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Ground Penetrating Radar Data Analysis on Frequency-Domain for Railway Ballast Assessment

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Abstract

Railway ballast is one of the key components of the railway that is often problematic. The problems often lie in invisible underground structures, allowing Ground Penetrating Radar (GPR) to play a role in detecting such problems before it's too late. In this research, two important parameters related with ballast assessment are the fouling level and the appearance of cavities inside the ballast has been study. Instead of using real measurement result, a high accuracy synthetic model was used. The interpretation of the data was analysed on the frequency-domain, which has the advantage of being able to identify ballast faults more clearly than time-domain interpretation. The results show that GPR data analysis approaches are more user-friendly and reduce the complexity of data processing.

Keywords: Frequency-Domain Analysis, Railway Ballast Assessment, Ground Penetrating Radar and gprMax

1 Introduction

In rail transportation, maintenance of rail-track is one of the most important tasks to operate with safety. Railway ballast is the key components of the railway that is often problematic. Two important parameters related with ballast assessment are the fouling level and the appearance of cavities inside the ballast. These two problems tend to develop gradually in the underground structure, which is the invisible part, and when such problems become noticeable, it is often too late. Ballast fouling, figure 1(a), often changes the mechanical properties of a ballast resulting in an impact on the structure of the railway or even the train itself. The occurrence of cavities inside the ballast, if left unresolved, can result in the collapse of railways and lead to accidents affecting lives or property, figure 1(b). Therefore, early detection of such problems can prevent accidents and losses.

One of the technologies being used to combat this problem is GPR. However, the challenges in implementing GPR is that it requires high data interpretation and processing skills, which are not user-friendly. This is a reason why, the authors are studying to develop a more user-friendly GPR system. This started with the development of synthetic models that would be used to simplify and shorten the development time of GPR systems. In a previous study, a procedure to simulate realistic GPR acquisitions over ballast soils has been presented [1]. The obtained models were corroborated with real measurements obtained with an experimental GPR system in controlled scenarios showing high correlation [2].

This work goes a step forward, simulating models that are used to address the detection of the two above-mentioned ballast parameters has been studied. By using a single A-Scan data, the classification of two common problems arise inside ballast structure (Fouled-Ballast and Cavity) are shown. In this case, two parameters were studied: Fouled level (f) and Size of Cavity (r). The realistic railway ballast model is used to simulate with gprMax an open source EM simulator based on the FDTD method. After that, the results were compared to show the difference between two studied parameters. The results show again the advantage of using simulations in GPR in pursuit of more robust ballast estimators. The remainder of this paper is structured as follows. The following section shows more details about the synthetic-ballast models used to simulate and introduces three models that will be used as example. Last section then presents the results comparing three models data, then closes with conclusions.

(a) Clean-ballast stones (left) vs. fouled-ballast stones (right)

(b) Railway track collapsed from cavitation

Figure 1: Two common problems arise inside track structure

2 Methods

To create synthetic railway models, the author's uses techniques and methods from the author's previous publications, additional details regarding the process of packing the stones to form a compact layer can be found in [1]. First, a large number of ballast stones with random sizes and shapes under the constraints of standards for ballast in rail tracks had been created in Blender Program. The ballast stones are built as European standards (EN13450: Aggregates for railway ballast)[3], the size of railway ballast stone are between a minimum of 31.5mm and a maximum of 63mm (Grading D-F). The average size of the stones generated is shown in Figure 2, is in compliance with the specified standards with the median of 52mm. The total thickness of a ballast layer is 500mm [4]. The stones are then voxelized and imported to gprMax(version 3.1.5) [5] via a HDF5 file.

In gprMax, the ballast stones have been combined with other structures to form the Synthetic ballast Model of the railway track structure. The generated Synthetic Ballast Model parameters are shown in Table 1. The embedded model of a commercial GSSI 1.5 GHz GPR antenna has been used for the simulations. The antenna was placed above the air-ground interface at 30mm height and at the centre of the model. Figure 3 shown a three-dimensional simulation model, includes a cross section 2D-cut showing the structure of the models with different parameters.

