Non-destructive technologies for sustainable assessment and monitoring of railway infrastructure: a focus on GPR and InSAR methods

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Abstract
Health monitoring of ballast in railway infrastructure is crucial to assure long-term structural stability. An efficient and sustainable management of maintenance operations is therefore fundamental for asset owners in setting up strategic and effective action plans. Amongst the available methods to assess the conditions of railway infrastructure, non-destructive technologies (NDT) are gaining popularity due to their capability to overcome main drawbacks from conventional routine methods, such as digging trenches and visually inspecting sections along the track. The present study reports an overview on the use of the ground penetrating radar (GPR) and the interferometric synthetic aperture (InSAR) technologies for a sustainable monitoring of railway infrastructure. Main conventional and non-destructive methods utilised for maintenance of railway ballast materials are presented, with a special focus on their sustainability. A review about research methods on the use of GPR and InSAR technologies for railway infrastructure monitoring is also reported, including main investigations carried out in the laboratory and the real-life environments. Furthermore, a conceptual framework based on an integrated approach between satellite-based and ground-based investigations is proposed, where network- and local-level information can be merged for a more effective detection of critical sections and the implementation of an advanced predictive maintenance system.

Keywords Railway infrastructure · Sustainable assessment and monitoring · Non-destructive testing · Ground penetrating radar (GPR) · Interferometric synthetic aperture radar (InSAR) · Advanced predictive maintenance system

Introduction
Modern transportation greatly relies on ballasted railways, as they have proven to offer good drainage and bearing performance at relatively moderate costs, as opposed to other railway construction types. A major role of infrastructure is to sustain the commuters’ journey and allow smooth delivery of economic goods on a daily basis between major cities and economic transport areas (Indraratna 2016). From top to bottom, a ballasted railway track is composed by the steel rails, anchored to the sleepers through a fastening system, a coarse ballast layer - often laid over a finer graded sub-ballast layer - and, ultimately, the subgrade (Indraratna et al. 2014). According to the literature, this system is usually sorted into two major components, namely, a superstructure and a substructure. However, this classification can vary based on the literature reference sources (Benedetto et al. 2017a). (Giese et al. 1925; Tzanakakis 2013; Pyrgidis 2016), as the ballasted layers can be either included as part
of the superstructure (Indraratna et al. 2016b) or the substructure (Li et al. 2016).

For the purpose of this paper, the authors have assumed the track configuration shown in Fig. 1, with the substructure being formed by the subgrade and the ballasted layers, and the superstructure including the sleepers, the fastening mechanism, and the steel rails (Indraratna et al. 2014). All these components act as part of a more complex system reacting to loads exerted by the passing convoys and assuring proper safety and efficiency of the transport service.

It is clear that these functions are effectively fulfilled only in case the full structure is well-maintained during its service life (Solomon 2001). This is particularly true for ballast layers, due to their fundamental structural role, such as
(i) bearing the compression stresses applied to the sleepers;
(ii) preserving a correct alignment of the rails; (iii) rapidly draining water and other liquids out of the track (Clark et al. 2001; Al-Qadi et al. 2010a). To that extent, the monitoring of ballast conditions with an appropriate time frequency is crucial to ensure that the above functions are not inhibited by any degradation processing affecting materials.

The durability of ballast is severely affected by the abrasion of the sharp edges of aggregates and their fragmentation under the effects of repeated loading cycles. This topic has been widely addressed in the literature, typically applying the Los Angeles Abrasion (LAA) test on ballast samples to relate a variation in the aggregate shape characteristics to the abrasion index obtained by LAA standards (Wnek et al. 2013; Makarov et al. 2019; Qian et al. 2014; Okonta 2014; Sun et al. 2016). Indeed, repeated stress cycles generated by railway traffic can rapidly damage the ballasted layer and, in turn, they can further lead to formation of fouling (material particles ≤ 1.2 cm) (Ebrahimi et al. 2015), with a negative impact on the whole track stability.

This contamination process starts as the voids between the aggregates get filled with fine materials (Anbazhagan et al. 2016). Amongst the various causes for the formation of ballast fouling, the most common are the fragmentation of aggregates (76%), the migration of fine-grained material away from the subgrade (13%), infiltration within sub-ballast material (7%), the wearing of concrete or wooden sleepers (3%), and the infiltration of weathered particles and coal droplets (1%) (Selig and Waters 1994; Leng and Al-Qadi 2010). Fouling can inhibit the strength and drainage capacity of the ballast layer (Al-Qadi et al. 2010a; Leng and Al-Qadi 2010) and, hence, it can severely affect safety of the track. As an example, in case of existing poor drainage conditions caused by a reduction of the intergranular voids, water accumulation in the ballast layer may determine a considerable drop in the stiffness of the material (Ibrekk 2015). Accordingly, inaccurate estimation of fouling may affect planning of effective maintenance, and eventually lead to peripheral and less effective decisions. As an example, introducing traffic control signals (e.g., the provision of temporal/permanent speed limits) in case cumulated deformations occur on rails may contribute to increase the likelihood of catastrophic events, such as train derailments (Solomon 2001). Rapid and effective diagnosis of fouling and moisture levels within the ballast layer is therefore crucial for asset owners in setting up effective maintenance programmes (Artagan and Borecky 2020).

Health assessment of ballast is conventionally performed by visually checking the condition of the superstructure at given location points along the track using inspection trenches. However, these methods are clearly destructive, labour-intensive, and time-demanding, and they can provide significant information only at the inspected point location. On the opposite, non-destructive testing (NDT) methods are being increasingly adopted due to their capability to overcome main disadvantages of conventional techniques. Amongst the various NDT methods, the ground penetrating radar (GPR) technology is gaining popularity for the assessment of ballast, as it permits the acquisition of dense and accurate information through efficient and sustainable

Fig. 1 Cross-section layout for a ballasted railway
surveys. GPR allows avoiding considerable amount of earth movements and limit the consumption of non-renewable resources. Parallel to this, the interferometric synthetic aperture radar (InSAR) is nowadays emerging in the monitoring of ballasted railway tracks at the network level, as it allows collection of data for vast areas across different time intervals.

The present work reports an overview on the use of the GPR and the InSAR methods for sustainable monitoring of railway infrastructure. To elaborate, the section “Railway ballast decays: overview and assessment methods” shows the decay modes of ballast highlighting main characteristics and effects of mechanisms leading to ballast deterioration. The main conventional and non-destructive methods for railway ballast maintenance are discussed in the section “Railway ballast maintenance”, with a special focus on sustainable maintenance activities. The section “Research methods on the use of InSAR and GPR techniques in railway infrastructures” reports a review of research methods and applications on the use of InSAR and GPR techniques in railway infrastructure at the laboratory scale of investigation as well as in real-life practice. The benefits of a newly proposed network-level NDT monitoring approach are then discussed and conceptualised in the section “Benefits of network-level satellite remote sensing and NDT monitoring”. Conclusions and main remarks are reported in the section “Conclusions and final remarks”.

