



NON-DESTRUCTIVE METHODS FOR DETECTING AND ASSESSING VOIDS IN RAILWAY TUNNELS

Background and applicability to the Douro Line

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Dedicated to my grandfather.

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ABSTRACT

The rehabilitation of old railway tunnels presents a significant challenge in the context of transport infrastructure modernisation, particularly on historic lines such as the Douro Line. These tunnels, excavated in the 19th century using explosives and other rudimentary dismantling methods, often exhibit discontinuities and voids between the lining and the surrounding rock mass, resulting from the original construction methods and degradation over time.

As part of the ongoing electrification works on the Marco de Canaveses – Régua section, interventions have been carried out to fill these voids by injecting grout, with the aim of improving structural behaviour and ensuring adequate safety and durability. However, the characterisation of the geometry and extent of these voids is a determining factor for the effectiveness of the interventions.

The aim of this dissertation is to analyse different methods for the detection and characterisation of voids in railway tunnels, with particular emphasis on non-destructive testing (NDT) techniques, such as ground-penetrating radar, acoustic methods and other geophysical approaches and to investigate the importance of the composition of the grout for the proper filling of voids. Based on a literature review, a qualitative assessment is made of how these methodologies relate to the investigation and intervention approach adopted in the Douro Line project, with reference to the operational and construction constraints involved.

The analysis identifies ground-penetrating radar as the most capable primary prospecting NDT method for systematic void detection in old railway tunnels and establishes that grout mix design and NDT are interdependent components of a single rehabilitation framework rather than independent technical domains. The conclusions are contextualised in the Douro Line project and recommendations are offered for future rehabilitation works of comparable scope.

KEYWORDS: rehabilitation, railway, tunnels, electrification, injection, grout, non-destructive testing.

RESUMO

A reabilitação de túneis ferroviários antigos representa um desafio relevante no âmbito da modernização de infraestruturas de transporte, particularmente em linhas históricas como a Linha do Douro. Estes túneis, escavados no século XIX com recurso a explosivos e outros meios de desmonte rudimentares, apresentam frequentemente descontinuidades e vazios entre o revestimento e o maciço rochoso envolvente, resultantes dos processos construtivos originais e da degradação ao longo do tempo.

No contexto da empreitada de eletrificação da ferrovia do troço Marco de Canaveses – Régua, atualmente em curso, têm sido realizadas intervenções de preenchimento destes vazios através da injeção de argamassa, com o objetivo de melhorar o comportamento estrutural e garantir condições adequadas de segurança e durabilidade. No entanto, a caracterização da geometria e extensão desses vazios constitui um fator determinante para a eficácia das intervenções.

A presente dissertação tem como objetivo analisar diferentes métodos de deteção e caracterização de vazios em túneis ferroviários, com particular destaque nas técnicas de ensaio não-destrutivo (NDT), como o radar de penetração no solo, métodos acústicos e outras abordagens geofísicas e estudar a relevância da composição das injeções para um correto preenchimento dos vazios. Com base numa revisão da literatura, é efetuada uma avaliação qualitativa de como estas metodologias se relacionam com a abordagem de investigação e intervenção adotada no projeto da Linha do Douro, tendo em conta as restrições operacionais e de construção envolvidas.

A análise identifica o radar de penetração no solo como o método NDT de prospeção primária mais adequado para deteção sistemática de vazios em túneis ferroviários antigos e estabelece que a mistura da argamassa e os NDT são componentes interdependentes de um único âmbito de reabilitação, em vez de domínios técnicos independentes. As conclusões são contextualizadas no projeto da Linha do Douro e são apresentadas recomendações para futuros trabalhos de reabilitação de semelhante âmbito.

PALAVRAS-CHAVE: reabilitação, túnel, eletrificação, ferrovia, injeção, argamassa, ensaio não-destrutivo.

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

<i>AMV</i>	Turnout (<i>Aparelho de Mudança de Via</i>)
<i>CP</i>	<i>Comboios de Portugal</i>
<i>EP</i>	<i>Estradas de Portugal</i>
<i>ERT</i>	Electrical Resistivity Tomography
<i>GPR</i>	Ground-penetrating Radar
<i>IE</i>	Impact-Echo
<i>IP</i>	<i>Infraestruturas de Portugal</i>
<i>ISRM</i>	International Society for Rock Mechanics and Rock Engineering
<i>LDP</i>	Light Dynamic Penetrometer
<i>LNEC</i>	National Laboratory for Civil Engineering (<i>Laboratório Nacional de Engenharia Civil</i>)
<i>NATM</i>	New Austrian Tunnelling Method
<i>NDT</i>	Non-destructive Testing
<i>PETI3 +</i>	Strategic Transport and Infrastructure Plan
<i>P.K.</i>	Kilometric point (<i>Ponto Kilométrico</i>)
<i>REFER</i>	<i>Rede Ferroviária Nacional, E.P.E.</i>
<i>RQD</i>	Rock Quality Designation
<i>TBM</i>	Tunnel Boring Machine
<i>TER</i>	Transient Electromagnetic Radar
<i>UST</i>	Ultrasonic Tomography

1

INTRODUCTION

1.1 BACKGROUND AND CONTEXT

Portuguese railway history officially began on the 28th of October 1856 with the inauguration of the first section between Lisbon and Carregado, an event that marked the beginning of a profound economic and social transformation in the country. The network grew quickly throughout the second half of the 19th century as a result of industrialisation, connecting the interior to the coast and creating vital links with Europe over the Spanish border. During the 20th century the sector went through stages of institutional consolidation, which culminated in the unification of various private companies into Comboios de Portugal (CP) and faced the challenge of growing road transport after the revolution of April 25th, 1974. Currently, railways are undergoing a new paradigm of modernisation and sustainability, with investments centred on electrification, high speed and integration into trans-European networks, reinforcing their role as essential infrastructure for a future of efficient and environmentally friendly mobility (Infraestruturas de Portugal, 2024; Nogueira, 2016).

Regarded as one of the masterpieces of Portuguese railway engineering and one of the most important links in the national rail network, the Douro Line, which took on an international role soon after construction began, is today a regional line serving the districts of Porto, Vila Real, Bragança, Viseu and Guarda and currently connects Porto to Pocinho over a distance of more than 170 kilometres (Comboios de Portugal, 2026).

Its construction was intended to break the region's isolation, given that, at the time, travel relied on roads in poor condition and difficult navigation along the Douro and to ensure the transport of people and goods, particularly wine. Starting in Ermesinde, in the municipality of Valongo, construction began in 1875, with the train reaching Régua in 1879 and a year later it was prolonged to Pinhão. Initially, the plan was for the train to stop at Pinhão but due to pressure from D. Antónia Ferreira and the bourgeoisie and financial circles of Porto, the line was extended to Spain (Comboios de Portugal, 2026).

The Douro Line was completed in 1887, when the section between Barca d'Alva, La Fregeneda and La Fuente de San Esteban became operational as far as Salamanca, marking the completion of the third international rail link, designed to improve connections between Porto and the rest of Europe, as well as Madrid. Until 1988, the line in operation within Portugal was approximately 200 kilometres long. With the closure of the section between Pocinho and Barca d'Alva, the line was reduced to its current length of 172 kilometres, served by 37 stations and halts (Comboios de Portugal, 2026).

The “Electrification of the Marco de Canaveses – Régua section of the Douro Line” is part of the Complementary Corridors of the Ferrovia 2020 Programme (Infraestruturas de Portugal, 2025). With the objective of aligning the national and the European Union's transports strategy, the Portuguese government drafted the Strategic Transport and Infrastructure Plan for the Horizonte 2016-2020 (PETI3+) that establishes a long-term vision of transport and infrastructures up to 2050, based on a set of Strategic Objectives for the time period of 2014-2020, defined by a balance between the “promotion of growth”, “social and territorial cohesion” and “promotion of transport system's sustainability” (Infraestruturas de Portugal, 2025).

1.2 MOTIVATION AND JUSTIFICATION

The modernisation of the section between Marco de Canaveses and Régua is one of the priority areas for investment in the national rail network, involving an investment of around 110.7 million euros, a figure that rises to 165 million when complementary signalling and telecommunications systems, as well as the new electric traction substation at Bagaúste, are considered. This project, which benefits from EU co-financing, focuses on the full electrification of approximately 43 km of track and the comprehensive upgrading of the infrastructure.