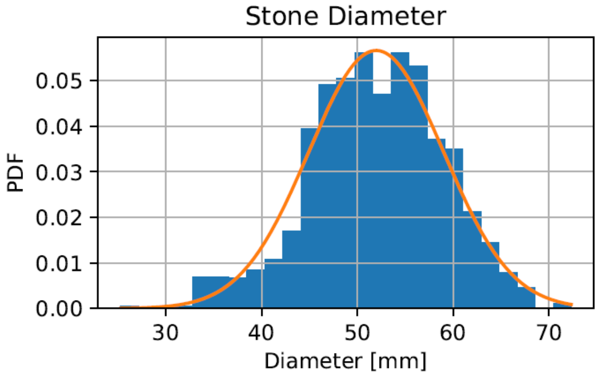
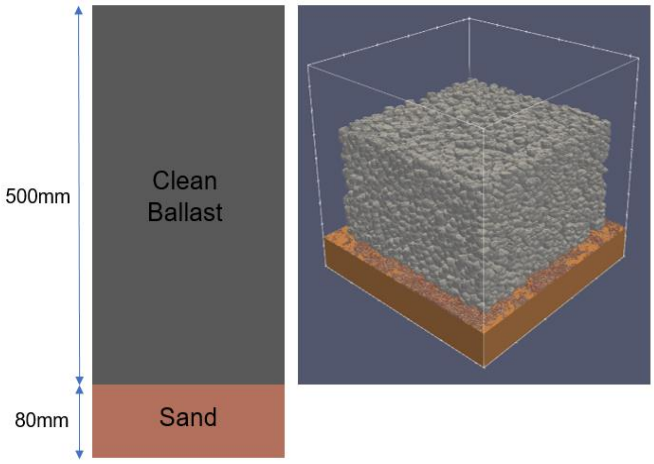


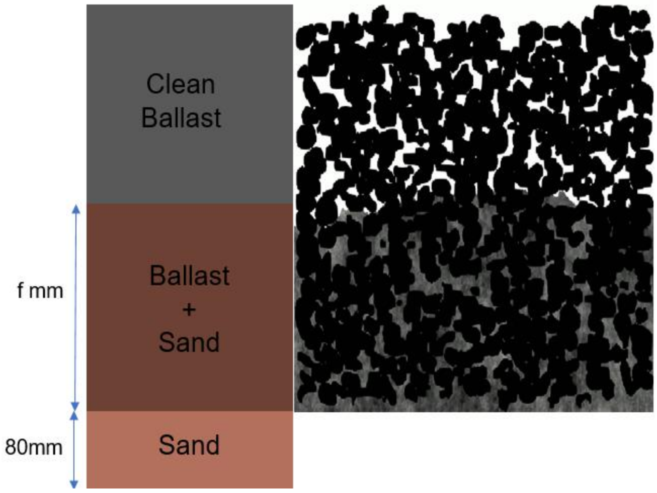
Figure 2: Histograms of the ballast-stone diameter (maximum dimension)

Parameters	Values
Simulation domain	1042mm x 1044mm x 866mm
Ballast thickness	500mm
ε_r of stones	4
ε_r of fouled soil	3.5 (Heterogeneous soil) [6]
ε_r of sand	3
Sand thickness	80mm
Simulation type	A-Scan
Antenna height	30mm
Time window	12ns
Fouled level (h)	0%-80% (0mm – 400mm)
Cavity radius	50mm – 150mm

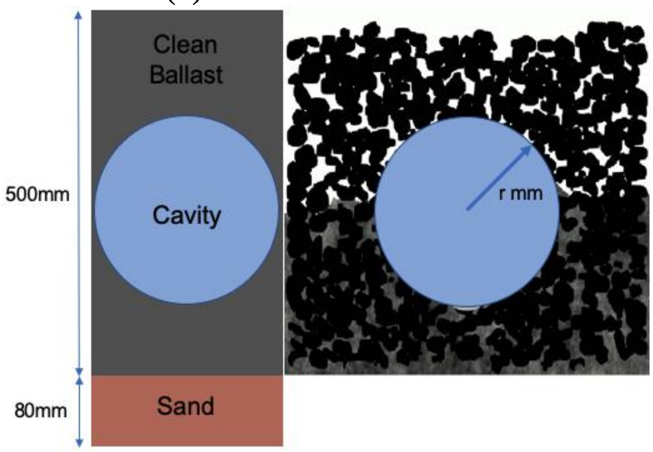
Table 1: Simulation parameters



(a) Clean-Ballast Model



(b) Fouled-Ballast Model



(c) Cavity Model

Figure 3: Synthetic Railway Models

Clean-Ballast Model: Figure 3a, a complete railway model that can perform at full potential as designed, will be used as the standard model for comparison with following models.