**Railway ballast decays: overview and assessment methods**

Different types of decay may occur on a ballasted railway, as the substructure and the superstructure can deteriorate in different modes. Structural deformations generate in the substructure and are typically related to issues such as polishing of ballast, poor drainage, and formation of ballast pockets (De Chiara et al. 2014; Riveiro and Solla 2016). In addition, various failures observed at the superstructure level may originate from decay evolving in the substructure. As an example, a track substructure with poor structural properties may result on the loss of the rail regularity and lead to significant wearing or even failure of rails, sleepers, and fasteners (Li et al. 2010).

Major superstructure track failures can be broadly grouped as (i) faults linked with the superstructure geometry (e.g., alignment, longitudinal levelling, and gauge) and (ii) faults linked with the rail surface (e.g., surface and corrugation) (Quiroga et al. 2013). It is worth noting that the above classes of failures are mutually dependent. Although rail surface quality does not directly affect safety and comfort of passengers, it can affect the quality of the track alignment and, consequently, the infrastructure lifetime (Artagan et al. 2019).

Under a structural point of view, strength characteristics of rail substructure components can be affected by excessive content of fouling in terms of reducing their durability, the formation of mud-holes, reducing permeability (drainage) and stability features, and increasing the amount of permanent deformations (Sadeghi et al. 2018; Rampersad et al. 2018).

With reference to the ballast fragmentation, fouling is caused by the formation of smaller crushed aggregates (Sussmann et al. 2012) with a gravel-like consistency. At an early stage, this occurrence can erroneously be linked with an increase in the strength of the ballast layer, due to high-strength fragments in the voids limiting settlement of larger ballast aggregates. However, this apparent increase of the ballast mechanical properties results on a reduction of the track resilience and the layer permeability. Hence, a thin threshold divides “induced” strength conditions of ballast layers from their fragmentation and the constraints on their drainage capacity (Koohmishi and Azarhoosh 2020; Paiva et al. 2015; Al-Qadi et al. 2008).

**Fouling quantification**

Fouling affecting a ballasted track can be qualitatively classified in three main groups, i.e., clean, moderately fouled, and highly fouled ballast (Anbazhagan et al. 2011a) (Fig. 2).

Clean ballast represents the as-built conditions of new ballast aggregates with proper air-void contents. As the amount of fines pollution increases from degradation

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Fig. 2 Layouts of fouled ballast levels: a clean ballast; b moderately fouled ballast; c highly fouled ballast
mechanisms, the high-fouling level is reached once all the air voids get filled with fine particles (Tennakoon et al. 2012).

Several quantitative indexes are reported in the literature to estimate fouling pollution levels in ballast layers. They typically define the rate of fouling in terms of the size of the fine-grained particles filling the intergranular voids between the coarse-grained ballast aggregates (Ebrahimi et al. 2015; Anbazhagan et al. 2012). A description of the main fouling indexes is reported below.

Fouling index: The fouling index (FI) (Eq. (1)) proposed by Selig and Waters (1994) is commonly used in railway engineering practice and it has been extensively adopted in the US

\[ \text{FI} = P^4 + P^{200}, \]  

where \( P^4 \) is the percentage by mass of ballast passing the 4.75 mm (No. 4) sieve, and \( P^{200} \) is the percentage by mass passing the 0.075 mm (No. 200) sieve. Table 1 reports different ballast fouling levels for the proposed FI values (Selig and Waters 1994).

Volumetric fouling index: Fouling causes a variation of the original specific gravity of ballast, as the original void ratio varies with an increase of the pollution from fines. As such, the contact points between fouled particles and ballast aggregates are proportional to the void volumes clogged up. A volumetric fouling index (VFI) (Eq. (2)) was therefore established by Ebrahimi et al. (2015) to estimate the volumes of contaminants in ballast subject to different fouling agents

\[ \text{VFI} = \text{FI} \times \frac{G'_f}{G'_r}, \]  

with FI being the fouling index expressed by Selig and Waters (1994), \( G'_f \) the specific gravity of the reference ballast material (~2.6), and \( G'_r \) the specific gravity value of the considered fouling agent, respectively. This expression matches with that proposed by Feldman and Nissen (2002), which evaluated the fraction of the total void volume of contaminated ballast through a percentage void contamination model (PVC). In addition, a similar volumetric model named void contamination index (VCI) was developed by Indraratna et al. (2011) to comprehensively estimate the volume of multiple fouling agents (e.g., clay and coal) relative to the total volume of ballast voids.

Ballast particle contact-point contamination: As mentioned, fines between coarser aggregates decrease the number of contact points between the ballast aggregates and, accordingly, they can affect the stiffness of the track (Ebrahimi et al. 2015; Sadeghi et al. 2018; Benedetto et al. 2017b; Mishra et al. 2014). This model has been developed to determine the ratio of macro-voids in the ballast matrices under various conditions of fouling by comparing the ballast under investigation to reference clean ballast conditions (Ebrahimi et al. 2015) as follows:

\[ e^{B}_{\text{mac}} = \left( \frac{G'_f \gamma_w V}{M_b} - 1 \right), \]  

where \( e^{B}_{\text{mac}} \) is the ratio of macro-voids in ballast, \( G'_f \) is the specific gravity of ballast, \( \gamma_w \) is the density of water, \( V \) is the total volume of the sample ballast, and \( M_b \) is the mass of ballast particles (> 12 mm) in the volume.

Breakage index: The breakage index (BI) (Eq. (4)) is calculated through the fractal gradation curve test (Einav 2007), and it is expressed as the difference in the areas between the original and the final gradation curves. The index is expressed as follows:

\[ B_{\text{bal}} = \left( \frac{A}{A + C} \right) \times 100, \]  

with \( B_{\text{bal}} \) being the breakage index and \( A, C \) the gradation areas calculated through the gradation chart in Fig. 3 (Koohmishi and Palassi 2017).

Relative breakage index: The relative breakage index (RBI) (Eq. (5)) is defined as the difference in terms of areas between the original gradation and the final gradation curves (Koohmishi and Palassi 2017). The index is expressed as follows:

\[ B'_{\text{bal}} = \left( \frac{A}{A + C + D} \right) \times 100, \]  

where \( B'_{\text{bal}} \) is the relative breakage index, and \( A, C, D \) are the gradation areas calculated through the gradation chart in Fig. 3 (Koohmishi and Palassi 2017; Indraratna et al. 2016a).