Key works include the rehabilitation of the railway platform, the elimination of level crossings through grade-separated solutions and the modernisation of stations and halts, with a particular focus on accessibility and the passenger building at Régua. In terms of structural engineering, particular importance is attached to the reinforcement of 40 embankments and the complex work in tunnels, notably the Juncal Tunnel which, at 1,600 metres, represents one of the greatest technical challenges of the project due to its length and age.

The completion of this work will not only improve safety and operational efficiency but also significantly reduce the carbon footprint, estimated at 16,000 tonnes of CO₂ per year, and journey times (Infraestruturas de Portugal, 2025).

In the context of modernising transportation infrastructure, rehabilitating old railway tunnels is a major challenge, especially on historic lines like the Douro Line, which are also highly valued for tourism.

1.3 METHODOLOGY

The methodology adopted in this dissertation was based on an action-research model in which the observing process is active in a real construction environment, through a work placement at Tabique Engenharia, Lda. This internship aimed on consolidating the theoretical knowledge acquired in the course units of the Civil Engineering master's programme, specialising in Territory Planning and Transports and further research on specific related topics. The study focused on the technical analysis of procedures for the rehabilitation and consolidation of historic railway tunnels.

1.3.1 Establishing a theoretical foundation

This initial phase focused on the theoretical foundations of 19th century tunnel engineering. The study focused on the excavation methods available at the time of construction and their consequence for the structural condition of old masonry-lined tunnels, particularly the formation of voids between the outer lining of the tunnel walls and the surrounding rock mass. The research extended to the study of non-destructive testing methods (NDT) applicable to void detection, such as ground-penetrating radar (GPR) and to the principles governing the composition of grout injection for void filling.

1.3.2 Analysis of documents and characterisation of the project

The supporting documentation for the investigation is drawn directly from the construction drawings and project specifications for the Marco – Régua railway project. An analysis will be carried out of the supporting documentation, with a focus on identifying the essential works to recognize the areas with the highest incidence of anomalies, voids and water infiltration. This phase involves the data gathering of the geometric and geological characteristics of the tunnels under study, enabling the theoretical morphology of the voids to be correlated with the composition of the surrounding rock mass and the existing lining.

1.3.3 Construction supervision and technical inspection

The practical component of this research is based on direct observation and critical monitoring of the work sites, as part of Tabique's supervision structure. The internship period coincided with a phase of high operational intensity, characterised by a work schedule involving night and day operations with railway closures, in accordance with the phasing plan for the Marco – Régua section of the contract.

Although the dissertation devotes particular attention to the rehabilitation and consolidation of tunnels, where the process of injecting cement grout is monitored according to pressure and volume criteria, the on-site monitoring included several other multidisciplinary activities. This approach enabled the supervision of the implementation of various subsystems fundamental to the modernisation of the line, namely the stabilisation of embankments and the adaptation of the track superstructure to accommodate the catenary.

1.3.4 Context and scope of the dissertation

The theme of this dissertation emerged directly from the experience of the internship and from one specific technical observation made during the supervision of the tunnel injection works, the stop criteria. The original intention of this dissertation was therefore to investigate this question directly, by examining NDT methods capable of characterising void geometry with greater precision and by comparing the injection reports from the works against the applied stop criteria, with the aim of identifying cases where the known void extent could have justified a different injection protocol. However, since the injection records of this project are being supervised and assessed by the National Laboratory for Civil Engineering (LNEC) as part of the formal quality control process, those reports are confidential documents that could not be published or reproduced in an academic dissertation.

This constraint redirected the dissertation toward a theoretical and systematic framework following the logic of the problem, from its structural origin to its resolution: the construction methods of tunnels and the reasons why voids form between the outer lining of the walls and the surrounding rock mass, the NDT methods available for detecting and characterising those voids and the principles controlling the composition of the grout injected to fill them.

1.4 STRUCTURE OF THE DISSERTATION

In order to provide a logical and systematic overview of the work carried out, this dissertation is structured into five main chapters, described below:

Chapter 1 – Introduction provides the background to the Douro Line electrification project, setting out the reasoning, the main objectives and the research methodology that formed the basis of the project.

Chapter 2 – Literature review provides an overview of the state of the art regarding the various elements of the railway system, with a particular focus on the structural complexities of tunnels. This section establishes the theoretical framework for understanding how these components interact under dynamic loading. Furthermore, it introduces prospecting methods, highlighting also the NDT techniques currently available for tunnels anomaly detection and structural assessment, providing a technical foundation for the diagnosis of century-old masonry tunnel linings.

Chapter 3 – Company presentation and site supervision describes the context of the internship undertaken at Tabique Engenharia, Lda. This chapter identifies the project's main intervenients and outlines the supervised interventions on the Marco – Régua section, detailing the multidisciplinary supervision and monitoring activities carried out on site, with particular emphasis on structural rehabilitation operations in tunnels.

Chapter 4 – Comparative analysis of void detecting methods represents the analytical core of this dissertation. The primary objective of this chapter is to conduct a detailed study of various NDT techniques employed for the detection and characterisation of voids in tunnel linings.

Chapter 5 – This chapter focuses on the importance of grout composition and its rheological properties in ensuring structural integrity, while also addressing the role of stop criteria as operational controls on the injection process.

Chapter 6 – Conclusions and future work chapter summarises the main findings and the lessons learnt during the monitoring of the project. Technical suggestions are also presented for future railway modernisation projects, with an emphasis on the importance of these types of works.

2

LITERATURE REVIEW

The current chapter is devoted to reviewing and analysing the state of the art regarding the primary subjects that serve as foundation of this research. To understand the challenges inherent to the activities of rehabilitation and electrification of century-old tunnels, it is crucial to incorporate historical knowledge of the original construction methods employed with more modern techniques for the diagnosis and maintenance of railways its different structures. The ultimate objective of these maintenance and rehabilitation efforts is to guarantee that the railway remains safe, comfortable and ensures cost-effective services (Couto, 2025).

In order to accomplish this goal, the railway system's various elements and layers must interact intricately with each other, in reaction to the loads generated by the rolling stock, under diverse environmental conditions. For a structural system to be sturdy and resilient and to prevent significant permanent deformation of the rails and component degradation, each element must effectively carry out its designated role (Fortunato, 2005). This system is structurally divided into two separate but equally important groups.

- Superstructure – The track assembly consists of the ballast and the track “skeleton” (rails, sleepers and fastenings) (Couto, 2025).
- Infrastructure – The structure comprising the layers located beneath the ballast, embankments and excavation slopes, surface and drainage systems and including the engineering structures designed to support the track (Infraestruturas de Portugal, 2025).

2.1 SUPERSTRUCTURE

The railway superstructure is the first set of components that receive the direct load from the rolling stock and distribute it to the underlying layers. It guarantees the trains proper guidance and geometric stability.

Understanding the composition and behaviour of the superstructure is directly relevant to the tunnel rehabilitation works of the kind carried out on the Douro Line. Track lowering operations within tunnels require the complete removal and replacement of the existing track formation to achieve the vertical clearance demanded by the electrification structure gauge.

Furthermore, the dynamic loads introduced by rail traffic act continuously on the tunnel lining through the track formation, meaning that the superstructure and the tunnel structure interact with one another. This interaction is the underlying reason why structural consolidation of the lining, including the filling of voids in the outer linings of the tunnel walls, must be interpreted within the context of ongoing service loads.

2.1.1 Ballast

Ballast is a granular layer placed beneath the sleepers to distribute the forces coming from them to the underlying layers, reducing pressures at the infrastructure level to within permissible limits and avoiding transverse and longitudinal displacement of the track (Figure 1). It also converts part of the shocks in elastic deformation and ensures the drainage of rainwater (Couto, 2025).

Regarding material requirements, ballast should be made of crushed stone from hard, sound, weather-resistant rocks, like granite which is the most common material used in Portugal (Couto, 2025).



Figure 1 - Ballast

2.1.2 Sleepers

Sleepers are transverse track components positioned beneath the rails whose main function is to distribute the static and dynamic loads transferred by the rails to the ballast. They also ensure the correct spacing between rails, preserve track gauge and ensure electrical insulation between the two rails, whilst providing a surface for fastening systems. From a structural perspective, sleepers need to have enough elasticity and resistance to distribute loads effectively without creating excessive local stress concentrations (Couto, 2025).

