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"Test-site operations for the health monitoring of railway ballast using Ground-Penetrating Radar"

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Abstract

Effective maintenance of railway infrastructures requires a comprehensive knowledge of the actual condition of the involved construction materials. In this regard, Ground-Penetrating Radar (GPR) stands as a viable alternative to the invasive and time-consuming traditional techniques for railway inspections. This work reports the experimental activities carried out on a test-site area within a railway depot in Rome, Italy. Specifically, a 30 m-long railway stretch was divided into 10 sub-stretches reproducing different various physical and structural conditions of the track-bed. In particular, combinations of varying scenarios of fragmentation and fouling of the ballast were reproduced. The set-up was then investigated using different multi-frequency GPR horn antenna systems. These were towed along the rail sections by means of a dedicated railway cart. Main electromagnetic parameters of railway ballast were estimated for each scenario using time- and frequency-domain signal processing techniques. Interpretation of results has shown viability of the GPR method in detecting signs of decay at the network scale, thereby proving this technique to be worthy for implementation in asset management systems.

Keywords: GPR; NDT; railway; ballast fouling; railway maintenance

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1. Background

Worldwide, ballasted rail tracks permit daily travels of freights, bulk goods and commuters, thereby connecting production poles, transport terminals and cities. In such a framework, always higher performances are required to the track-bed for sustaining the increasingly fast convoys. Accordingly, the track-beds need to be effectively and timely

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maintained, to grant the proper safety and productivity standards over the network. In fact, a constantly growing demand of high-speed travels, carriage tonnage, and operating frequencies determines a faster decay involving a shortened economic life and increased maintenance costs for railway tracks (Nålsund, 2014).

Currently, railway infrastructure managing bodies are tackling the challenging task of optimising limited resources for competitively assuring and sustaining a safe, well-founded, prompt and comfortable transport for customers. This complex objective can be accomplished by working on the present-day vision within the operation and the maintenance departments and moving from a reactive (i.e. “find and fix”) to a proactive (i.e. the maintenance is determined by an early-stage diagnosis of the decay) action planning approach (Bond et al., 2011; Khouy 2013).

In pratical terms, a railway track-bed can be broadly divided into superstructure and substructure. The former includes steel rails, fastening system and sleepers, whilst the latter is composed of rock-derived granular layers laying upon the subgrade, namely, ballast and sub-ballast. In more detail, ballast is a homogeneously hard-rock-derived graded material (Benedetto et al., 2016).

Differential track settlements mainly occur in the substructure, thereby making its mechanical response a major concern for designers and maintenance managers (Indraratna, 2016). In fact, the cyclic loading due to the passing convoys produces a breakage of the sharp corners of ballast aggregates and a fragmentation of the weaker grains. Accordingly, the grading of the substructure changes (Selig and Waters, 1994; Ebrahimi et al., 2012) involving serious implications on the stiffness and drainage capacity of the layer. Furthermore, the air-filled voids can get polluted by fine materials produced at the ballast-sleeper and wheel-rail contact or poured by the passing freights (Indraratna et al., 2014; Tennakoon et al., 2015), and by the upward migration of fine clay particles from the subgrade along with capillary water (Al-Qadi et al., 2010).

2. Monitoring of the track-bed

In view of the above, a detailed and up-to-date knowledge of the quality of the railway substructure is mandatory for scheduling proper maintenance, with the final goal of optimizing the productivity while keeping the safety at the highest standard.

As for other maintenance-related activities, the monitoring procedures generally have to comply with cost-benefit analysis. This involves that the quality of the monitoring, in terms of allocated resources, is typically related to both the rate of utilization of the specific railway stretch and the parameters defining the health condition of the track-bed.

2.1. Traditional methods

Traditionally, field operators conduct visual inspections in order to detect railway stretches subjected to decay. Specific reports filled during these on-site inspections are thus employed for evaluating the overall condition of all the components of the superstructure, i.e. rails, sleepers and ballast. For each of this element, the inspector is required to report on the presence and extension of relevant distresses.