Table 2 lists the main ballast degradation indexes and relevant literature in this area of research.

Table 1 Categories of fouling according to (Selig and Waters 1994)

| Fouling level   | Abbreviation | Fouling index |
|-----------------|--------------|---------------|
| Clean           | C            | < 1           |
| Moderately clean| MC           | 1–10          |
| Moderately fouled| MF         | 10–20         |
| Fouled          | F            | 20–40         |
| Highly fouled   | HF           | > 40          |
Railway ballast maintenance

Diagnosis and maintenance

Regular inspections of the railway network are fundamental to ensure the safety and efficiency of the asset by an early detection of critical sections and potential damaged areas in the track. However, the maintenance of this complex system is a demanding task in terms of costs and duration of the activities.

An effective assessment of the ballast layer and the subgrade is therefore crucial to plan timely interventions. This can contribute to reduce costs and to limit the impact on the safety of infrastructure.

It has been observed that in case of limited funds available for the management of railway assets, the budget for maintenance (e.g., ballast cleaning and renewal operations) tends to be reduced accordingly. This approach is reasonable only for short-term interventions, as it is likely to jeopardise the long-term costs of the overall track asset.

Delaying routine and extraordinary maintenance could escalate into more severe consequences and, thereby, it can lead to a dramatic increase of rehabilitation costs (Solomon 2001).

According to Tzanakakis (2013), three different time stages can be identified throughout the service life of a railway track, i.e., the youth, the intermediate life, and the old age (Fig. 4).

During the youth stage, the track is subject to significant deterioration due to expected infrastructure settlements. Preventive maintenance is therefore fundamental to avoid an early and sharp structural decay. The intermediate life is the period when corrective maintenance (i.e., rectification of the alignment or replacement of unsuitable materials) is applied to mitigate the deterioration and maintain safety standards to an acceptable level. The old age is the stage approaching the end of the service life of the track when higher decay is expected to take over. The track components must here be partially or fully replaced in case the track does not comply with sufficient quality standards (Tzanakakis 2013).
It is worthy of mention that the track-bed components are non-renewable materials. Accordingly, an accurate and timely monitoring of the ballast condition can allow to intervene before decay is completely formed and adapt specialist techniques to the specific decay type. This approach results less demanding in terms of required maintenance, as well as in terms of consuming a lower amount of non-renewable materials. Currently, various techniques allow to perform a more sustainable monitoring of the railway substructure by detecting the ballast decay at both the network level and the local level. These methods can be roughly sorted into mechanised and non-mechanised.

Amongst the non-mechanised methods, the “through packing” approach is one of the most popular (Ponnuswamy 2012; Chandra and Agarwal 2008; Prasad 2016). Despite its accuracy, maintenance is however generally carried out by mechanised techniques, which have taken over manual tasks widely performed in the past (Solomon 2001). Manual maintenance of rail tracks requires in fact ten times the man-hours demanded by a fully mechanised process, on average (Profillidis 2006).

Amongst the mechanised techniques, tamping is typically carried out for prevention and correction of track geometry issues (i.e., sinking of the sleepers), whereas grinding is conducted in case of rail surface deteriorations (Quiroga et al. 2013). Stages of tamping are discussed by Selig and Waters (1994) and displayed in Fig. 5.

They consist in: (a) the track and the sleepers are set in an incorrect position prior to tamping initialisation; (b) the rails and the sleepers are raised by the tamping machine to a required level, thereby creating an empty space beneath the sleepers; (c) the tamping tines are inserted into the ballast at both sides of the sleeper; (d) a pressure is exerted on the ballast through the tamping tines towards the created void, hence retaining the correct position of the rail and the sleeper; (e) removal of the tamping tines from the ballast and repeating the operation on the next sleeper.

Assessment techniques for railway infrastructure management

Various techniques have proven successful in assessing the condition of the track ballast components. These can be grouped into destructive and non-destructive, depending on their invasiveness to the structure. Although destructive techniques are still widely adopted for monitoring ballast layers and railway foundations, non-destructive testing methods are gaining popularity in recent years as they have proven effective in reducing costs of maintenance.

The following sections report main techniques and a classification based on their productivity.

Destructive techniques

Conventional techniques are usually destructive, as they are mostly based on the evaluation of samples collected on the track. Their use can provide accurate information, although this is significant only at the section where tests are carried out. Furthermore, they have poor time efficiency and they cannot provide a comprehensive assessment of the damage and its formation mechanisms in the ballast and sub-ballast layers, but rather an indication about the decay conditions. These techniques typically include visual inspections, selective drill approaches, and the dig-at-interval methods (Al-Qadi et al. 2010a). In view of the complexity of decay that may occur in railway substructures, rapid, dense, and integrated assessment techniques are therefore required. Non-destructive methods are therefore nowadays preferred over conventional destructive techniques as they can provide more rapid and effective inspections at lower costs.
Non-destructive techniques

Various technologies with different data coverage and productivity performance can be listed for the assessment of ballast conditions (Table 3). In the following sections, these technologies are classified based on these features, and an individual summary description is provided.

Low productivity techniques Inertial methods: Inertial methods can be used as an indirect measurement of the decay in ballasted layers as they rely on a double integration of the acceleration value collected by accelerometers. As an example, the vertical position of a wheel can be calculated via a double integration of the acceleration from the axle box (Tsunashima et al. 2012), as the wheel is continuously in contact with the rail (Fig. 6).

Given the regularity of the surface of a sound rail, these methods assume that unexpected accelerations of the convey wheels are associated with defects in the rails that, in turn, may be caused by structural problems in the ballast layers. Accordingly, the aim of these models is to evaluate rail irregularities and search for the transfer function to relate input and output functions in the frequency domain (Real et al. 2011). The solution is then transformed in the time-domain by implementation of the inverse Fourier transform.

Acoustic and ultrasonic techniques: Similarly to the inertial methods, acoustic-related methods can be applied to indirectly detect decays in ballast layers by inspecting the conditions of the rails. The acoustic and ultrasonic techniques are based on the transmission of an acoustic source pulse to the rail surface and the reception and amplification of the recorded pulse (Fig. 7). This allows to measure the time elapsed with an accuracy of ± 1%. As the velocity of waves in a medium is dependent on its elastic properties and mass, these can be estimated by knowledge of the mass and the wave propagation in the medium (Trtnik et al. 2009; Labropoulos et al. 2010; Santa-aho et al. 2017).

