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Railway ballast condition assessment using ground-penetrating radar – An experimental, numerical simulation and modelling development

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HIGHLIGHTS

- A GPR-based assessment of clean and fouled railway ballast.
- Four ballast/pollutant mixes analysed (100% clean ballast to highly-fouled (24%)).
- Use of different GPR air-coupled antenna systems (1000 MHz and 2000 MHz).
- Use of several processing methods for assessing the ballast electric permittivity.
- Application of the RSA and the FDTD paradigms to the laboratory physical models.

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ABSTRACT

This paper reports on the ground-penetrating radar (GPR)-based assessment of railway ballast which was progressively "polluted" with a fine-grained silty soil material. It is known how the proper operation of a ballast track bed may be undermined by the presence of fine-grained material which can fill progressively the voids between the ballast aggregates and affect the original strength mechanisms. This occurrence is typically defined as "fouling". To this effect, a square-based methacrylate tank was filled with ballast aggregates in the laboratory environment and then silty soil (pollutant) was added in different quantities. In order to simulate a real-life scenario within the context of railway structures, a total of four different ballast/pollutant mixes were introduced from 100% ballast (clean) to highly-fouled (24%). GPR systems equipped with different air-coupled antennas and central frequencies of 1000 MHz and 2000 MHz were used for testing purposes. Several processing methods were applied in order to obtain the dielectric permittivity of the ballast system under investigation. The results were validated using the "volumetric mixing approach" (available within the literature) as well as by performing a numerical simulation on the physical models used in the laboratory. It is important to emphasize the significance of the random-sequential absorption (RSA) paradigm coupled with the finite-difference time-domain (FDTD) technique used during the data processing. This was proved to be crucial and effective for the simulation of the GPR signal as well as in generating synthetic GPR responses close to the experimental data.

1. Introduction

The structure of a traditional railway is typically constituted of steel rails fastened to the sleepers and laid on a coarse rocky material, i.e., the ballast. Railway ballast can be defined as a homogeneously graded material coming from the crushing of hard rocks or, seldom, of coarse gravel with small-sized particles sieved out. A railway track bed structure made of ballast aggregate particles is typically laid on the subgrade directly. In some configurations, a filter layer between the ballast and the subgrade, i.e., the sub-ballast, is also included. This is manufactured by smaller-sized soil materials, such as sand or gravel. Typically, the thickness of a track bed structure ranges between 0.45 m and 0.75 m. From a structural and operational point of view, the ballast/sub-ballast system accomplishes the tasks of dissipating the vertical, lateral and longitudinal stresses induced by the loads (i.e., trains passing on

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the rails), and draining the meteoric water by means of the high percentage of air-filled voids [1].

The proper operation of a ballast track bed is ruled by the friction between the aggregates, which in turn is granted by their own angularity. This strength mechanism may be undermined by the presence of fine-grained material which can fill progressively the voids between the ballast aggregates. This occurrence is typically defined as "fouling" and may be related to three main factors, i.e., i) the segregation of the ballast aggregates under load, ii) the production of metal dust from the wheel/rail contact and iii) the rise of fine-grained materials from the subgrade by means of capillary actions. This last factor affects greatly the strength properties of the entire railway track bed, mostly in the case of clayey soil material which flows from the foundation level [2].

Although the modern railroads are provided of geotextiles between the ballast layer and the subgrade to avoid fouling in the rail track bed, most of the dated railway asset was not purposely designed and it is nowadays affected by this occurrence. Above certain levels, the ballast fouling can involve several issues such as the loss of regularity of the rails (reduction of the train speed) and the instability of the rail track (potential derailments). Thereby, the early-stage assessment of fouling is of paramount importance for railway managers in order to minimise the costs of maintenance and the risk of accidents. This concern implies the routine assessment of the geometric, physical and mechanical properties of the ballast/sub-ballast system and, accordingly, the effective detection of fouling. This operation is carried out traditionally in the laboratory environment according to international standard test methods [3–12]. The application of these standards is extremely time-consuming, although the information retrieved are highly reliable. Similarly, the collection of ground-truth data by digging test pits has drawbacks in terms of time-efficiency and data representativeness. In view of the above, the use of time-efficient and cost-effective technologies may be an added value within the context of the effective management of railway infrastructures.

