along the rail, producing localized stress concentrations and leading to higher settlements. The results indicate that even small geometric or stiffness imperfections, such as gaps or misalignments, can considerably increase ballast compression and subgrade deformation. The physical reason behind this behavior is that track irregularities break the continuity and uniform transfer of train loads, forcing the stresses to concentrate at specific points rather than being evenly distributed along the rail. When stiffness or geometry changes (such as gaps, uneven rail levels, or sleeper-fastener irregularities) exist, the rail no longer behaves as a smooth load-transferring beam. Instead, the load is partially carried by localized zones, which experience repeated dynamic loading with higher intensity. Specifically, at 100 km/h, the maximum settlement increased from 4.5 mm in the ideal case to 11.12 mm in the presence of rail irregularities; at 200 km/h, from 4.7 mm to 11.52 mm; and at 300 km/h, from 4.6 mm to 11.41 mm. This trend highlights the sensitivity of the rail–track system to deviations in geometry and support conditions.

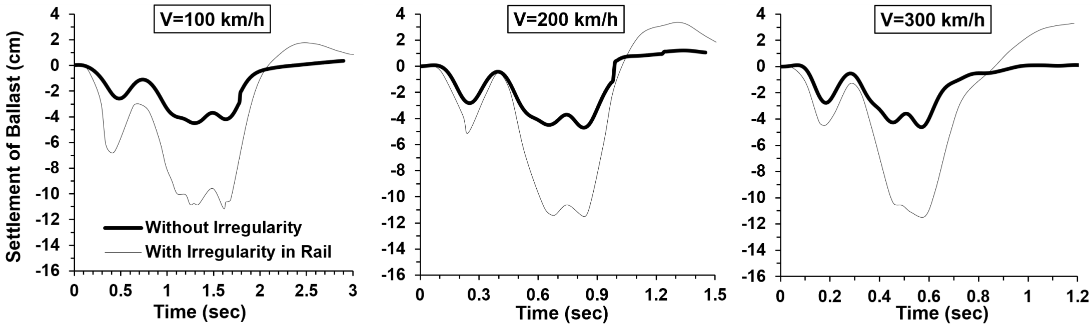

Figure 8. Comparison of ballast settlement for train passages: case without irregularity vs. case with rail irregularity

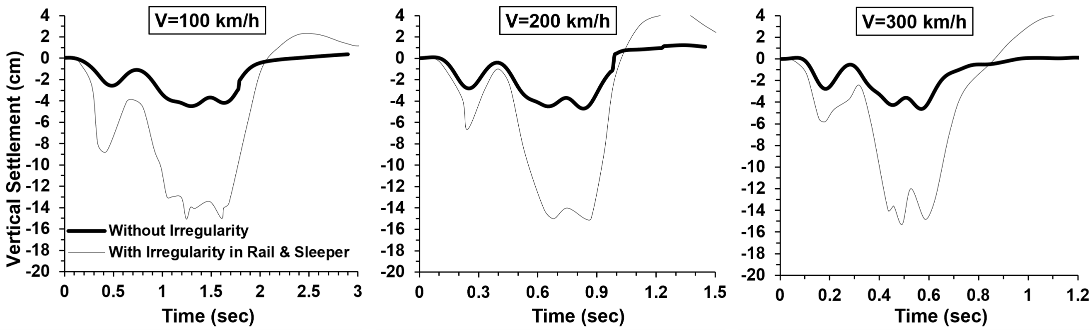

Figure 9. Comparison of ballast settlement for train passages: case without irregularity vs. case with rail and sleepers' irregularity

At higher speeds, irregularities become more critical as they amplify dynamic effects through vibration and impact loading. The physical reason is that higher speeds increase inertial and impact forces, causing irregularities to excite stronger vibrations in the track. These observations are consistent with the findings by Kouroussis et al. [5] and Seyedi [7], who reported that train-induced vibrations intensify when discontinuities or stiffness variations exist along the track. Moreover, the present study provides quantitative confirmation of how these localized dynamic effects translate into measurable increases in ballast settlement–information that has been largely missing from the literature.

Figure 9 shows that the deformation increases even further when irregularities are present in both the rail and sleepers. Ballast compression is accelerated and stress concentrations are increased when rail connection and sleeper support are lost simultaneously. The maximum settlement rose from 4.6 mm to 15.23 mm at 300 km/h, from 4.7 mm to 15.00 mm at 200 km/h, and from 4.5 mm (optimal condition) to 15.05 mm at 100 km/h. When compared to the ideal condition, this combined condition results in a nearly threefold increase in settlement, suggesting that irregularities in the sleeper layer are just as problematic as those in the rail and that their existence magnifies each other. The results of this study support those of earlier research, which highlight how crucial it is to preserve consistent stiffness and geometry in rail–track systems in order to avoid early ballast degradation. However, by measuring the settlement amplification under different train speeds and separating the contributions of rail and sleeper irregularities, the current study provides additional insight into the relative significance of individual track components in governing ballast performance under dynamic loading.

From a practical standpoint, the results give train engineers and maintenance planners useful advice on how to increase track longevity and performance. Rail wear, vibration, and settlement can be reduced by routinely checking the stiffness of the track and performing targeted maintenance in places that are prone to irregularities. It is also necessary to consider these effects in future rail track designs and in the calculation of the critical speed to ensure safer and more efficient train operations. Smoother train operations, lower maintenance costs, and increased safety can all be achieved by incorporating these findings into design and maintenance plans.

4 Conclusion

This study investigated the influence of rail and sleeper irregularities on the deformation behavior of rail–track systems under varying train speeds using advanced three-dimensional finite element modeling in PLAXIS 3D. The results clearly show that even minor defects significantly degrade track performance by disturbing uniform load transfer, producing localized stress concentrations, and accelerating ballast settlement. When only rail irregularities were present, maximum settlement increased from 4.5 mm to approximately 11.1–11.5 mm across speeds of 100–300 km/h, demonstrating that small geometric imperfections can more than double permanent deformation. When irregularities affected both rails and sleepers simultaneously, settlement increased to about 15 mm, representing nearly a threefold rise compared to the ideal condition, highlighting the cumulative effect of combined defects. Train speed was identified as a major amplifying factor, where higher speeds intensify inertial forces, vibration, and impact loading, causing defects that are less critical at lower speeds to become significantly more damaging.

These findings translate into direct engineering implications. Tracks with irregularities–particularly combined rail–sleeper defects–should be treated as high-risk sections requiring prioritized maintenance and monitoring, especially on lines operating at 200–300 km/h. Regular rail grinding, alignment corrections, sleeper support restoration, and stiffness-control measures such as ballast renewal or under-sleeper pads can effectively reduce settlement progression. The proven sensitivity of the system underscores the value of numerical simulation as a predictive tool for identifying vulnerable zones and optimizing maintenance strategies. By capturing the interaction between dynamic loading, soil behavior, and structural discontinuities, the proposed modeling framework supports the design of more resilient rail infrastructures and informed decision-making for inspection planning.

Overall, this research demonstrates that maintaining geometric accuracy and structural continuity in rail–track components is critical for prolonging service life, enhancing safety, and reducing maintenance costs, particularly in modern high-speed railway networks. The insights presented in this study can assist railway authorities, maintenance planners, and infrastructure engineers in developing strategies that improve the durability, safety, and long-term performance of rail transportation systems.

Author Contributions

Conceptualization, M.S.; methodology, M.S.; software, A.M.H.A.; validation, A.M.H.A.; formal analysis, A.M.H.A.; writing—original draft preparation, A.M.H.A.; writing—review and editing, M.S.; supervision, M.S. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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