Medium productivity techniques Image-based methods: Since traditional visual inspections are time-consuming, laborious, and highly dependent on the interpretation skills of the operators, automatic image-analysis algorithms have been proposed for the inspection of the superstructure (e.g., rails and sleepers) and the ballast layer. To date, only a few contributions are reported in the literature about using computer vision technology in railway maintenance (Malar and Jayalakshmy 2015). In the research presented by Malar and Jayalakshmy (2015), the purpose of an automatic rail inspection system was aimed at detecting sleepers

| Technique                      | Standard/guideline*       | Data coverage | Productivity (daily) | Resolution   |
|--------------------------------|---------------------------|---------------|----------------------|--------------|
| Inertial                       | G: ASTM E950 – E950M (2018)| Local level   | Low (< 10 km)        | 0.04 Hz      |
| Acoustic and ultrasonic        | R: BS EN 16729-1 (2016)   | Local level   | Low (< 10 km)        | 10⁻² ÷ 10⁻⁴ m|
| Image-based                    | R: Guidelines Johnson (2016)| Local level   | Medium (10–20 km)   | 10⁻² ÷ 1 m   |
| Optical-based                  | G: Guidelines Habel et al. (2009)| Local level | Medium (20–50 km) | 10⁻² m       |
| Electromagnetic                | R: BS DD ENV 50121-1 (1996); G: ASTM D6087 (2008)| Local level | Medium (30–70 km) | 10⁻² ÷ 5 × 10⁻² m|
| Satellite remote sensing       | G: ASTM F2327 (2015)      | Network level | High (> 100 km)     | 10⁻³ m       |

*Standards/guidelines are general (G) or railway-related (R)
and/or fasteners, from real images collected through a digital camera. In Mazzeo et al. (2010), a system for the automatic detection of external material on the ballast surface was presented. Bianchini Ciampoli et al. (2017) report an investigation at the laboratory scale into the railway ballast aggregates’ properties based on the use of an image-analysis algorithm (Fig. 8).

Optical-based methods: Optical methods are typically based on the use of optical fibre sensors (OFSs), which are being increasingly employed in civil engineering applications (Ye et al. 2014). These systems are composed of an optical source exciting a transducer through a fibre optic cable. A schematic system of OFS is illustrated in Fig. 9.

OFSs have many advantages as opposed to other conventional sensors. Amongst others, we can mention the contained dimensions, light weight, a low sensitivity to corrosion effects and EM interferences, and a general high reliability of measurements, as sensors are embedded directly into the structure/infrastructure (Ye et al. 2014; Barrias et al. 2016).

In addition to the above, Campanella et al. (2018) report a wide spectrum of measurements associated with use of OFSs, e.g., strains, vibrations, electric, acoustic and magnetic fields, accelerations, rotations, pressure, temperature, linear and angular positions, and the measurement of other important physical and chemical factors.

Electromagnetic techniques: Working principles of these methods stem from the electromagnetic (EM) theory and the material constitutive relationships, and they rely on the use of radar technology (Fig. 10). Amongst these methods, GPR is becoming popular due to its efficiency and reliability. GPR is a non-invasive, rapid and versatile technology that permits the investigation of long sections of the railway track (i.e., hundreds of kilometres) in a relatively short time, as the acquisitions can be performed at remarkable survey speeds. It provides high-resolution images (data collected every few centimetres) and, according to its non-destructive working principles, it can be repeatedly used over the same location to monitor the evolution pattern of a decay.

High productivity techniques: Satellite remote sensing: Radar interferometry or interferometric radar is a remote-sensing technique arising from space technology with applications in infrastructure monitoring (Fig. 11). This technique can detect surface displacements using the phase information of a microwave signal back-reflected from scatterers on the ground. The scale and the accuracy of detect-
able displacements depend on several contributing factors, including the nominal wavelength and resolution of the satellite sensors, and it can reach up to millimetres (Pieraccini 2013). Research is currently focussing on finding effective solutions to issues related to the management of extensive databases, the harmonisation of datasets from multiple sensors, and the integration between data interpretation methods from different areas of expertise (Chang et al. 2017).

Radar interferometry can be sorted in two main areas, i.e., the real interferometry radar (RAR) and the synthetic interferometry radar (InSAR). The InSAR technique was developed to overcome limitations observed on the former through an azimuth independent by the slant range to the target, smaller antenna dimensions and relatively longer wavelengths (ESA 2018).

The InSAR technique relies on the analysis of the variation of the signal phase between images collected at different times by an orbiting satellite (Ciampoli et al. 2019). Once the resulting interferogram is filtered from relevant noise, the phase variation can be related to the motion of the observed target on the ground, during the time range separating the two acquisitions. Accordingly, InSAR represents an effective technique to monitor potential settlements in a railway network across multiple periods of observation (Gagliardi et al. 2021).

**Fundamentals and principles of GPR and InSAR methods**

Amongst the above-mentioned techniques for railway infrastructure monitoring, the integration of the GPR method (electromagnetic techniques) and the InSAR technology (satellite remote-sensing) is emerging as one of the most promising approach for detecting decays in railroad sub-structures. The integration of GPR at the local level and the InSAR method at the network level can allow for a timely diagnosis of decay, and it lends itself to be considered as an effective tool in the monitoring of ballasted railways.

The fitness of InSAR and GPR integration stems from their complementarity. GPR can provide unique information about the subsurface characteristics of the railway infrastructure, whereas the InSAR technique can detect effectively the ground displacements. According to the literature, it is possible to retrieve grain-size-related information with GPR [e.g., (Bianchini Ciampoli et al. 2017; Annan 2003; Göbel et al. 1994)], including the formation of ballast fouling [e.g., (Anbazhagan et al. 2016; Roberts et al. 2006, 2007; Anbazhagan 2013)], amongst others. In case as-built ballast aggregate conditions change drastically and lead to formation of fouling, it has been proven that severe settlements can occur along the railway track (Selig and Waters 1994). In this context, use of the InSAR technology can stand as a fundamental and complementary monitoring tool to identify potential critical sections where to carry out more in-depth GPR inspections at an early stage of development of settlements.

Fundamentals and principles of these two non-destructive techniques are discussed in the following sections.

**GPR working principles**

GPR principles rely on the physics of the EM field propagation described by the Maxwell’s equations and material properties, defined in turn by constitutive relationships. The propagation of the EM waves depends on the three main EM properties of the host material (Benedetto et al. 2017b). Amongst these, the dielectric permittivity and the electric conductivity affect the wave velocity and attenuation, respectively, whereas the magnetic permeability does not influence the wave propagation in case of non-magnetic materials.

The frequency of the emitted signal and the type of material investigated are main factors affecting the penetration depth.

The most popular elements and factors investigated with GPR in railway engineering are (Maturana et al. 2011): (i) the thickness of structural layers and foundations characteristics (ballast, sub-ballast, and subgrade); (ii) the degree of contamination of the ballast; (iii) the ballast moisture content; (iv) potential settlement areas.