Four main sleeper types have been used in railway construction:

1. Timber sleepers (Figure 2) – offer good load absorption, electrical insulation and adaptability to varying track conditions and remain the preferred choice inside tunnels. Their service life depends on wood species and treatment, with impregnated pine reaching around 20 years and hardwoods such as oak and beech achieving longer lifetimes when well maintained, though biological deterioration and gauge retention can be limiting factors (Couto, 2025).

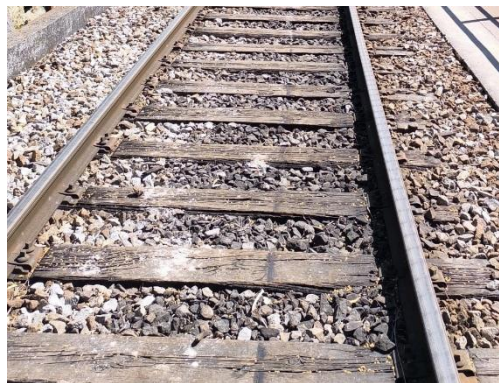


Figure 2 - Timber sleepers

2. Twin-block sleepers (Figure 3) – consisting of two reinforced concrete blocks joined by a steel bar, offer good transverse resistance and behaviour under bending and torsion, with service lives reaching approximately 50 years, though they are sensitive to ballast condition and may require special insulation accessories (Couto, 2025).



Figure 3 - Twin-block sleepers

3. Monoblock sleepers (Figure 4) – are the standard solution in modern ballasted track, combining high stability, excellent resistance to environmental deterioration and service lives of around 40 years. They distribute loads effectively and suit heavily trafficked and high-speed routes, although their transverse resistance is generally lower than that of twin-block sleepers (Couto, 2025).



Figure 4 - Monoblock sleepers

4. Metal sleepers – shaped as inverted half-troughs seated in the ballast, are no longer in common use in Portugal and are of historical rather than practical relevance to the current national network (Couto, 2025).

2.1.3 Rail

Rails are the structural elements of the track that directly receive loads imposed by the rolling stock's wheels and transfer them to the remaining components of the superstructure. Aside from supporting the passage of trains their main function is to direct wheelsets and, in some cases, act as electric conductors for traction or signalling systems.

The most common rail profiles in Portugal are the 54E1 (Figure 5) and 60E1 (Figure 6), with a mass of 54 kg per meter and 60 kg per meter, respectively.

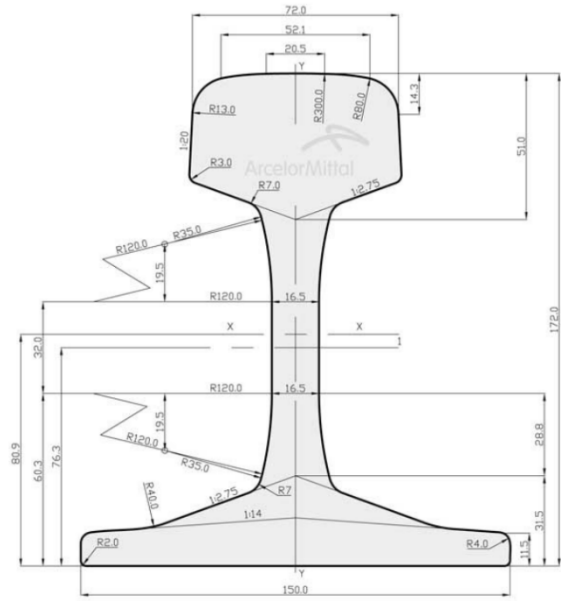
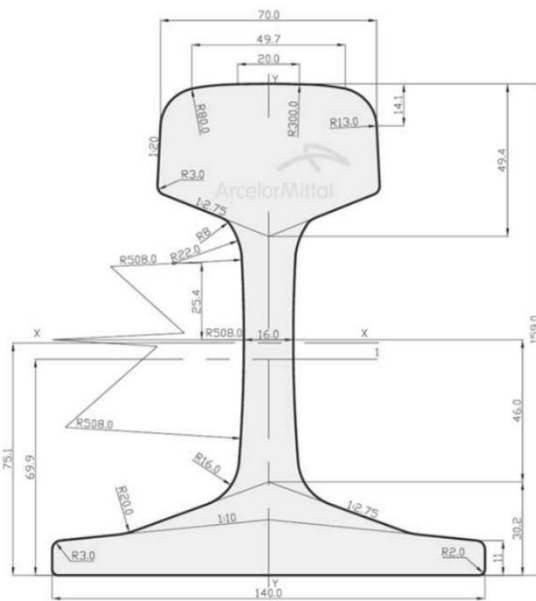


Figure 5 - Rail profile 54E1 (ArcelorMittal, 2024) Figure 6 - Rail profile 60E1 (ArcelorMittal, 2024)

Heavier profiles are typically associated with greater durability and a greater ability to resist wear and fatigue while also reducing stress transmission to the sleeper and the ballast.

While earlier railway systems utilised short joined bars (Figure 7), modern lines often use continuous welded rail (Figure 8), allowing for much longer sections and fewer joints, thereby improving ride quality and reducing maintenance (Couto, 2025).

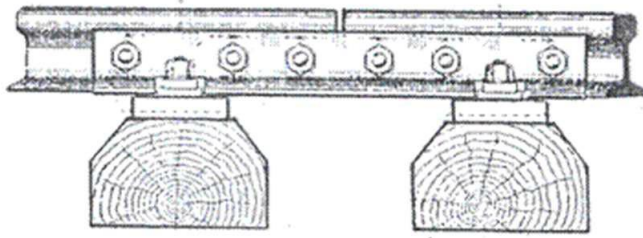


Figure 7 - Joint bar (Couto, 2025)



Figure 8 - Continuous welded rail

The quality of sleeper support and ballast conditions determine how well the rail performs since it acts like a beam on an elastic foundation. Repeated loads can result in surface wear, corrugation and cracking, making necessary constant inspections and preventive preservation (Couto, 2025).

2.1.4 Fastenings

Rail fastenings systems serve as the vital link between rails and sleepers, ensuring structural integrity under dynamic loading while supporting track geometry and maintenance requirements (Figure 9). These systems preserve gauge stability, transfer longitudinal, lateral and vertical forces from the rail to the sleeper and, when necessary, provide electrical insulation for signalling (Couto, 2025).

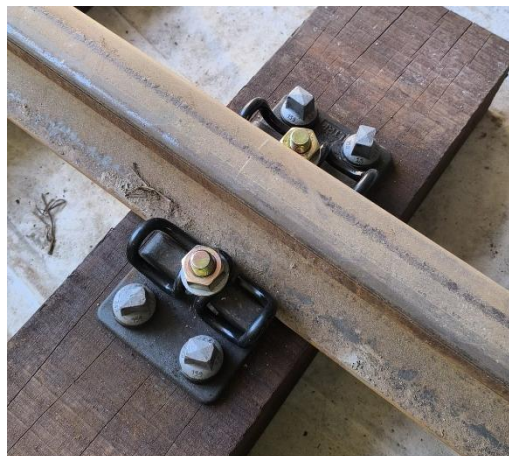


Figure 9 - Elastic fastening

2.2 INFRASTRUCTURE

The railway infrastructure consists of all components beneath the ballast responsible for the physical and geometric support of the track superstructure (Couto, 2025). It includes sub-ballast, track platform, earthworks and retaining structures, drainage systems and engineering works like bridges and tunnels.

Infrastructure is the system's unseen but critical component, considering that its quality has a significant impact on the line's load-bearing behaviour, drainage capacity and long-term stability, defining whether the superstructure can function correctly. For this reason, any meaningful renewal strategy must start with the infrastructure (Couto, 2025; Fortunato, 2005).

2.2.1 Sub-ballast

The sub-ballast is a granular layer positioned between the ballast and the track platform with the aim to improve the distribution of vertical loads, increase the regularity of support and contribute to drainage. It has a particular important function during renovation projects, where the existing platform might not be able to provide the mechanical and hydraulic performance needed by contemporary traffic. The behaviour for this layer depends strongly on compaction, moisture content and the quality of the materials employed, since these factors determine its stiffness and resistance to long-term deformation (Fortunato, 2005).

2.2.2 Track platform

The track platform is the foundation on which the sub-ballast is founded. Although it is not a separate material layer in itself, it is the support level that determines how well the entire railway infrastructure performs. It should be formed with a slight outward cross-fall, usually between 4% and 5%, in order to prevent rainwater from accumulating beneath the track (Guerreiro Bastos Leitão, 2019).