Concerning the detection of decays in ballasted track-bed, the visual inspection permits to observe signs of both fouling and fragmentation only at the extent they are present at the surface of the track-bed. This implies that deep pollution of ballast, as well as fragmentation of the grains that are below the immediate surface, might pass unseen at the visual inspection. In case of severe deep fouling or fragmentation, visual inspection may be able of detecting the indirect effect of the decays, i.e. deformation of the rails and subsidence, rather than the direct signs of the distress themselves.

2.2. Non-destructive surveys

Nowadays, the visual inspections are often integrated by means of automatic systems able to record the geometric parameters of the rails and, therefore, to perform quasi-continuous measurement of potential deformation of the rails occurring over the monitored asset.

Such measures are collected by special convoys that are instrumented with optical-based equipment allowing of observing geometrical features of the superstructures, such as the gauge, horizontal and vertical alignment of the rails.

The density and the frequency of these assessments are typically related to the importance of railway stretch in terms of passengers and commercial traffic.

According to the above, also these non-destructive diagnostic surveys can assess the condition of the track-bed only by observing the effects of potential fouling and fragmentation on the regularity of the rails. In view of this, some convoys are being equipped with additional systems capable of collecting a direct measure of the condition of the ballast. Among these, Ground-Penetrating Radar (GPR) is one of the most acknowledged.

2.3. Ground-Penetrating Radar for ballast assessment

GPR is a well established geophysical technique that enables the inspection of structures or ground surfaces through the analysis of the propagation of electromagnetic (EM) waves. The features of this propagation depends of both the characteristics of the employed device and the properties of the assessed material.

In general terms, the velocity of the travelling EM wave is ruled by the dielectric permittivity ε of the material, while its attenuation in depth is affected by its electric conductivity σ.

When the EM impulse emitted by a source encounters a dielectric contrast in the medium, part of the energy is reflected, whereas the remaining part is transmitted beyond. By collecting such reflections through a receiving antenna, it is possible to image the subsurface features, in both two or three dimensions.

The attention of both researchers and field operators has focused on the use of GPR for the health assessment of ballasted railway track-beds only in the last 20 years. First GPR surveys are reported to have been conducted by systems having frequencies below 500 MHz. Recently, these low-frequency antennas have been replaced by higher frequency (1 GHz÷2 GHz) air-coupled systems, holding many advantages in terms of effectiveness of the assessment and productivity of the surveys (Al-Qadi et al., 2008; Fontul et al., 2014; Roberts et al., 2006).

Field-related scientific contributions have addressed different objectives over the years. These researches are typically based on GPR datasets collected through on-site surveys and mainly focus on *i)* the assessment of track-bed geometry (Hugenschmidt, 2000); *ii)* the detection of highly polluted spots (Al-Qadi et al., 2010); *iii)* the stability analysis of the track-bed (Olhoeft and Selig, 2002); *iv)* frequency-based evaluation of the signal (Shao et al., 2010; Benedetto et al, 2016; Bianchini Ciampoli et al, 2017).

Since they are known to be costly and time-consuming, fewer laboratory and test-site activities can be found in the literature, although they provide essential information to calibrate railway-based models through a proper characterization of the surveyed materials (Shangguan et al., 2012; Fontul et al., 2014; Tosti et al., 2016).

3. Aim & objectives

This work reports on the preliminary results of an extensive survey campaign carried out on a specific test-site placed along a real-life railway. The major objective of the research project is to investigate the effectiveness of GPR for assessing the health condition of railway track-beds. To this effect, the influence of both fouling and fragmentation of the ballast on the electromagnetic signal is evaluated and interpreted with particular reference to potential applications in maintenance and monitoring activities.

4. Experimental activity

In order to assess the effects exerted by fouling and fragmentation on the electromagnetic signal as collected by GPR, a specific experimental activity was planned and conducted by the Department of Engineering of Roma Tre University, over a railway stretch included within a depot area managed by Italian Railways (RFI) S.p.A (Fig. 1(a)).

