Impact of reinforced concrete sleeper on ground penetrating radar signal behavior in railway ballast monitoring

S. Harajchi[1], E. Slob[2]

[1] Delft University of Technology; [2] Delft University of Technology

Summary

Railway ballast is essential for maintaining track stability, ensuring proper drainage, and efficiently distributing loads across the track bed. Regular monitoring of ballast conditions is crucial for the safety and durability of railway infrastructure. Ground Penetrating Radar is commonly employed to assess ballast conditions; however, its signals can be significantly affected by structural elements such as sleepers, which may distort signal propagation due to their material properties. Specifically, reinforced concrete sleepers with embedded metal reinforcement contribute to additional attenuation and scattering, complicating signal interpretation. Numerical simulations using the Finite-Difference Time-Domain method were conducted to model wave propagation in three configurations: no sleeper, pure concrete sleeper, and reinforced concrete sleeper. Simulations at 1 GHz and 400 MHz frequencies reveal that reinforced concrete sleepers significantly enhance signal reflections and introduce complex scattering, particularly at higher frequencies. These results exhibit frequency-dependent behavior, where higher frequencies provide better resolution but also more signal distortion caused by the sleeper material. The study offers valuable insights into optimizing GPR signal interpretation in railway ballast inspections and emphasizes the importance of considering sleeper type and frequency selection in data acquisition and processing.

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Introduction

Railway ballast plays a crucial role in providing track stability, facilitating drainage, and distributing loads effectively across the track bed. The consistent monitoring of ballast conditions is therefore vital to maintain the safety and longevity of railway infrastructure (Esveld , 2001). Among various non-destructive testing techniques, Ground Penetrating Radar (GPR) has emerged as a widely used method for railway ballast assessment due to its ability to detect subsurface anomalies and degradation (Wang et al. , 2022). However, GPR signals can experience significant attenuation and scattering due to the presence of multiple structural elements such as sleepers, rails, fastening systems, and ballast stones (Jol , 2009). On one hand, increased ballast fragmentation leads to faster signal attenuation. On the other hand, the presence of sleepers—particularly reinforced concrete sleepers— introduce complex reflections and diffractions that complicate signal interpretation in railway applications (Benedetto et al. , 2019; Wang et al. , 2022).

Concrete sleepers are a standard component in railway track structures, with reinforced concrete sleepers gaining preference due to their durability and load-bearing capacity (FIP Commission , 1987). The presence of reinforcing metal bars within these sleepers, however, can distort GPR signals due to their high conductivity, leading to further reflections and attenuation. As this may alter signal behavior significantly, understanding the impact of it can help in improving data interpretation and implementing mitigation techniques in signal processing (Benedetto et al. , 2019; Ciampoli et al. , 2018). Despite numerous studies on GPR applications in railway monitoring—ranging from general track inspection to ballast characterization and condition assessment through experimental and numerical approaches —limited research has specifically addressed the influence of internal reinforcement within concrete sleeper on GPR signal behavior (Hugenschmidt , 2000; Roberts et al. , 2007).

This study addresses a critical gap by conducting realistic numerical simulations to evaluate the influence of reinforced concrete sleepers on GPR responses in railway ballast monitoring. By comparing three configurations—the absence of sleepers, pure (non-reinforced) concrete sleepers, and reinforced concrete sleepers—the study provides detailed insights into how structural reinforcement affects the electromagnetic signal characteristics. Particular emphasis is placed on the frequency-dependent behaviour of GPR signals, illustrating how different GPR frequencies interact with each sleeper type. The findings advance understanding of optimal frequency selection for reliable and accurate subsurface imaging in railway applications.

Methodology

This study employs numerical simulation based on the Finite-Difference Time-Domain (FDTD) method to investigate the electromagnetic wave propagation in railway ballast environments. A variety of numerical modeling approaches are available in the literature, ranging from basic ray-tracing and 1D transmission–reflection schemes to more advanced finite-difference, finite-volume, Z-transform, and discrete-element techniques, including various hybrid approaches (Jol , 2009). Despite their differing formulations, these methods are unified in their objective to simulate the propagation of GPR waves and their interaction with subsurface structures. Among these, the FDTD method is a robust and widely used numerical tool, particularly effective for simulating complex or heterogeneous environments (Taflove et al. , 2005). It offers key advantages in modeling the dispersive and lossy nature of subsurface media and accurately capturing 3D geometries and material variations (Jol , 2009).