Because any weakness at this level will manifest as settlements, loss geometry and higher maintenance requirements, the track's regularity, moisture condition and bearing capacity are fundamental to its longevity (Fortunato, 2005).

2.2.3 Earthworks and slope stabilisation

Depending on whether the platform is located above or below the supposed project's level, earthworks include the shaping of the railway formation through excavations and embankments (Figure 10). Excavations create space needed for the line in lower terrain, while embankments raise the track over surrounding land (Fonseca *et al.*, 2024). In both cases, because deformation and instability originated from these activities are directly communicated to the track geometry and can compromise long-term performance, slope stability becomes essential.

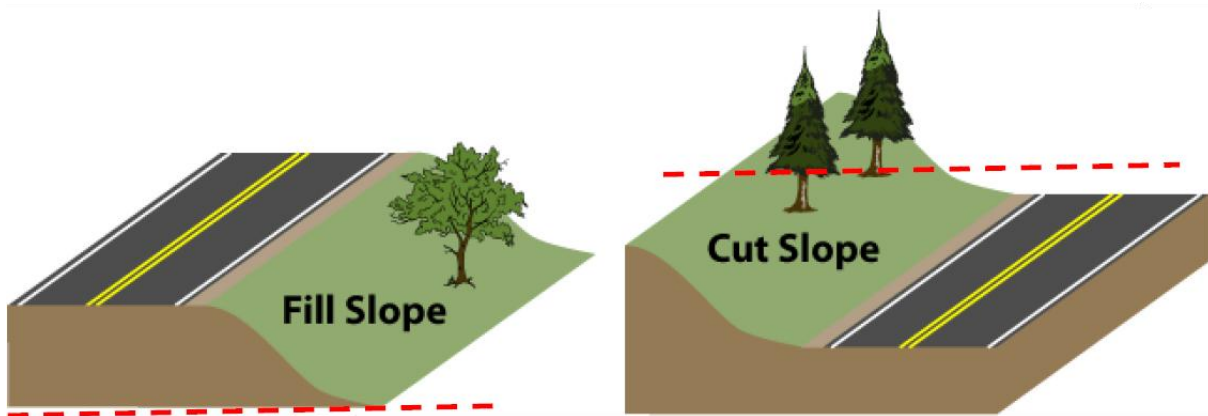


Figure 10 - Example of embankment and excavation (Fonseca *et al.*, 2024)

Therefore, slope stabilisation works are an integral part of railway earthworks, especially when excavations are deep or where the ground has limited self-supporting capacity. Soil nailing and anchoring are amongst the most pertinent measures to guarantee stability. They are utilised to restrain unstable masses and improve overall slope resistance (Fonseca *et al.*, 2024; Fortunato, 2005).

2.2.4 Drainage systems

Drainage in railways are divided into two separate categories relative to the track alignment, transverse and longitudinal, both with the function of collecting and directing water outside the track platform.

The longitudinal system serves to collect and divert surface and subsurface water away from the railway, preventing the saturation of the platform, while the transversal drainage system is designed to conduct water across the railway embankment to prevent water accumulation against the infrastructure (Guerreiro Bastos Leitão, 2019).

2.2.5 Bridges

Railway bridges are civil engineering structures that preserve the continuity, gradient and geometry necessary for railway operation while enabling the rail alignment to cross over obstacles such as rivers, roads, valleys among others (Gilbert, 2009; Ricketts, 2007).

Early systems relied heavily on masonry arches, which provided longevity, good compressive behaviour and compatibility with the materials and construction methods available at the time (Orbán, 2004; Santis, De e Felice, de, 2014).

Steel bridges later enabled larger spans and more slender structures, while reinforced prestressed concrete alternatives extended that versatility further into the 20th century (Gilbert, 2009).

2.2.6 Tunnels

Railway tunnels are enclosed engineering structures that enable the railway track to pass through or beneath topographic, geological or urban areas while maintain acceptable slopes, curvature and operational continuity. It specially focusses on maintaining the geometric and operational requirements of the line, where surface earthworks would be impractical, unsafe, unrealistic and with a much heavier cost (Kalender e Vojtek, 2021; Ramsay, 2010). Tunnels must be examined as both structural and route-enabling assets as part of the railway infrastructure, with their form determined by the surrounding terrain, the construction method and the traffic requirements of the railway.

2.2.6.1 *Excavation methods*

The ground conditions, tunnel geometry, required rate of advance, surface restrictions and the compatible mobilised support system are all limitations for the selection of the right excavation technique (Kalender e Vojtek, 2021). Four major excavation families are particularly significant for railway tunnels:

1. Drill-and-blast excavation – In this approach, the face is drilled, charged with explosives, blasted, cleared before support is installed and it is continuously repeated, depicted in Figure 11. Highly adaptable to changing geology, varying tunnel shapes and conditions that increase the difficulty for use of machine excavation. Nevertheless, the blasting can damage the surrounding rock, create overbreak and demand careful control since the excavation only has one face (Ramulu, 2012).

2. Sequential mechanical excavation and NATM-type methods – These methods are generally preferred where blasting is undesirable or where ground conditions are not favourable to full-face mechanised excavation. The New Austrian Tunnelling Method's (NATM) key idea is that stability is provided by the interaction between the surrounding ground and the support system, not by lining action alone (Hiroshi, 2001). Support timing is therefore part of the method itself. If support is installed too early it takes high load, if it is installed after controlled deformation the ground carries a greater share of the load and the support demand can be lower (Kalender e Vojtek, 2021).
3. TBM excavation – Excavation through tunnel boring machines (TBM) represent the main full-face mechanised alternative. Suited for long tunnels with an emphasis on regular geometry, high advance rates and controlled working conditions. These machines, however, in weak, highly fractured, saturated or rapidly changing grounds, performance can drop significantly and the machine may require auxiliary grouting, pilot excavation or other special measures (Zhao *et al.*, 2023).
4. Cut-and-cover construction – Structurally different from other excavation families, these procedures are used where the tunnel is relatively shallow and open excavation from the surface is feasible (Nică e Iftimie, 2019).

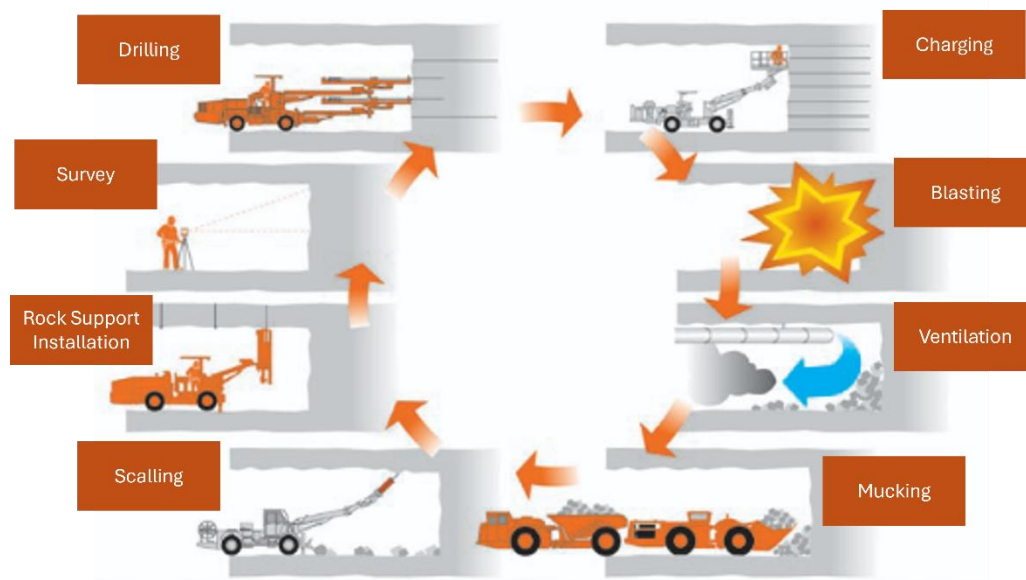


Figure 11 - Drill-and-blast cycle, adapted from (Heiniö, 1999)

2.2.6.2 Support systems and lining construction

Temporary support serves as a stabilising structure during excavation advance, whilst permanent lining, as the name suggests, provides the durable structural cover to ensure long-term railway service, water control and clearance (Hiroshi, 2001; Nică e Iftimie, 2019).