Fouled-Ballast Model: a Railway model that have been used for a while which space between stones become filled with fouled material, greatly reducing their properties. This fouled material is mainly derived from crushed ballast (when it was repeatedly pressed by the weight of the train), but also from organic material caused by pollution or effects of weather erosion. The structure of the model is shown in Figure 3b, where 'h' is a Fouled level, which will be simulated 5 levels of fouling from 0mm-400mm(0%-80% fouling).[7,8]

Cavity Model: Cavitation in railways can be caused by a number of reasons, but most of the time it is caused by rainwater. The rainwater washed away parts of the track structure with it, it repeats over a long period of time creates water cavity. When the water dries up, air cavities will form and this is where the problem occur. Overtime, these air cavities will getting bigger and bigger, if not detected, the railway will eventually collapse, figure 1b. In this simulation, a spherical cavity is placed at the centre of the model. The structure of this model is shown in Figure 3c, where 'r' is a cavity radius. In the simulation, the size of the cavity ranges from 50mm-150mm.

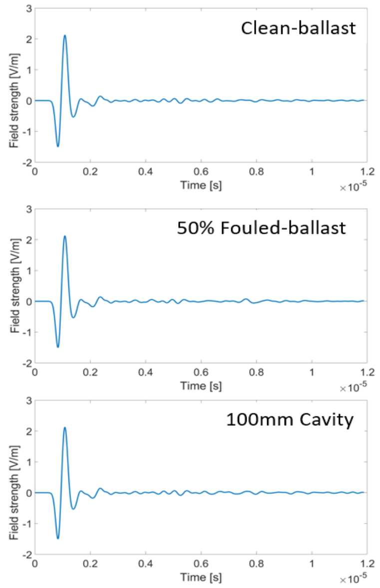
3 Results

As mentioned earlier, interpreting GPR data is a huge challenge that requires user with processing expertise to obtain accurate and precise information. This is therefore an important barrier in the implementation of GPR for railway inspections. For example, in Figure 4 shows A-Scan and B-Scan of the three models: clean-ballast, 50% fouled-ballast and 100mm cavity. For A-scan, it can be seen that it is almost impossible to notice the difference or detect fouling level and cavity. As for the B-scan, although it is easier to spot anomalies than the A-scan, however, without prior experience with GPR results it is also difficult to detect problems as well. For this reason, the authors came up with the idea of processing GPR data in frequency-domain, by applying a fast Fourier transform (FFT) algorithm to an A-scan. In the frequency-domain, the authors found that problems occurring in ballasts could be detected and classified.

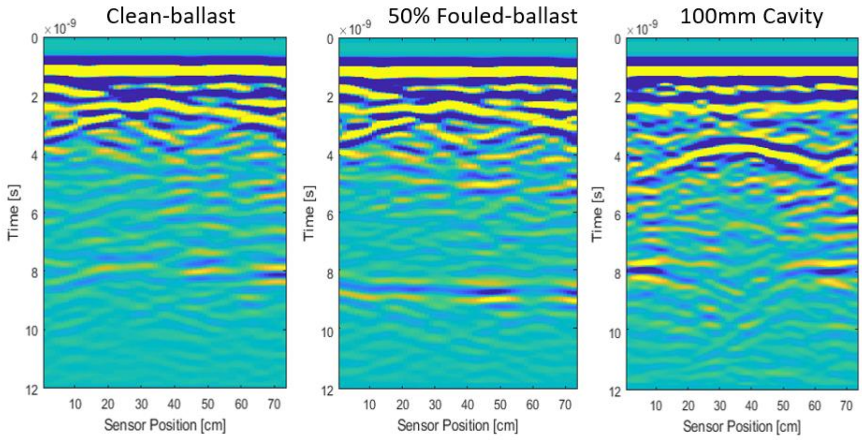
In figure 5(a), shown A-scan results of a clean-ballast model comparing with fouled-ballast models at different levels of fouling. In the time-domain the differences are very small and difficult to analyse, but in the frequency-domain it can be seen that at frequencies approx. 4GHz, it is easier to see and differentiate between clean-ballast and fouled-ballast with various fouling level. In a frequency-domain shows a clear difference at fouling levels of 60% (f=300mm) and above, where ballast begins to lose its properties and can cause problems to the railway track. Therefore, detecting this malfunction will provide maintenance teams with initial information to assess the quality of railway tracks.