In this study, numerical simulations were carried out using gprMax, an open-source software tool designed for solving Maxwell's equations in three dimensions using the FDTD method (Warren et al. , 2016). The simulation domain consisted of a homogeneous railway ballast layer, 0.3 m in thickness, underlain by a 0.5 m layer of dry sand to approximate typical railway substructure conditions. The dielectric properties of the ballast were modeled using the Complex Refractive Index Model (CRIM), which offers an effective empirical approach for computing the bulk permittivity of dielectric mixtures (Birchak et al. , 1974).

To evaluate the effect of sleeper types on GPR signal propagation, three distinct configurations were simulated: (1) a ballast-only scenario, with no sleeper, serving as a reference case; (2) a pure concrete sleeper without any metallic reinforcement; and (3) a reinforced concrete sleeper embedded with metallic bars.

The GPR source was defined using a Ricker wavelet, that approximates the time-domain shape of a real radar pulse. Two dipole antenna configurations were employed, operating at center frequencies of 1 GHz and 400 MHz. These simulations aim to provide deeper insights into the effect of sleeper type, subsurface layering, and simulation frequency on the electromagnetic response of railway trackbeds, ultimately contributing to improved interpretation of GPR data in railway geotechnical applications.

Simulation Setup

The numerical modeling was conducted using a 3D FDTD framework to simulate GPR wave propagation within a representative railway track cross-section. The simulation domain were measured 0.74 m $\times$ 0.74 m $\times$ 1.098 m and was discretized with a uniform spatial resolution of 0.002 m in all directions, ensuring adequate accuracy for high-frequency electromagnetic wave modeling.

The ballast was modeled as a dry homogeneous dielectric medium with a effective relative permittivity ($\varepsilon_{r,\mathrm{efct}}$) of 3.73 and electrical conductivity (σ) of 0 S/m. The underlying dry sand layer was assigned $\varepsilon_{r,\mathrm{efct}} = 4.54$ and $\sigma \approx 1 \times 10^{-6}$ S/m. The dry concrete sleeper was characterized by $\varepsilon_{r,\mathrm{efct}} = 5$ and $\sigma = 0$ S/m. The metal reinforcement within the sleeper was treated as a perfect electric conductor (PEC).

To prevent spurious reflections from the boundaries, a Perfectly Matched Layer (PML) consisting of 10 absorbing cells was implemented along all domain boundaries. A total simulation time window of 15 ns was used to capture the full wave propagation and reflection behavior. The transmitting and receiving antennas were positioned 0.078 m above the surface, with a horizontal offset of 0.2 m between them. This setup was designed to replicate realistic GPR survey conditions in a controlled numerical environment.

Results and discussion

Figure 1 presents the simulation results for different configurations of ballast and sleeper materials under two frequency scenarios: 1 GHz and 400 MHz.

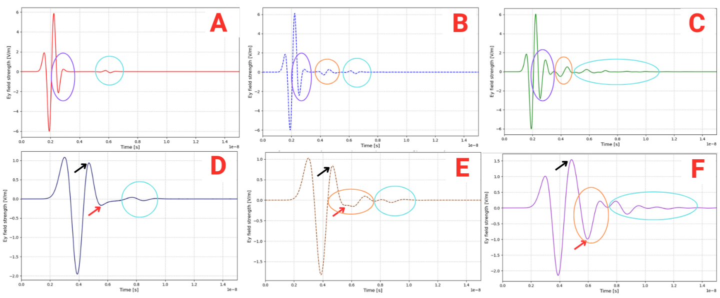

Figure 1 *The simulation results from various interfaces in different configurations. Simulation results at 1 GHz (top) and 400 MHz (bottom). (A, D) 0.3 m homogeneous ballast layer over a 0.5 m sand layer. (B, E) Pure concrete sleeper embedded in the model. (C, F) Reinforced concrete sleeper embedded in the model.*

The top three graphs correspond to a 1 GHz center frequency. Graph A shows the scenario with a homogeneous ballast layer overlying a sand layer. The reflection from the bottom of the ballast layer is clearly visible at approximately 5.7 ns (blue circle). Graph B depicts the scenario where a pure concrete sleeper embedded within the ballast layer. The reflection at 4 ns (orange circle) indicates the presence of the concrete sleeper, and the reflection from the bottom of the ballast layer is at around 6 ns (blue circle). Distinguishing the interfaces between the bottom of the pure concrete sleeper and the ballast layer is clearly possible. Graph C illustrates the scenario with a reinforced concrete sleeper, based on the design from Benedetto et al. (2019). In this case, the reflection from the top of the ballast layer, which was previously a low-amplitude signal in Graphs A (purple oval) and from the surface of the pure concrete sleeper in Graph B (purple oval), becomes enhanced in amplitude due to the metal reinforcement within the sleeper. This enhanced reflection appears as a higher amplitude at 2.3 ns (purple oval) and continues in time until 3.6 ns. This is followed by a reflection from the bottom of the concrete sleeper at 3.7 ns (orange oval). The reflection from the bottom of the ballast layer observed at 5.5 ns (blue circle). This reflection continued as a diminishing small-amplitude reflection, attributable to the combined effects of the metal bars, the bottom of the concrete sleeper, and the bottom of the ballast layer.