In older tunnels, the permanent lining often followed behind excavation, commonly built in bricks or masonry rings, reflecting the construction methods and materials available at the time (Atkinson, Paraskevopoulou e Miller, 2021). Often excavation profile was irregular and the space between the excavated ground and the permanent lining was filled with materials from the immediate excavation.

Through NATM-type excavation, the temporary support and the ground carry much of the load before the final lining is cast. The initial support usually includes shotcrete and bolts, sometimes combined with steel ribs, where in conjunction with the ground, serve as stabilisation of the opening, while a secondary lining may be required for water pressure resistance, eccentric loading and for long-term deterioration of the primary support (Hiroshi, 2001).

2.3 PROSPECTING WORKS

Prospecting works form the field basis of geotechnical characterisation. Geotechnical site investigation combines direct observation, boreholes, in-situ testing, sampling and groundwater observations to define surface and subsurface conditions for design, construction and rehabilitation, each providing a different type of information (Shukla e Sivakugan, 2011).

This section will focus on the most relevant prospecting works in tunnels within the scope of the rehabilitation and modernisation project, namely, trial pits, inspection windows, boreholes with core recovery and light dynamic penetrometer tests (LDP), shown in Table 1 and Bieniawski Rock Mass Rating (RMR), which, although not strictly a prospecting work, is highly relevant in this context (Rehman *et al.*, 2018; Santa, Fernandes e Chaminé, 2024).

Table 1 - Summary of the most relevant prospecting works in tunnels of the current project

Method	Main purpose	Output
Trial pits	Direct shallow inspection	Visual stratigraphy, groundwater observations, samples
Inspection windows	Direct local inspection of the lining or interface	Visible condition, contact state, local defects
Boreholes with core recovery	Subsurface investigation at depth	Lithology, discontinuities, recovered core, Rock Quality Designation (RQD)
LDP	Rapid shallow profiling	Penetration resistance index

2.3.1 Trial pits

Trial pits are shallow excavations opened to inspect the ground near the surface directly, used to expose stratification, identify fill materials or weak layers, observe groundwater where present and obtain samples from the exposed profile. Their main advantage is that the ground can be observed directly rather than interpreted indirectly from boreholes logs and recovered samples, whereas their main limitation is depth, since safety and stability constraints usually restrict them to shallow investigations (Cox, Dawson e Hall, 1986).

2.3.2 Inspection windows

Inspection windows are small local openings created to expose a limited area of the structure for direct visual inspection. These methods include opening walls or floors and excavating inspection pits to reveal concealed construction details and hidden structural elements (Tomaževič, 2025). Their main value is that they can reveal local construction details, contact conditions, moisture, voids or visible deterioration that cannot be judged confidently from the surface alone. Their main limitation is that they are intrusive and strictly local, so they are best used selectively to complement broader prospecting methods rather than as a standalone investigation technique.

2.3.3 Boreholes and coring with core recovery

Boreholes with core recovery are used where the investigation must extend below shallow depth or where the rock mass must be described in more detail (Santa, Fernandes e Chaminé, 2024; Shukla e Sivakugan, 2011). By drilling and recovering core it is possible to identify lithology, deterioration, fracturing, discontinuities and groundwater conditions at depth. Core recovery is also important because it serves as the record from which the RQD and part of the rock mass description are obtained (Rehman *et al.*, 2018; Santa, Fernandes e Chaminé, 2024).

2.3.4 Light dynamic penetrometer tests

LDP is a quick, simple and economical, in-situ method used mainly for shallow ground investigation. It is performed by repeatedly dropping a hammer from a fixed height onto a rod fitted with a cone tip and recording the penetration per hit or the number of hits required for a fixed penetration interval. The result is a penetration resistance index that is useful for rapid profiling and for identifying changes in soil condition with depth, usually interpreted together with other investigation methods (Mutabazi *et al.*, 2025).

2.3.5 Bieniawski Rock Mass Rating

Bieniawski Rock Mass Rating is an empirical rock mass classification system used to express rock mass quality in a form that supports engineering assessment and preliminary design decisions for tunnels, defined from a set of parameters that includes (Rehman *et al.*, 2018; Santa, Fernandes e Chaminé, 2024):

- Intact rock strength.
- RQD.
- Spacing of discontinuities.
- Condition of discontinuities.
- Groundwater conditions.
- Orientation of discontinuities, relative to the engineering work.

The sum of the parameter values results in a numerical score between 0 and 100, placing the rock mass into one of five quality classes. Figure 12 shows each parameter and its value.

PARAMETER	INTERVALS						
UCS (MPa) UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK MATERIAL	<250	250-100	100-50	50-25	<25		
	15	12	7	4	25-5	5-1	<1
RQD (%) ROCK QUALITY DESIGNATION	100-90	90-75	75-50	50-25	<25		
	20	17	13	8	3		
SPACING (mm) BETWEEN DISCONTINUITIES	>2000	2000-600	600-200	200-60	<60		
	20	15	10	8	5		
CONDITION OF DISCONTINUITIES ROUGHNESS, PERSISTENCE, SEPARATION, WEATHERING OF WALLS AND GOUGE	VERY ROUGH SURFACES NO SEPARATION UNWEATHERED WALL ROCK NOT CONTINUOUS	SLIGHTLY ROUGH SEPARATION < 1 mm SLIGHTLY WEATH. WALLS NOT CONTINUOUS	SLIGHTLY ROUGH SEPARATION < 1 mm HIGHLY WEATH. WALLS	SLICKENSIDED WALLS Or GOUGE < 5 mm Or SEPARATION 1-5 mm	SOFT GOUGE > 5 mm or SEPARATION > 5 mm CONTINUOUS		
	30	25	20	10	0		
GROUNDWATER IN JOINTS (PORE PRESSURE RATIO)	COMPLETELY DRY (0)	DAMP (0-0.1)	WET (0.1-0.2)	DRIPPING (0.2-0.5)	FLOWING (0.5)		
	15	10	7	4	0		

Figure 12 - Bieniawski Rock Mass Rating, 1979 (Romana, Séron e Montalar, 2003)

2.4 NON-DESTRUCTIVE TESTING

The present subchapter serves as a brief introduction of different non-destructive testing methods most relevant for tunnel void assessment that are currently in use. In chapter 4 a further analysis of each method will take place, their relevancy and importance regarding void detection.

2.4.1 Ground-penetrating radar

Ground-penetrating radar (GPR) is an electromagnetic method used to detect changes behind the tunnel lining from reflected radar signals. It is one of the most widely used NDT techniques for determination of hidden defects behind tunnel linings, greatly benefiting from its ability to provide continuous information along the tunnel surface, making it possible to identify anomalies, such as voids, insufficient backfill, delamination and variations in lining thickness (Karlovšek, Scheuermann e J Willimas, 2012; Peng *et al.*, 2021; Prego *et al.*, 2016). For this reason, it is considered one of the most relevant prospecting methods in tunnel inspection.

2.4.2 Impact-echo

Impact-echo (IE) is a stress-wave-based technique that analysis the lining's dynamic reaction following a controlled surface impact to find internal discontinuities. It is also useful for the local detection of debonding and voids behind the lining, particularly where changes in stiffness or support conditions are suspected (Aggelis, Shiotani e Kasai, 2008; Cao *et al.*, 2019). Although being a slower method than radar, in some sections of the tunnel lining, it can provide useful confirmatory information.

2.4.3 Ultrasonic tomography

Ultrasonic tomography (UST) is a wave-based method that reconstructs the internal condition of the lining from transmitted or reflected acoustic signals measured at multiple points. It is especially appropriate for the local assessment of bonding, internal impairment and filling quality behind tunnel linings, often employed as a supplementary technique where greater confidence is required, due to its higher local resolution (Jorne, Henriques e Baltazar, 2014; Lu *et al.*, 2018; White *et al.*, 2014).

2.4.4 Infrared thermography

Infrared thermography detects variations in surface temperature that may be associated with hidden defects, moisture or areas of detachment. It has the benefit of quick and non-contact data collection in tunnel inspection, especially over large areas, however, its effectiveness strongly depends on environmental conditions and on the presence of a measurable thermal contrast between sound and defective zones (Poncetti *et al.*, 2025).