Figure 12 shows the typical propagation pattern of a GPR signal through a ballast layer. The direct signal (S1) is the part of energy that is directly radiated from the transmitter to the receiver. Part of the signal (S2) is reflected at the surface of the ballast. Another portion (S3) is the energy generated due to scattering from voids in clean ballast. In case a clear interface is formed between the clean and the fouled ballast or sub-ballast, a further portion of the signal (S4) is reflected by this interface.

Railway ballast is formed by uniformly graded coarse aggregates with large air voids (Al-Qadi et al. 2008b),

![A satellite remote-sensing survey (ESA 2018)](image-url)
that may reach 30% in volume. Hence, the scattering response from the voids must be considered when dealing with the GPR acquisitions on ballasted tracks. In case of high-frequency antennas, scattering from voids may be the dominant factor when wavelength of the signal is coherent with the size of the air voids. The variation in the scattering pattern is in fact dependent on the size of the scatterer compared to the incident wavelength (Annan 2003). As the ballast becomes fouled, the volumetric contribution of the air voids in the material decreases. Accordingly, scattering-related responses in GPR data may be used to estimate fouling from most common formation mechanisms (Annan 2003; Göbel et al. 1994).

**InSAR working principles**

The InSAR technique, or SAR interferometry, allows to detect displacements along the observation direction of SAR satellites. It measures the variation in the signal phase between images collected on the same area at different time stages. The occurrence of a vertical or lateral motion at the infrastructure surface level (e.g., the ballasted railway in Fig. 13) implies that an increase in distance between the sensor and the target is generated. This affects the phase of the signal back-received by the sensor.

Contrary to other satellite-based products, the collection of SAR images does not depend on the atmospheric and lighting conditions whilst they allow the coverage of extensive areas, coherently with the footprint of the sensor. The progressive orbit of satellites permits the collection of
regular and dense datasets in time, as opposed to on-site surveys that require huge organisational and economic efforts to achieve a similar productivity. The acquisition and processing of SAR images are not necessarily linked with field operations. Hence, they do not constrain the closure of infrastructure to traffic, nor they are dependent on control from any operator on site. These factors have major positive economic and safety impact compared to other conventional monitoring techniques.

An interferogram is generated from the calculation of the phase difference between two SAR images in the form of numerical values ranging from $-\pi$ to $\pi$. These are referred to a cell on the ground with dimensions mainly dependent on the working frequency of the sensor. Therefore, through the observation of an interferogram, it is possible to evaluate potential deformations on the ground during the survey time. This analysis is complex, as the interferometric phase includes signal contributions of different sources, along with noise and decorrelation effects. To elaborate, the interferometric phase ($\Delta \phi$) is affected by four principal components, as reported in Eq. (6)

$$\Delta \phi = \frac{4\pi}{\lambda} \Delta R + \alpha + t + \text{noise}, \quad (6)$$

where $\lambda$ is the wavelength of the emitted signal; $\Delta R$ is the displacement in the line of sight (LOS); $\alpha$ is a phase shift due to different atmospheric conditions (e.g., moisture in suspension); $t$ is the contribution given by the local topography; whereas the noise parameter includes the temporal change in the scatterers as well as a noise component related to differences in looking angles and volume scattering.

The atmospheric contribution limits the range of current applications for conventional InSAR methods and may inhibit accurate deformation monitoring. This occurrence is reduced with the application of the multi-temporal InSAR technique, such as the “Persistent Scatterers Interferometry”, where the processing phase provides a specific tool for the atmospheric phase contribution named “Atmospheric phase screen (APS)”, which estimates and removes the atmospheric contributions.

Furthermore, the baseline parameters (i.e., the temporal and perpendicular baseline) are factors significantly contributing to the accuracy of the interferogram information. Larger baselines can influence the coherence value of the interferometric pair.

Research methods on the use of InSAR and GPR techniques in railway infrastructure

A review of research on the application of InSAR and GPR techniques in railway engineering is reported in this section. Research methods are discussed based on the investigation scale (i.e., laboratory and numerical environments, test site, and real-world applications). For each individual scale of investigation, main applications of GPR to railway infrastructures are first reported followed by the applications of the InSAR technology coupled with GPR.

GPR has been widely used in railway infrastructure monitoring. Applications include the evaluation of layer thicknesses (Fernandes et al. 2008), the investigation of the embankment stability (Sussmann et al. 2003; Donohue et al. 2011), the localisation of trapped water areas (Hyslip et al. 2003), the indirect estimation of the track modulus (Narayanan et al. 2004), and the detection of permafrost sections (Saarenketo et al. 2003; Du et al. 2011; Nurmi-Kolu 2012; Guo et al. 2015). A recursive analysis of GPR measurements collected periodically on the infrastructure allows to predict the deterioration rate of the substructure and to control maintenance more effectively. This strategy can contribute to plan activities with more benefits in terms of costs and time (Maturana et al. 2011).

In this framework, the InSAR technology has proven viable in detecting surface deformations at the network level. An integration between InSAR and GPR can therefore allow to combine the versatility, the high resolution, and the capability to infer the source of decays in the subsurface from GPR, with the provision of extensive multi-temporal information on ground settlements from InSAR.

Using this integrated data management approach can lead to a more advanced concept of infrastructure resilience. A higher accuracy is expected to improve the infrastructure resistance to either major external events or ordinary decay. This is due to faster and more precise interpretation of the active decay processes (Colla et al. 2002; Sanaye et al. 2006; Solla et al. 2011).

In this context, it is worth reminding that the application of InSAR techniques in the monitoring of railway networks is relatively recent compared to the use of the GPR technology, where first applications date back to 1980, as reported by Roberts et al. (2006). However, the interest in using SAR imagery for civil engineering infrastructure monitoring has grown only in the last few years (Artagan et al. 2019).

Laboratory-scale investigations and numerical developments

Ballast characterisation is one of the most popular areas of research for investigations at the laboratory scale, as it is relatively easier to test in laboratory rather than using real-life setup.

De Bold (2011) demonstrates that GPR can be used for the assessment of ballast, with a high correlation between EM response and fouling index. Sussmann et al. (2003) report a GPR investigation on a railway subgrade with
specific condition indicators supporting the data interpretation stage. More recently, a comprehensive GPR analysis has been presented for the EM characterisation of railway ballast aggregates. Several GPR antennas and frequency systems were used in a unique experimental setup to identify potential critical factors and most suitable survey configurations (Tosti et al. 2017). The importance of selecting proper central frequencies of the antennas based on the scope of the inspection is also highlighted by Saarenketo (2006), whereas in Al-Qadi et al. (2010b), the authors propose a multifrequency approach (500 MHz, 2000 MHz) for a more comprehensive interpretation of the rail substructure.