The bottom three graphs correspond to a 400 MHz center frequency. Graph D shows the reflection from the bottom of the ballast layer at 7 ns (blue circle). Graph E illustrates the scenario with a pure concrete sleeper, where the reflection at around 6 ns (orange circle) indicates the presence of the concrete sleeper, but compared to Graph B, distinguishing between the bottom of the concrete sleeper and the ballast layer at 7.7 ns (blue circle) is more difficult. Graph F shows the results for the reinforced concrete sleeper. The reflection from the top of the ballast layer, which was a low-amplitude signal in Graphs D (black and red arrows), and the reflection from the surface of the pure concrete sleeper, which was even lower in amplitude in Graph E (black and red arrows), is now significantly enhanced due to the metal bars in the reinforced concrete sleeper. This is compounded by the reflection from the bottom of the concrete sleeper (black and red arrows). The reflection from the bottom of the ballast layer at 7.7 ns (blue circle) is now higher in amplitude but very difficult to distinguish from the combined effects of the interfaces. This small-amplitude reflection from the combined effects of the metal bars, the bottom of the concrete sleeper, and the ballast layer is observed to continue in time. This scenario proves more difficult to interpret compared to Graph C, as the interfaces become less distinguishable.

The principal observations derived from the simulations include the following:

- **Signal Attenuation and Scattering:** The presence of the sleeper, particularly the reinforced concrete sleeper, results in significant signal attenuation and scattering. These effects are more pronounced at 1 GHz, where the signal is more sensitive to small variations in material properties.
- **Reflection Patterns:** The reflection patterns vary notably between the pure and reinforced concrete sleepers. The reinforced sleeper introduces additional reflections and scattering due to the metal reinforcement, which alters the wave propagation dynamics. These enhanced reflections, especially at 1 GHz, complicate the identification of interfaces.
- **Frequency-Dependent Behavior:** Comparing the 1 GHz and 400 MHz results reveals distinct frequency-dependent behavior. The 1 GHz antenna provides higher resolution and better separation of interfaces, but it also suffers from higher attenuation, leading to more prominent distortions induced by the sleeper. On the other hand, the 400 MHz antenna exhibits lower resolution but generates higher amplitude reflections due to the reinforcement, making it more challenging to distinguish between interfaces.

Conclusion

This study investigated the influence of concrete sleepers—both pure and reinforced—on GPR wave propagation in railway ballast monitoring through numerical simulations at 1 GHz and 400 MHz. The results reveal that the presence of sleepers, particularly those with metal reinforcement, significantly alters GPR responses through a combination of signal attenuation, scattering, and complex reflection patterns.

The simulations demonstrate that reinforced concrete sleepers induce stronger signal attenuation and scattering compared to pure concrete sleepers. These effects are especially pronounced at 1 GHz, where electromagnetic waves are more sensitive to small-scale heterogeneities and conductive materials. The metal reinforcement introduces additional internal reflections and scattering, complicating the identification of interfaces and obscuring subsurface features.

Furthermore, a distinct frequency-dependent behavior is observed. The 1 GHz antenna yields higher resolution and improved separation of subsurface layers but suffers from greater attenuation, making the signal more susceptible to distortion from the sleeper structure. In contrast, the 400 MHz antenna offers deeper penetration and higher amplitude reflections, particularly in the presence of metal reinforcement, though at the expense of spatial resolution. This trade-off highlights the importance of frequency selection in GPR-based railway inspections.

In conclusion, the findings underscore the critical role of sleeper material composition and antenna frequency in GPR signal interpretation for railway ballast monitoring. To enhance the reliability of GPR-based assessments, it is essential to account for reinforcement-induced artifacts in both data acquisition and processing stages. Future work should aim to incorporate additional structural elements—such as rails, fastening systems, and heterogeneous ballast configurations—into the simulation framework to improve realism and further refine interpretation strategies.

Acknowledgements

This research is conducted as part of the RESET project, supported by ProRail, the Dutch government organization responsible for maintaining and expanding the national railway network infrastructure.

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