2.4.5 Laser scanning

Laser scanning is a method based on laser distance measurement that generates a precise three-dimensional record of tunnel geometry. It is used to document deformation, profile changes and other geometric irregularities (Poncetti *et al.*, 2025; Sjölander *et al.*, 2023).

2.4.6 Photogrammetry

Photogrammetry is an image-based method that reconstructs the visible surface by overlapping photographs, useful for documenting cracking, leakage and visible deterioration (Poncetti *et al.*, 2025; Sjölander *et al.*, 2023). These last two methods are useful in rehabilitation studies because they can complement the interpretation of results obtained by deeper NDT methods and offer a detailed geometric record of the lining.

2.4.7 Laser vibrometry

This NDT is a contactless vibration technique that detects changes in the dynamic response of the lining, whose role in tunnel diagnosis is specialised and complementary, especially where remote assessment is needed (Poncetti *et al.*, 2025).

2.4.8 Electrical resistivity tomography

Electrical resistivity tomography (ERT) assesses the distribution of electrical resistivity within the investigated zone and is therefore sensitive to contrasts associated with water, air, grout and ground conditions. It is particularly useful in tunnel rehabilitation where the goal is to find cavities or compare conditions before-and-after filling operations (Vargemezis *et al.*, 2019, 2021). It is more useful for identifying more general physical changes in the treated zone than for exact geometric definition.

2.4.9 Seismic methods

The propagation of mechanical waves through materials with varying elastic properties is the basis for seismic refraction. In the context of tunnel rehabilitation, it can be utilised to help identify anomalous zones and, in some cases, to support the verification of consolidation or filling effectiveness (Vargemezis *et al.*, 2019, 2021). It is generally more indirect than radar or ultrasonic methods but it can contribute useful complementary evidence.

2.4.10 Transient electromagnetic radar

Transient electromagnetic radar (TER) is a specialised electromagnetic method that interprets apparent resistivity-related anomalies behind the lining. It can support the detection of voids, poor contact and thickness anomalies but is less established than GPR in the general tunnel inspection arsenal (Poncetti *et al.*, 2025).

3

PRESENTATION OF THE CASE STUDY

The electrification and modernisation of the Douro Line between Marco de Canaveses and Régua constitutes a complex engineering endeavour that required meticulous planning and a carefully phased approach to construction. The project is integrated in a multiple staged national electrification effort, being the third phase of possibly four on this particular line. In 2002, Ermesinde to Caíde was the first section of the Douro Line that was modernised and electrified, later, in 2019, Caíde to Marco de Canaveses and finally, the ongoing rehabilitation and electrification project between Marco and Régua. The contractual deadline of 1,095 calendar days, established by Infraestruturas de Portugal, demanded the simultaneous advancement of multiple work fronts across a stretch of approximately 43.3 km of single-track railway. A railway suspension period was planned within winter, coinciding with lower touristic activities, during which the most intrusive and structurally challenging interventions had to be carried out (Infraestruturas de Portugal, 2025).

This chapter opens with an introduction to the main intervenients and their role on this project, before presenting an overview of the planned works and finally a detailed account of the works executed during the first suspension period, which ran from the 13th of October 2025 to the 1st of April 2026. The latter section draws upon direct site observation conducted during an internship in Tabique Engenharia, Lda. focusing specifically on the tunnel interventions, slope stabilisation works and railway track works.

3.1 PROJECT ORGANISATION AND PARTICIPANTS

The successful execution of a project of this magnitude relies on the coordination of several specialised entities. In the context of this dissertation, three primary stakeholders are highlighted.

3.1.1 Infraestruturas de Portugal, S.A.

Infraestruturas de Portugal, S.A. (IP) is the Portuguese state-owned company responsible for the planning, design, construction, finance maintenance and operation of all national road and railway infrastructure network. Established in 2015 through the merger of Estradas de Portugal (EP) and REFER, E.P.E., IP is the contracting authority for all work done on the national railway network and has concessionary rights over it. In the context of this project, IP has the responsibility of defining the technical and operational requirements of the project, the public procurement process, the approval of design documentation and the final acceptance of the completed works.

IP is responsible for defining and approving the railway possession schedule, including the duration of the suspension periods and nocturnal interdictions and also for coordinating with the railway operator, Comboios de Portugal, to ensure road-based alternative transport services for passengers during those suspension periods (Infraestruturas de Portugal, 2025).

3.1.2 CASAIS-SOMAFEL joint venture

The contract for the execution of the works was awarded to a joint venture, CASAIS-SOMAFEL, formed by Casais – Engenharia e Construção, S.A. and Somafel – Engenharia e Obras Ferroviárias, S.A. As the building contractor, the joint venture has the obligation for the execution of the works, in accordance with the execution project documents, the contract specifications and the applicable technical standards. This includes:

- Preparation and submission of a detailed general construction programme, prior to the beginning of construction.
- Coordination and safety management of all work fronts.
- Mobilisation and management of all labour and materials.
- Provision and maintenance of the construction site and its facilities.
- Submission of test results and quality assurance documentation.
- Correction of non-conformities.

Given the operational complexity of the project, which requires the contractor to work alongside a functioning railway line for a part of the contract duration, CASAIS–SOMAFEL is also responsible for implementing and maintaining all railway safety measures prescribed by IP's internal railway safety regulation. The contractor is equally responsible for coordinating the work of all specialist subcontractors and for ensuring that interfaces between disciplines are managed without creating irresolvable conflicts or safety hazards.

3.1.3 Tabique Engenharia, Lda.

The role of site supervision and inspection was attributed to Tabique Engenharia, Lda., acting as the representative of IP on site. It acts simultaneously as IP's eyes and ears on the field, as the primary link between the client and the contractor for all day-to-day technical and contractual issues and has the authority to approve or reject submitted documents, to give instructions, certify partial payments and formally document any alterations from the approved programme.

Tabique's site supervision team is responsible for the continuous monitoring of all works in progress and for issuing non-conformities, where the resulting product of the works are different from the specified requirements, whilst also being responsible for the approval or rejection of each works phase before the contractor is permitted to proceed to the next one. Beyond its technical inspection role, Tabique also fulfils safety coordination responsibilities during the construction phase, according to the project's Safety and Health Plan.

3.2 PROJECT OVERVIEW

The scope of works for this project encompasses a broad and interconnected set of civil, geotechnical, structural and railway engineering interventions. The executing entity was awarded a contract valued at approximately 110.7 million euros, corresponding to a 36-month programme, with certain works in critical sections requiring temporary suspension of railway services during the winter months (Infraestruturas de Portugal, 2025).

This section of the line (Figure 13) incorporates six tunnels (Juncal: 1,624 m, Riboura: 120 m, Loureiro: 402 m, Má Passada: 37 m, Santinho: 82m and Régua: 342m) totalling a length of approximately 2.6 km.

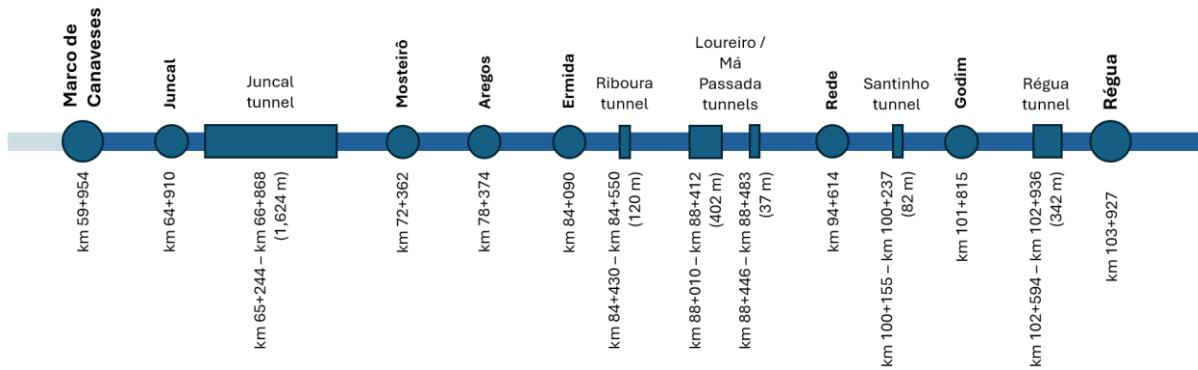


Figure 13 - Marco - Régua section, adapted from (Infraestruturas de Portugal, 2025)

The Juncal tunnel, in specific, was identified as requiring major structural reinforcement and was the primary driver behind the decision to implement the railway suspension. Given its size and complexity, the execution programme was organised around two separate work fronts for the tunnel group, one exclusive for the Juncal tunnel and the other serving the remaining five tunnels. Three full suspension periods of approximately five months each, spanning November to March in successive winters, were planned to accommodate the tunnel work programme, whilst during the rest of the year, the works were to be addressed using daily nocturnal track possessions of six to seven hours and extended weekend possessions of 55 hours.