Another topical research area relates to the assessment of fouling in ballast layers. Similar to the previous application, GPR has proven relatively successful at the laboratory scale of the investigation (Clark et al. 2001; Anbazhagan et al. 2016, 2011b; Al-Qadi et al. 2008a, b, 2010b; Bold 2011; Suits et al. 2010; Zhang et al. 2011). In Clark et al. (2001), the authors present a comparative analysis of the relative dielectric permittivity of railway ballast with different rates of fouling and humidity. The EM-wave propagation velocity in ballast is inversely proportional to its dielectric permittivity and its correct value is important for effective time-to-depth conversion of the GPR data. Various studies (Solomon 2001; Göbel et al. 1994; Maturana et al. 2011; Jack and Jackson 1999; Tosti et al. 2016) have attempted to experimentally calculate the EM-wave velocity in railway ballast. Benedetto et al. (2017b) assess clean and fouled ballast using GPR through comprehensive laboratory experiments, signal processing, and numerical modelling. A scattering amplitude envelope method based on the energy scattered from the voids between ballast aggregates has been also presented and used to identify clean and fouled ballast by off-ground GPR antenna systems (Al-Qadi et al. 2008a, b).

Water content estimation in railway substructures using GPR data is another major research area (Maturana et al. 2011; Khakiev et al. 2014). In Artagan and Borecky (2020), authors propose an investigation of the GPR response to evaluate railway ballast (different fouling and moisture conditions) at the laboratory and the real-life scales. The theory-based mixing model was used to verify the dielectric permittivity values obtained experimentally.

Use of numerical simulation has gained momentum in the past decade. This approach contributes significantly to reduce economic and computational costs (Benedetto et al. 2017b). Several studies have used the finite-difference time-domain (FDTD) technique for the simulation of the GPR signal (Bianchini Ciampoli et al. 2017; Zhang et al. 2011).

Collection of significant GPR data on the ballast underneath concrete sleepers and rails is another major area of research. Due to the masking effects of reinforcement bars, research has been done to limit this constraint and enable collecting representative data for the ballast. A focus on dedicated surveying procedures and antenna configurations was given to consider the impact of ties and rails on the signal (Al-Qadi et al. 2010b; Manacorda et al. 2002; Hyslip et al. 2003). In terms of signal processing methods, Hugenschmidt (2000) reports a post-processing framework including, migration, horizontal scaling, stacking, and background removal to minimise the effect of sleepers. A 40-trace running average is applied to the collected data by Donohue et al. (2011) to remove ringing noise from the sleepers. Finally, a spectral-based method based on the error optimisation between (i) the frequency spectra of GPR traces at the sleepers’ sections and (ii) the frequency spectra of the traces between two consecutive sleepers is proposed in Bianchini Ciampoli et al. (2018).

Test-site investigations

Test-site investigations are typically carried out in ballasted track-bed prototypes built on purpose to perform dedicated GPR investigations. A main advantage is to control the track-bed boundary conditions and investigate into aspects, which are difficult to control in real life.

Research is reported for the assessment of the ballast conditions. Gallagher et al. (1999) discuss the GPR capability to identify track-bed ballast deterioration, in terms of variation of the relative dielectric permittivity, and detect the interface between ballast and formation. Large-scale track models and methods used for GPR data collection are also presented for another test-site research. The experiments are here used to evaluate variations in the GPR response of the ballast in terms of density, water content, grain size distribution, and the variation of the fouling percentage content. To assess these parameters, a full-scale railway track was realised at the University of Massachusetts (Kashani et al. 2015).

Regarding the ballast contamination, GPR is employed by Kind and Maierhofer (2006) in a test specimen of a track-bed with multi-offset antennas to measure the signal travel time and the material dielectric permittivity of structural layers. The GPR study developed by Anbazhagan et al. (2016) is carried out on model and actual railway tracks with several antennas to inspect three types of fouling materials. Antennas with central frequencies of 100 MHz, 500 MHz, and 800 MHz are used, and the authors have proven that more representative results could be achieved with the 800 MHz antenna system.

With the aim of studying the pulse velocity variation under different ballast fouling conditions, tests in controlled conditions were carried out by Maturana et al. (2011). A 4.0 × 0.5 × 0.5 m wooden cell is here built to simulate a ballast platform, with the aim to collect GPR data periodically over months and compare the effects of time on the data. The following parameters are studied: (1) pulse velocity in sands...
GPR surveys have been also performed to assess the stability of the ballasted track, as reported by Sussmann et al. (2003). In this study, two embankments affected by structural instability are investigated. Evidence of substructure instability causing settlement of rail tracks has been found as a result of the GPR surveys.

Real-life investigations

Thickness measurement of railway ballast layers and material quality evaluation are the main application areas of GPR in real-life railways.

In Hugenschmidt (2000), the Swiss Federal Railways has inspected their railway tracks through GPR at regular intervals. Inspections are aimed at evaluating the thickness of the clean ballast, which was limited by subsoil material penetrating upwards into the ballast. Potential issues related to a transition from laboratory to test-site environments are addressed in Eriksen et al. (2006). The authors outline most recent advancements in the acquisition, processing, and interpretation of GPR data for a high-speed train instrumented with multiple-antenna GPR systems. The acquisition system combines GPR antennas, train tachometer inputs, GPS, and video technologies for an accurate calibration of the GPR systems and the high accuracy of results. The system has proven effective at collecting a high-quality and very dense dataset (sampling interval lower than 5 cm) at speeds of 100 km/h.

On the other hand, the dielectric properties of ballast have been investigated by Clark et al. (2001) and Sussman et al. (2002), with a special focus on the effect of moisture content and fouling levels. Clark et al. (2003) present an estimation of the dielectric permittivity values of good- and poor-quality ballast materials, and their comparison in dry, moist, and wet conditions. Signal travel time and material dielectric permittivity of the subsurface layers have been also investigated using multi-offset GPR antennas (Keogh and Keegan 2006). It is demonstrated that the GPR signal propagation velocity can sharply decrease of 10–30% from clean to fouled ballast conditions due to variations of fine particles.

A comprehensive study ranging from laboratory to real scale is reported in Artagan and Borecky (2020). The authors discuss the use of the GPR method for the analysis of railway ballast with different fouling and moisture contents. Comprehensive laboratory experiments and field surveys are presented. In detail, field tests with 400, 900, and 2000 MHz GPR antenna frequencies are carried out on the same type of granite ballast used for preliminary laboratory tests.