4.1. Experimental design

In particular, a 30 m-long railway stretch was selected for being subjected to GPR surveys. The characteristics of the railway track are depicted in Fig. 1(b,c). It is composed of a 30 cm-thick ballasted track-bed, on which are laid mono-block reinforced concrete sleepers, with a space interval of 60 cm.

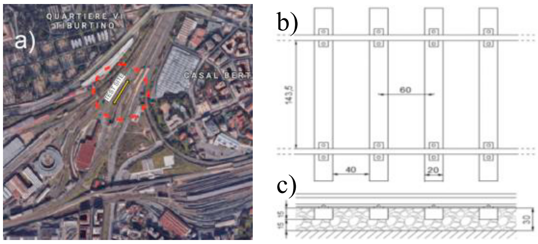

Fig. 1. (a) location of the test-site; (b) plan-view of the inspected railway stretch; (c) cross-section of the track-bed.

Therefore, several intervals between the sleepers were emptied out and re-filled with controlled material, in order to arrange 10 different configurations of fouling and fragmentation of the track-bed, composed of three consecutive intervals each (Fig. 2).

Fig. 2. (a) a set of three volumes emptied out of the original ballast; (b) the re-arranged configuration filled up with controlled material.

4.2. Materials

Two types of ballast were selected for arranging the test samples, namely, an ex-quarry ballast complying with the field-related quality Italian standards (RFI, 2016) and an "exhausted" ballast that had been removed from service due to evident fragmentation of the aggregates.

For reproducing fouling condition, an adequate volume of fine-graded soil was excavated from a depot of railway material dismissed due to reported high up-raised pollution of the track-bed.

Both materials were analysed in laboratory in order to evaluate their features in terms of grading and susceptibility to water. In particular, the grading curves obtained by testing the materials with sieving method (EN 933-1:2012), i.e. grading curve 1 (GC1) and grading curve 2 (GC2), define two fragmentation conditions representing a sound ballast and a fragmented ballast requiring renewal activity (Fig. 3). Regarding the fouling, two conditions of the ballast were accounted for, representing clean ballast (CB), i.e. all the voids between aggregates are filled with air, and fouled ballast (FB) having the voids highly clogged up by the polluting soil.

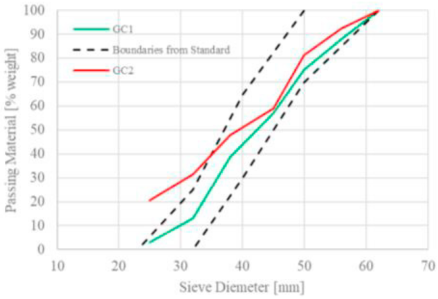

Fig. 3. Outcomes of sieving test on the ballast samples employed for tests.

4.3. Test configurations

The overall 10 configurations were arranged by dividing each volume into two 15 cm-thick layers and varying fouling and fragmentation conditions.

In particular, the tested configurations are briefly reported in Table 1:

Table 1. Tested configurations.

Conf.	**Top Layer**		**Bottom Layer**	
	Ballast	Fouling	Ballast	Fouling
1	GC1	CB	GC1	CB
2	GC1	CB	GC1	CB
3	GC1	CB	GC1	FB
4	GC1	FB	GC1	FB
5	GC1	CB	GC2	CB
6	GC2	CB	GC2	CB
7	GC2	CB	GC1	CB
8	GC1	CB	GC2	FB
9	GC2	FB	GC2	FB
10	GC2	CB	GC2	FB

GC=grading curve; CB=clean ballast; FB=fouled ballast

The first two configurations are composed of sound ballast, in terms of both grading and fouling, and have been used for reference purposes. Configurations 3 and 4 represent a growing rate of uprising pollution of sound ballast from the subgrade. On the other hand, configurations from 5 to 7 represent different conditions of fragmentation of ballast, namely, unsuitable deeper layer (e.g., upper layer renewed), completely fragmented track-bed, fragmented shallower layer. Finally, configurations from 8 to 10 reproduce various mixed conditions of parallel fouling and fragmentation events.