The tunnel adaptation works represent one of the most technically demanding components of the project, namely:

- Structural beneficiation and reinforcement.
- Track lowering to achieve vertical clearance required for the installation of overhead catenary systems, enabling compliance with a P2 traffic code, equivalent to a PTb+ gauge (Figure 14), along the entire length of the railway section (Couto, 2025).
- Waterproofing of the tunnel linings.
- Installation of geodrains and drainage channels.
- Application of mortar for repointing of granite masonry joints.
- Structural injection of voids in the outer lining of the walls and the application of shotcrete and waterproof membranes where required.

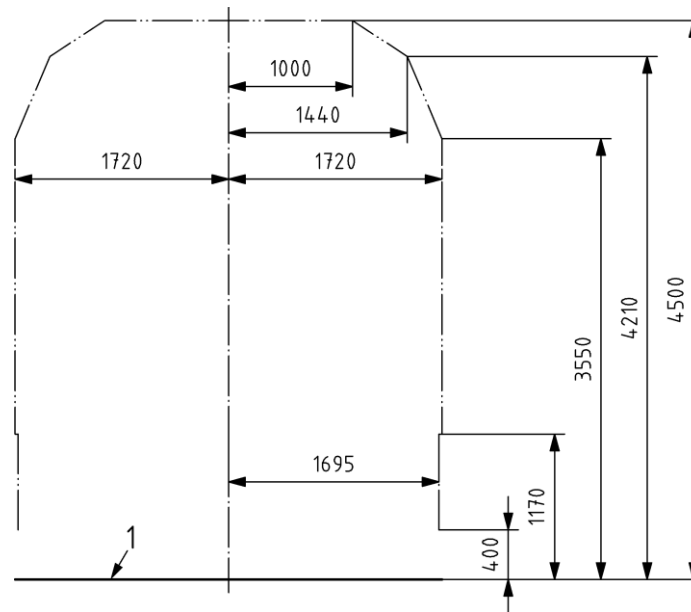


Figure 14 - Reference profile of gauge PTb+ (Couto, 2025)

Where track lowering was required, the planned sequence included the removal of the existing ballast and track formation, excavation, construction of new technical blocks, installation of a central longitudinal drain and the complete renewal of track with concrete twin-block sleepers. The slope stabilisation programme set out to address forty slopes identified along the line. Planned interventions included vegetation clearance, removal of loose or unstable rock blocks, drilling and grouting of soil nails and rock bolts and the installation of mesh systems. These works were organised into distinct intervention fronts, each corresponding to specific kilometric locations and geotechnical conditions, with certain fronts planned to extend beyond the first suspension window.

The modernisation of stations and halts included raising to 760 mm and the extension of passenger platforms to a minimum length of 150 m and 200 m at Régua station's Line 1. The seven stations and six halts along the line were to benefit from a range of interventions including platform track renewal, drainage, retaining structures and track replacement (Infraestruturas de Portugal, 2025). The construction phasing at each station was carefully studied to minimise impact on railway operations. The new track superstructure consists of E54 rails laid on a ballast layer of around 25-30 cm depth and side shoulder width of 1 m.

Additional planned components included the installation of catenary systems with poles positioned on the left-hand side of the track to preserve river views, electronic signalling, GSMR telecommunications, automation of level crossings, public information systems and CCTV, rehabilitation of station buildings and a comprehensive redesign of the Régua station layout.

3.3 WORKS EXECUTED DURING THE FIRST SUSPENSION PERIOD

The first railway suspension period ran from the 13th of October 2025 to the 1st of April 2026, spanning 124 calendar days. This window was specifically designed to allow the most critical and operationally disruptive interventions to proceed without conflict with the running of train services. In accordance with the work programme, multiple simultaneous work fronts were mobilised across the line, encompassing all six tunnels, several slope stabilisation sites and track renewal works at multiple stations and halts.

The internship placement that underpins the observation-based content of this chapter took place during the month of March 2026, covering the final weeks of the first suspension period. This timing allowed for the observation of works at advanced stages of execution across three main work categories providing a cross-section of construction activities at different levels of completion.

3.3.1 Tunnel Works

Of the six tunnels along the Marco – Régua section, all required adaptation works for electrification but their specific scope differed considerably according to their length, structural condition, constructive typology and the extent of track lowering required. Table 2 provides an overall summary of the tunnel's characteristics.

Table 2 - Summary of the tunnels on the Marco - Régua section

Tunnels	P.K. Entrance	P.K. Exit	Length (m)	Lithology	Support
Juncal	65+244	66+868	1,624	Medium to fine-grained granite with patches of medium to coarse-grained, slightly porphyritic texture	Granite masonry + shotcrete (partial)
Riboura	84+430	84+550	120		Granite masonry + shotcrete
Loureiro	88+010	88+412	402	Medium to fine-grained granite with patches of coarser grain, slightly porphyritic	Granite masonry + shotcrete (partial)
Má Passada	88+446	88+483	37		Shotcrete
Santinho	100+115	100+237	82		Metamorphic rock masonry + shotcrete
Régua	102+594	102+936	342	Decimetre-thick layers of metagraywacke, interspersed with striped schist-phyllites	

During the suspension period, works were carried out across all tunnel fronts, of particular relevance for direct site observation were the Riboura and Loureiro tunnels, which represent a fully masonry-lined tunnel and a tunnel with masonry extensions of 53 m at the entrance and 122.5 m at the portals, respectively, that were accessible and actively worked upon throughout the full duration of the internship.

3.3.1.1 Geotechnical investigation and non-destructive testing

The geotechnical investigation of the Marco – Régua section tunnels was not a single campaign but a structured accumulation of information developed across several decades of inspection and project phases. As illustrated in Figure 15, the works relevant to the current rehabilitation programme can be divided into two: a series of prior supplementary campaigns carried out before the current electrification project and the specific investigation programme developed under the current project's documentation.

Phase A – Prior campaigns

Before current project – 2004-2019

2004 – Juncal tunnel Visual inspection Laser scan
2008 – All tunnels (REFER) Visual inspection Anomaly surveys GPR surveys Core drillings
2010-2011 – Loureiro/Má Passada Structural rehabilitation project campaign Trial pits Core drillings Compression tests Recognition windows RMR classification (15 sections) Laser scanning
2018-2019 – IP Asset Management Routine inspections (all 6 tunnels) Visual inspection ISRM hammer

Phase B – Current project

Preliminary study + Execution project – 2018-2026

B1 – Preliminary study (December 2018)

Open section, RIV stations + Juncal Trial pits LDP tests Laboratory soil tests Juncal: Core drillings + borings
Santinho + Régua tunnels Trial pits Ballast sampling

B2 – Execution project (2020-2026)

Juncal – additional works Feb/May 2020: visual inspection + trial pits + core drillings (76 mm) LDP tests Short borings Seismic refraction (6 profiles) Laser scanning Structural convergence monitoring
All tunnels – preparatory works Visual inspection of inner lining of the walls Trial pits at base of walls Core drillings 76 mm (walls + crown)

Figure 15 - Structure of geotechnical investigation on the Marco - Régua tunnel group

Phase A – Prior investigation campaigns:

The earliest record of structural investigation relates to the Juncal tunnel, which in 2004 was subject to a partial structural intervention preceded by a visual inspection with digital mapping of lining pathologies, supported by a laser scanning survey of the tunnel profile.

In 2008, the REFER Tunnels Department conducted a thorough inspection campaign across all tunnels of the section, where it produced detailed records of pathologies including mortar joint deterioration, structural damage, infiltrations and biological growth. The characterisation of the outer wall lining condition, specifically the thickness of the masonry lining and the geometry of voids and detritic infill between the lining and the surrounding rock mass, was carried out through the combined use of GPR surveys and core drillings at representative sections. This GPR campaign was a previous and independent prospecting exercise, conducted before the current project was conceived and constitutes the primary pre-existing source of information on void distribution along the tunnel linings.