Figure 5(b) shown comparison between a clean-ballast model and cavity models with different radius sizes. In the time-domain there is almost no difference, but in frequency-domain we can distinguish the difference of the signal at 6.7GHz frequency range. In this case, the signal can be distinguished in the frequency domain for cavities with a radius greater than 50mm. By detecting such cavities at the initial stage of formation, railway track subsidence could be prevented.

From these results we can see that analysis of GPR results in the frequency-domain can differentiate the problem by converting one A-scan result, this will make building these problems detection system easier and faster, such as the use of math filters to filter abnormal signals and send alarms to users immediately. By using this mathematical filter, it does not require experienced users to process or use algorithms or AI to add complexity in data processing part.



(a) A-Scan



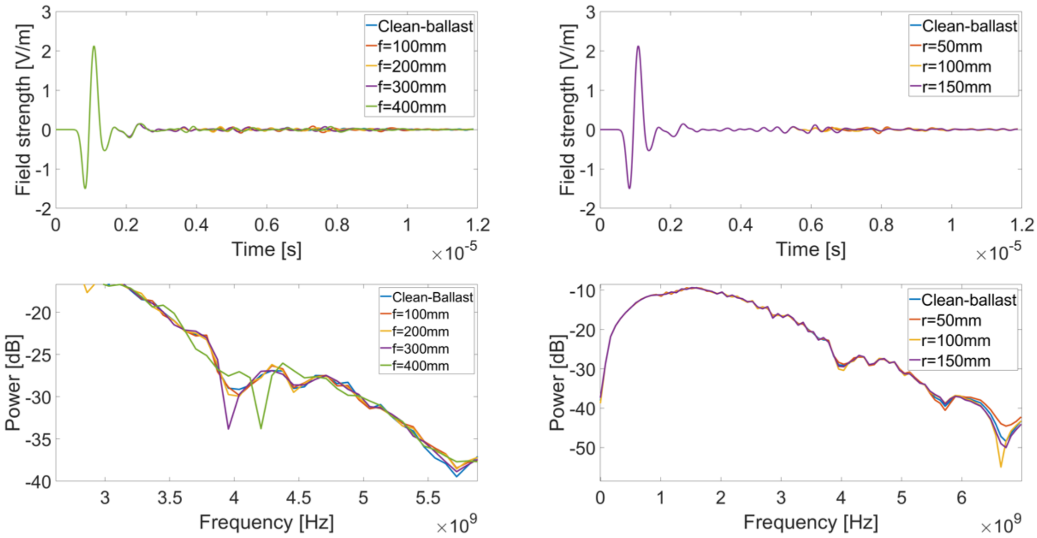
(b) B-Scan

Figure 4: Simulation results

4 Conclusions and Contributions

The results show that frequency-domain GPR data analysis are more user-friendly and reduce the complexity in data processing. Once the preliminary data is obtained, in order to plan the next step of maintenance drills, the user may use GPR to scan the area and analyse the problem with C-scan data subsequently. As know, railway inspection is a huge data-intensive task as the railway network is very long distance, therefore simplifying or estimating the data in the analysis can increase the efficiency of railway track inspection, resulting in increased safety of passengers and property. The frequency-domain analysis of GPR data for railway track, though, it is possible to differentiate the problems that arise within the railway track structure.

This research not only presents a way to simplify analysis of GPR data, but also demonstrates the advantage of using synthetic simulation model in pursuit of more robust ballast estimators.



(a) clean-ballast vs. fouled-ballast (b) clean-ballast vs. cavity ballast

Figure 5: The comparison between time-domain(top) and frequency domain(bottom) data

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