Moreover, for each of the 10 configurations described in Table 1, three levels of moisture were reproduced by progressively wetting the railway stretch. At each round of tests, a sample of soil was extracted from the subgrade and the moisture was controlled. In particular, water contents of 6%, 12% and 17% were assessed.

4.4. Test equipment

GPR tests were conducted by towing a GPR pulse system equipped with high-frequency air-launched horn antennas along the inspected stretch. Employed central frequencies of the antenna were 1000 MHz and 2000 MHz. Both system and antennas were manufactured by IDS Georadar.

The antennas were kept suspended in the air at a fixed height of approximatively 40 cm from the ballast surface by means of a wooden support laying on a hand-towed railway cart (Fig. 4(a)).

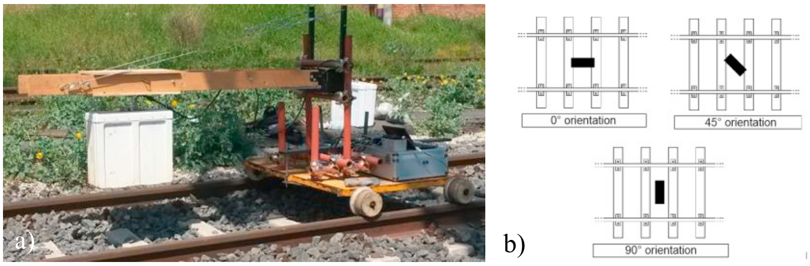

Fig. 4. (a) The experimental testing device; (b) tested antenna orientations

The suspension system allowed the antenna to be rotated around the vertical axis and, therefore, to change the polarization of the antenna with respect of the towing direction. For each antenna, data were collected with antenna oriented with an angle of 0°, 45° and 90° respect to the rails (Fig. 4(b)).

5. Results

According to the preliminary stage of the research, frequency-based analyses of the dataset are not presented in this paper, as well as those related to the influence of water content on the EM signal.

A dielectric permittivity ε_r accounting for the material embedded in the track-bed is calculated by observing the time interval between the reflection from the top and the bottom interface of the ballasted layer, according to the following relationship:

$$\varepsilon_r = \left(\frac{c}{v}\right)^2 \tag{1}$$

with v and c being the velocity of propagation of the EM waves through the material composing the track-bed and through the vacuum, respectively. The value of v for each tested configuration was defined as follows:

$$v = \frac{s}{\Delta t/_2} \tag{2}$$

where s is the thickness of the ballasted layer and Δt is the time interval between the reflection from the top and bottom of the layer, as observed by GPR signal collected on the center of the spacing between two sleepers. Results of the permittivity analysis are reported in Fig. 5.

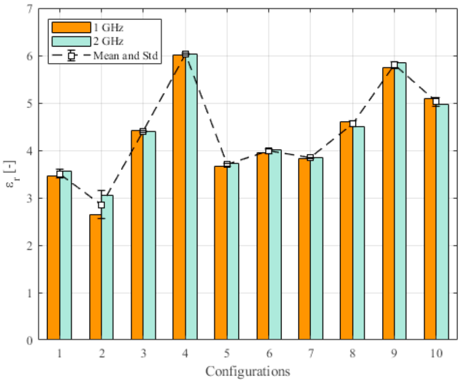

Fig. 5. Outcomes of the dielectric permittivity estimate

As expected, very limited differences between the value of ε_r provided by the two antennas were observed, with an average and maximum standard deviation of 0.05 and 0.20, respectively.

As far as the fouling of ballast aggregates is concerned, the relevant configurations (i.e. 3 and 4) were compared to the reference clean condition (configuration 1). The results are shown in Fig. 6 in terms of observed configurations and Fouling Index (Selig and Waters, 1994).