Railway ballast may generate different electromagnetic scattering patterns when radiated by an EM field, depending on the specific fouling conditions. In this context, a field survey with multiple sets of 1 and 2 GHz air-coupled GPR antennas was performed in 2005 at the Transportation Technology Center, Inc. (TTCI) in Pueblo, Colorado (Al-Qadi et al. 2008a). The authors report that the 2 GHz antenna is more sensitive to changes by scattering. Furthermore, a study utilising GPR horn antennas to evaluate railroad ballast, sub-ballast, and subgrade conditions is reported in Roberts et al. (2006). This research identifies a representative scattering amplitude envelope from the field data for implementation into an automatic data processing pipeline. Subsequently, 2 GHz data from 238 km of track are processed and the fouling conditions are automatically estimated from the GPR data.

In Olhoeft and Selig (2002), the authors employ a 1 GHz antenna to acquire data from the railway substructure. In this study, data are collected at the centreline and both sides of the rails for comparison purposes, assuming that significant variations between the acquisitions may be linked with instability at the foundation level.

A geophysical investigation is carried out by Donohue et al. (2011) following the failure of a major railway embankment in Ireland. The embankment is here inspected using GPR, electrical resistivity tomography (ERT), multi-channel analysis of surface waves (MASW), and geotechnical testing. A significant variation in the thickness of the ballast layer in the vicinity of the failure location is observed using GPR, confirming an ongoing geotechnical instability issue.

Finally, several studies have used GPR on railway infrastructures to investigate reflection patterns in the signal and their link with structural elements of the railway. To this extent, GPR is found to face disturbance noise in field inspections, including high radio-frequency interference from railroad communication and automation systems, and strong reflection values coming from the rails. In the study developed by Al-Qadi et al. (2010a), special techniques are used to remove these interferences and limit strong clutter effects from rails. Short-time Fourier transform is therefore applied to infer information about the fouling.

Research from Al-Qadi et al. (2008b) and Bianchini Ciampoli et al. (2018) investigate the influence of concrete railway sleepers on the GPR signal. A main objective is to propose a data processing framework capable to filter out the effect of concrete sleepers on the GPR signals with compound information.

As real-scale tests allow to investigate entire railway sections, the InSAR technique becomes of great interest in monitoring track settlements and analysing their evolution pattern over time. A real-life integrated application of
In the authors investigate a railway section located in Puglia, Southern Italy. A total of 57 SAR images collected in X-band frequency by the COSMO-SkyMed mission were acquired and processed through an interferometric procedure. Authors report that the InSAR technique an detect potential critical sections where the railway track is subject to settlements. In this study, this is instrumental for more detailed GPR tests, which in turn are useful to identify the causes of distress. D’Amico et al. (2020) propose an integration between the GPR and the interferometric InSAR techniques for the monitoring of transition areas at rail-abutment sections in railway bridges. A railway bridge located in Italy was inspected. GPR is used to achieve subsurface structural details and detect any potential issue related to construction. InSAR analyses are mainly focused to monitor subsidence at the rail-abutment transition area. Subsidence has been found at both the areas of transition, proving that the proposed integrated approach can effectively assess the structural integrity of railway bridges.

In regard to applications for the integrated use of InSAR and GPR technologies, Bianchini Ciampoli et al. (2020) report an overview on the data-fusion approach between the InSAR and the high-frequency GPR techniques. The study aims at evaluating solutions to compensate technology limitations of individual techniques based on a data-fusion approach.

Benefits of network-level satellite remote sensing and NDT monitoring

Despite the numerous advantages of using ballasted rail tracks, rapid decay of ballast material can heavily affect costs of maintenance for the track. Maintenance and repairing require major investments from asset owners to ensure proper serviceability of the railroad network. According to available statistics, €50,000/km of tracks are the average annual maintenance and renewal (M&R) expenditures in West-European networks. Therefore, it is essential to monitor effectively each individual railway element and pursuing proper maintenance standards (Jovanovic et al. 2015).

Several analytical models for railways can be used to achieve effective and efficient maintenance, including decision support systems (DSSs) integrating computational maintenance optimisation models (Rashidi et al. 2013). DSSs can assist asset managers in making more informative decisions and find a balance between budget constraints and compliance with other major management requirements.

Based on the benefits arising from an integration between satellite remote sensing and NDT technologies, a railway infrastructure management system is introduced in this section (Fig. 14) with the aim to optimise railway track maintenance and renewal activities. The proposed approach is developed based on the provision of inventory data, and built up in terms of identified railway network elements and as-built information. It is characterised by two concurrent routine monitoring stages developed at two different data coverage levels, i.e., the local level for NDT and the network level for satellite remote-sensing techniques. Amongst the NDT methods, GPR is the most effective technique for integration with satellite remote-sensing technology, as it allows to collect more accurate information about the causes of distress at the local scale. Remote-sensing technologies are instead used to assess the entire infrastructure network in terms of ongoing geotechnical/geodynamic processes, with a high productivity (> 100 km/day) permitted by the scale of the analysis.

In case critical sections are identified, targeted inspections can be carried out with dedicated NDT techniques with the aim to build a more comprehensive information system on the type and scale of the developing distress at the identified infrastructure sections. The information obtained at this stage can form the basis of prediction models for distress evaluation, leading to assess whether maintenance or rehabilitation are required, and what priority level must be allocated to the identified intervention. Sections without critical issues are subject to new screening loops until the outcome turns positive.

In parallel with remote-sensing technologies, ground-based NDTs working at the local level are used with a lower productivity (up to approximately 70 km/day). The main scope of this stage is to assess any potential distress in the infrastructure in terms of extent (e.g., sections in the asset with a low bearing capacity), causes (e.g., the presence of fine materials within the subbase course), and effects (e.g., low stiffness sections observed from deflection-based tests) that cannot be detected by satellite remote sensing.

This information is therefore integrated into an overall prediction model for the evaluation of distresses, which returns a priority scale for maintenance and rehabilitation activities on individual assets of the railway network. In case none of the information leads to the conclusion that M&R actions are required, the integrated approach is performed again following the time-scheduled monitoring routine, until variations of stable conditions are detected and concerning interventions are identified.

In case the need for an intervention is ascertained, the provision of several alternative M&R actions is assessed based on the compliance with safety requirements and economic constraints. For each of the alternatives, a cost–benefit analysis is performed, leading to the selection of the optimal strategy of M&R intervention.

Benefits of this integrated approach are demonstrated by several applications carried out in the past (Donohue et al. 2011; D’Amico et al. 2020; Bianchini Ciampoli et al. 2020).
proving the effectiveness of combining InSAR technology and GPR method. Findings suggest that use of an integrated approach can characterise the railway ballast deterioration more comprehensively. Use of complementary InSAR and NDT methods can assess the ballasted track-bed conditions more accurately and, parallel to this, they can pinpoint the causes of the deterioration based on individual features of specialist NDT methods.