Within this framework, ground-penetrating radar (GPR) represents a powerful tool, which is being increasingly used for the rapid and non-intrusive assessment and the health monitoring of railways. This method relies on the electromagnetic (EM) theory and it has found major application in differing areas, such as civil and environmental engineering [13], archaeology [14], planetary explorations [15] and forensics [16]. According to Roberts et al. [17], the first GPR application in railway engineering dates back to 1985 [18] and involved the use of a low-frequency antenna system mounted over the interaxis of the rails. The low resolution of the system caused uncertainty in the interpretation of the results; thereby, later applications have focused more on the use of higher frequency antenna systems [19–21]. Several GPR-based models for the assessment of the railway ballast condition and the prediction of fouling can be found in the literature [22–24]. These models are mostly based on the processing of the actual GPR data collected in the real life/laboratory environment.

In this paper, several configurations of ballast/fine-grained pollutant mixes were first analysed electromagnetically in the laboratory environment using different signal processing techniques. Subsequently, a novel numerical-simulation-based methodology was developed for the validation of the results.

It is important to emphasize the relevance of the proposed methodology in terms of the achievable efficiency in the investigation of the railway ballast condition. Indeed, the complex own nature and the highly variable physical-mechanical conditions of the railway ballast aggregates within a rail track bed may require the use of specialist antenna frequencies in combination with dedicated signal processing techniques. Within this context, the use of the simulation technique may provide invaluable support in the interpretation of the fouling process. The thorough assessment of the main geometric, mechanical and physical properties of the ballast and the pollutant material carried out in the laboratory, represented a comprehensive source of ground-truth data for the calibration and the validation of the proposed methodology. Information such as the grain size of the particles, the mineralogy and the compaction rate between the aggregates allowed to reproduce effectively the numerical simulation domain of the rail track bed as well as to obtain a reliable validation of the results. In addition, the use of differing antenna systems and frequencies of investigation allowed to demonstrate the actual applicability of the discussed methodology as well as to select the antenna frequencies suited for the purpose.

2. Objectives and methodologies

This paper reports on the EM assessment of railway ballast in both clean and fouled conditions using different signal processing methods. A new numerical simulation methodology was also introduced. Four configurations of ballast aggregate particles and pollutant fine-grained silty soil material were manufactured within a square-based methacrylate tank representing a railway ballast layer of a track bed structure. At each step of the fouling process, the data were collected using several GPR systems equipped with different air-coupled antennas and central frequencies of 1000 MHz and 2000 MHz. Various processing methods were performed for the computation of the dielectric permittivity of the ballast system. The results were obtained by using several models available within the literature. In addition, a new numerical simulation methodology based on the combination of the random-sequential adsorption (RSA) and the finite-difference time-domain (FDTD) paradigms was presented. The remainder of this paper is organized as follows. In Section 3, the EM basics and the main working principles behind the GPR technique are discussed. Section 4 focuses on the experimental design, the laying out of the laboratory setup and the main standard test methods followed for the assessment of the main geometric, physical and mechanical properties of the investigated materials. The results of the GPR surveys are presented in Section 5, where the values of the relative dielectric permittivity computed by the time-domain signal picking (TDSP) technique, the surface reflection method (SRM) and the volumetric mixing formula (VMF) approaches (across the various ballast/pollutant scenarios) are compared each to one another. The outcomes of the aforementioned simulation-based methodology obtained by the use of the 1000 MHz antenna frequency data are therefore analysed. Conclusion and future perspectives are discussed in Section 6.

3. The GPR method

GPR is a geophysical non-destructive technique based on the transmission of an EM impulse towards a generic surface and the reception of the back-reflected signal. When the EM wave tackles an electric discontinuity (e.g., the interface between two geological formations or road pavement layers), part of the energy gets reflected, whereas the remaining part gets transmitted and travels throughout the material before being absorbed. Therefore, it is possible to retrieve information about the subsurface non-destructively by the interpretation of the back-reflected signal.

From a theoretical standpoint, the EM behaviour of the surveyed material is ruled by its dielectric and magnetic properties, i.e., the relative dielectric permittivity ε, the electric conductivity σ and the magnetic permeability μ [25]. The values of ε and σ greatly influence the velocity and the attenuation of the wave propagation, respectively, whereas μ does not affect the EM behaviour in the case of non-magnetic targets.