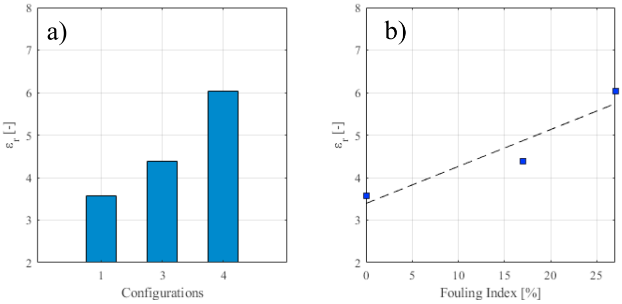

Fig. 6. (a) the permittivity value of the tested configurations; (b) variation of permittivity against fouling condition

Results have stressed out a significant impact of the polluting material, even in dry condition, which causes the permittivity to almost double up its value. Such results are in agree with the outcomes of laboratory experiments published in previous studies (Benedetto et al. 2016; Tosti et al., 2016).

In order to observe the influence of fragmentation of ballast on the electromagnetic response of the track-bed, configurations from 5 to 7 were compared to the reference case, namely, configuration 1 (Fig. 7(a)).

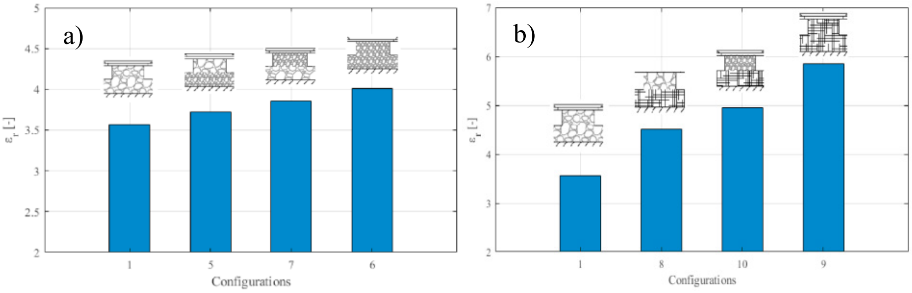

Fig. 7. Influence of (a) fragmentation conditions and (b) combined fragmentation and fouling on dielectric permittivity

Also in this case, the distress causes an increase of the overall permittivity of the material, due to the reduction of the air-filled voids. However, the growing rate of the permittivity is now lower than the former case, with ε_r increasing from 3.57 to 4.01.

The analyses of the mixed fouling/fragmentation condition are reported in Fig. 7(b), where configurations from 8 to 10 are compared to the reference case. The combined effect of voids pollution and fragmentation of the ballast particles returns a significant increase of the permittivity of the material, even if the most fouled condition is found to be still lower than the completely fouled sound ballast (configuration 4). This is most likely due to the greater volume of voids available to filling by polluting material in uncrushed ballast. Indeed, fouling materials typically have a higher permittivity than the ballast particles, thereby causing a greater increase of the overall permittivity.

6. Conclusions

This work reports on the experimental activities carried out on a test-site area within a railway depot in Rome, Italy. Specifically, a 30 m-long railway stretch was divided into 10 sub-stretches reproducing different various physical and structural conditions of the track-bed. In particular, combinations of varying scenarios of fragmentation and fouling of the ballast were reproduced. The set-up was then investigated using different multi-frequency GPR horn antenna systems. These were towed along the rail sections by means of a dedicated railway cart. Main electromagnetic parameters of railway ballast were estimated for each scenario using time- and frequency-domain signal processing techniques. Interpretation of the preliminary results has shown viability of the GPR method in detecting signs of decay at the network scale, thereby proving this technique to be worthy for implementation in asset management systems.

In particular, the effect of fouling and fragmentation of ballast on GPR signal, along with their combined occurrence, were analysed at growing rate of severity. Results have put in evidence a significant impact of fouling condition on the overall dielectric permittivity of the ballasted layer, whereas the influence of fragmentation on the same parameter turned out to be lower. This involved the simultaneous presence of ballast fragmentation in a fouled track-bed to lower the effect of voids fouling on dielectric permittivity. Such findings open novel perspectives in the detection of the ballast health conditions through non-destructive, high productive electromagnetic testing.

In the next future, further efforts are planned to be addressed on the analysis of the same configurations at different stage of water content. Moreover, frequency-based evaluation will be developed for assessing the potential influence of the distresses in the frequency domain.

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