To comprehend the role of the proposed railway management system, the discussion must therefore be broadened out to the maintenance concept. According to (2019), a preventive-oriented policy for maintenance can be divided into time-based, condition-based, and predictive maintenance (Fig. 15).

Time-based maintenance involves cyclic activities of inspection and survey. In its implementation, the time interval between an operation and the following plays a key role. The operation time definition is based on reliability law of the element. Therefore, a time-based maintenance requires collection of statistical data on the failures that, along with indications from manufacturers, can allow to determine the time interval.

Conversely, a condition-based or predictive approach relies on the verification of conformity by measurement, testing, and detection of the element characteristics and, hence, it allows to operate when the element requires maintenance. The main difference between the above
two approaches is that condition-based maintenance is based on the identification of decay symptoms prior to their appearance, whereas predictive maintenance is based on an estimation of the residual life of the infrastructure system.

The proposed integrated approach including satellite-based surveys at the network level and the ground-based non-destructive detection of critical sections at the local scale well fits into the above process as an effective predictive maintenance system.

It is worthy to distinguish two main stages of the system, based on their application time. A first phase relates to the beginning of the application, whereas a second phase starts when the methodology reaches its full productivity regime. In the first period after the application of the method, a limited database is available to interpreting the conditions of the asset. Whilst data collection are limited in time, only late-stage and rapidly evolving distresses can be detected. Accordingly, within the first phase, the outcome of this approach mainly fits with a condition-based maintenance, as opposed to a predictive maintenance.

Size of datasets from the collected information can increase by repeating the surveys, and it allows the methodology to reach its full capacity. This condition permits to assess the trend of deformations and distresses. Therefore, the method is here in the condition to timely predict the formation and the evolution of defects in ballasted tracks. At this stage, the proposed methodology, from now on referred to as “optimised”, becomes a totally predictive tool as a condition-based maintenance is only required in case of unexpected events, such as major natural events or traffic accidents. Indeed, starting from the first application of the method, the increasing dataset built from both the satellite- and the ground-based surveys forms the basis for the development of more robust and reliable distress prediction algorithms. These have the function to detect potentially dangerous decays at their very early stage of development.

Accordingly, three possible maintenance approaches are identified: (i) time-based maintenance; (ii) condition-based maintenance; (iii) optimised condition-based. All these approaches aim at the highest possible reduction of the maintenance-related costs on the long term.

In regard to the time-based maintenance, costs are due to several cyclic activities, such as tamping, ballast cleaning, and ballast renewal (Guler 2016). These interventions, which are typically very costly as they involve all the railway track components, are regularly scheduled regardless the actual state of decay of the asset.

Conversely, main benefits of the condition-based maintenance are financial. This approach is based on inspections and tests that allow to apply maintenance only where required, i.e., when service conditions of the infrastructure are highly affected. This method is thereby effective in reducing maintenance-related costs compared to the time-based approach, increasing the operational availability of maintenance machines due to a more limited utilisation and improving safety by limiting scale and severity of failures. An effective planning can reduce maintenance costs and resources, and it improves upon safety and operational efficiency of maintenance activities (Prasad 2016). Condition-based maintenance typically generates savings from 90 to 95% compared to costs of the time-based maintenance (Simon et al. 1713; Dong et al. 2019; Korpanec 1998). However, as a limitation of this approach, a separate analysis of the survey outcomes may fail in detecting decay trends, especially in case an accurate comparison between consecutive inspections is lacking. This might stand as a critical issue at the very first application of the condition-based maintenance, when a previous track record of surveys is missing and it is therefore impossible to retrieve information on the evolution trend of distresses.

In view of this, an optimised condition-based scenario stands as an improvement of conventional maintenance approaches, as it allows to minimise costs and maximise benefits in terms of operational safety and sustainability of the activities. The integration of ground-based surveys with space-borne surveillance permits to rely on back-dated time-series of subsidence in the area of interest. These are crucial to have full knowledge of any potential geotechnical issue affecting the asset at the network level, which could be neglected without using this retroactive approach.

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**Fig. 15** Ordinary maintenance plan framework (2019)
Furthermore, an initial backward inspection in time allows to recognise previous maintenance interventions on the network and assess their effectiveness. Accordingly, the optimised approach improves upon the time required for condition-based methods to be effective, as it allows the use of algorithms for prediction of the decay evolution since the first application (time-zero). Therefore, this conceptual framework can stand as a viable solution for asset owners in planning maintenance to limit effectively decay at an early stage of development. This can positively impact financial and ecological aspects related to the infrastructure management process.

Conclusions and final remarks

This paper presents a review on the use of the ground penetrating radar (GPR) and the interferometric synthetic aperture radar (InSAR) methods for sustainable monitoring of railway infrastructure. The paper focuses on efficiency aspects of the NDT methods and envisions a more proactive approach for maintenance planning in this sector.

An overview of main issues from the inspection and maintenance of the track deformations is initially reported. Main types of deformation occurring in ballasted railways are discussed, highlighting the impact of fouling as a major source of failure and pointing out that an early detection is fundamental to limit future costs of intervention and risk of potential accident events. It has been observed that the amount of fouling in a ballasted railway has been characterised and quantified using experimental and theoretical indexes.

Methods for the evaluation of the track geometry have been sorted into conventional and non-destructive, and classified based on their productivity. Within this context, satellite remote-sensing and non-destructive techniques have emerged as the most flexible, effective, and sustainable. Furthermore, it is emphasised the relatively easy integration between GPR and InSAR measurements. A review on main research methods for an integrated use of these technologies in railway infrastructure monitoring has been presented, with examples given at the laboratory scale of investigation as well as reporting real-life investigations.

Amongst others, the use of data-fusion methodologies involving GPR and InSAR techniques has emerged as a new challenging area of development. To elaborate, training datasets collected from both the techniques across limited sections of the infrastructure can be used for the development of fine-tuning algorithms for extensive application at the network level. This can allow a recurrent use of the technology with the highest “land coverage/data collection time” ratio (i.e., InSAR) and minimise the use of more time-consuming techniques (i.e., GPR).

In the last section of the paper, a conceptual framework based on an integrated approach between satellite-based and ground-based methods is proposed, where network- and local-level information can be merged for the detection of critical sections and the implementation of a more advanced predictive maintenance system. The application of the proposed approach has different benefits. These can be financial, e.g., for railway companies and operators due to the totally predictive nature of the tool, environmental, and ecological, i.e., for the lower use of non-renewable materials and resources. Areas of development for the proposed approach are in the need of a central railway management system to map railways both at local and network levels, and the requirement of a dataset of satellite-based information for the development of more robust back-dated time-series analyses.

It is important to mention that the proposed monitoring framework is part of a new research project where the authors are currently involved and—to the best of our knowledge—new research is still to be explored in this area of railway engineering science.

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