Between 2010 and 2011, a dedicated geotechnical investigation campaign was carried out for the structural rehabilitation project of the Loureiro tunnel, which involved trial pits, core drillings through the lining and into the rock mass, uniaxial compression testing on recovered rock cores and the opening of recognition windows in the lined sections to characterise the filling material of the outer wall linings. The same campaign also included a geomechanical classification programme using the Bieniawski RMR system at fifteen sections of the unlined central portion of the Loureiro tunnel with results ranging from fair to good quality at thirteen sections and poor quality at two, with active water ingress recorded at four locations. The campaign also included a laser scanning survey of the existing excavated profile in the unlined section.

Between 2018 and 2020, IP's Asset Management Department carried out global routine inspections of all six tunnels. These inspections involved visual survey of the inner lining of the tunnel walls, recording of visible pathologies and assessment of compressive strength using a geological hammer following ISRM (International Society for Rock Mechanics and Rock Engineering) guidelines.

Phase B – Current project investigation:

The current project's geotechnical investigation was carried out in two phases. The preliminary study campaign, completed in December 2018, covered the open sections of the track, station track segments and the Juncal tunnel, where the investigation included excavated trial pits (Figure 16), LDP tests at selected pits, laboratory testing on recovered soil samples, at the convergence zone of the Juncal tunnel core drillings (Figure 17) through the masonry, with core recovery (Figure 18) and enclosing rock mass and short inclined borings at the base of the walls.

At the Santinho and Régua tunnels, the preliminary campaign was limited to trial pits and ballast sampling.



Figure 16 - Trial pit in the Juncal tunnel, preliminary campaign



Figure 17 - Core drilling in the Juncal tunnel, preliminary campaign



Figure 18 - Core recovery, preliminary campaign

Within the scope of the execution project, a targeted inspection and investigation was conducted at the Juncal tunnel in February and May 2020, comprising visual inspection of the inner lining of the tunnel walls, trial pits (Figure 19) and core drillings (Figure 20).

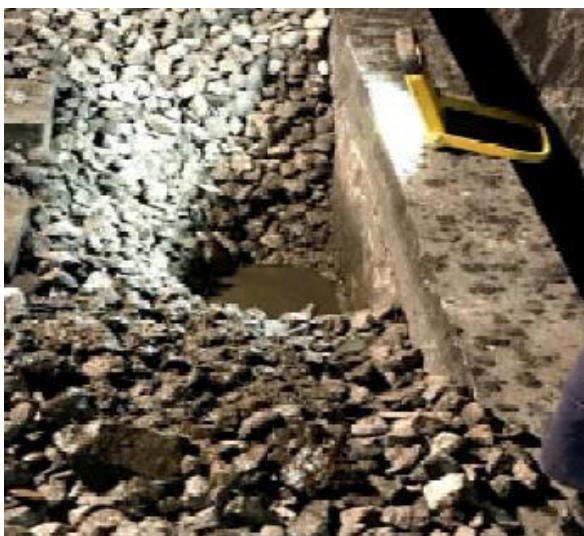


Figure 19 - Trial pit in the Juncal tunnel, execution project



Figure 20 - Core recovery, execution project

Additional works included LDP tests (Figure 21) and short borings, six seismic refraction profiles at the two portal approaches (two at the north portal and four at the other), each 55 m in length, laser scanning of the tunnel profile for geometric comparison with the design cross-section and the installation of a structural convergence monitoring system (Figure 22) consisting of reflective targets and measurement chords at sections separated by ten metres.



Figure 21 - LDP test in Juncal tunnel, execution project

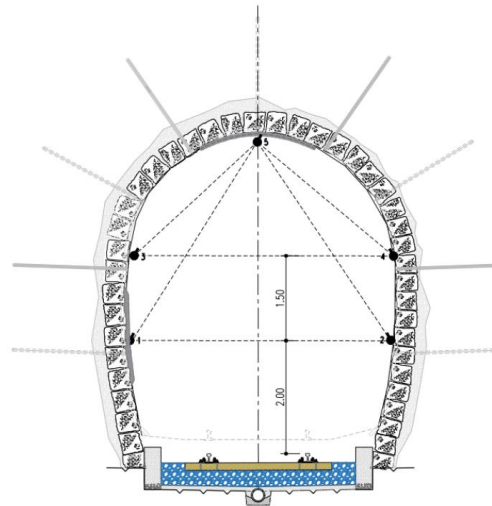


Figure 22 - structural convergence monitoring system

The execution project investigation defined the preparatory prospecting works to be carried out across all tunnel fronts before the start of the rehabilitation. This programme went according to the following sequence:

1. Visual inspection of the inner linings of the tunnel walls for identification of structural pathologies, humidity, water seepage and joint condition.
2. Manually excavated trial pits positioned at the base of each wall to determine the foundation core.
3. Rotary core drillings with 76 mm diameter and continuous recovery, executed at the crown and to each side of the walls in a pattern of three drillings per section, one at each wall and one at the crown, to assess masonry thickness, joint condition, mortar quality and void geometry.

3.3.1.2 Intervention methodology for masonry tunnels

The intervention methodology across masonry tunnels followed a consistent sequence adapted to each tunnel's specific characteristics. Once the preliminary surveys were complete, the rehabilitation proceeded through a series of clearly defined and sequentially dependent phases.

The first operation was a thorough cleaning of the tunnel lining surfaces and masonry joints (Figure 23), using pressure washing (2 – 10 MPa) water and sand blasting, applied in a ratio of approximately 80/20, water-to-sand by volume.

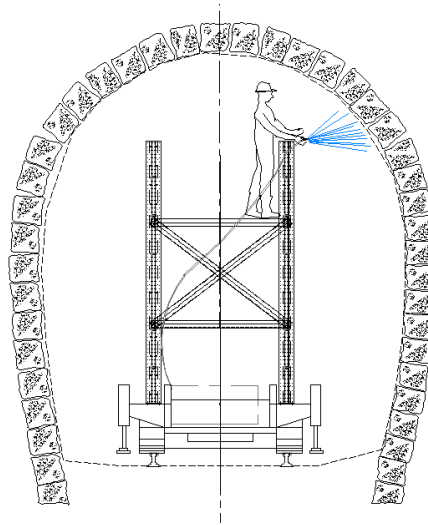


Figure 23 - Water and sand pressure washing

This operation removed accumulated soot deposits from the era of steam traction, biological growth, efflorescences, loose or altered material from the inside lining and other traces of grime and, specifically for the masonry joints, also served to expose and sanitize stripping deteriorated or missing mortar and revealing the full extent of joint distress. Where the water-sand blast was insufficient to adequately clean the joints, a mechanical scaling hammer with an adapted chisel point was used to complete the sanitation.

The first structural reinforcement operation of the masonry walls was the repointing of granite masonry joints with a pozzolanic lime-based mortar applied where the depth of joint stripping exceeded 4 cm, executed by hand or using a pump-fed injection pistol, depending on the accessibility of the joints.

The second was the injection of grout in the outer lining of the tunnel (Figure 24), consisting of a mixture of cement, fine sand, bentonite and water, in a cement-to-sand and water-to-cement ratios of 1, with a bentonite dosage of 6 kg per 100 kg of cement.

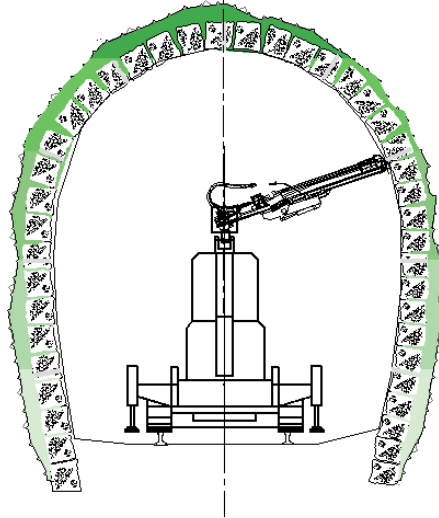


Figure 24 - Grout injection into the outer wall lining voids

The cement must comply with NP EN197-1 and satisfy the fineness and performance requirements established in the project:

- A residue on the:
 - 4,900 mesh/cm² sieve not exceeding 5%.
 - 900 mesh/cm² sieve not exceeding 0.3%.
- A setting time of no less than 3 hours.
- An autoclave expansion below 0.5%.

The fine sand must have a maximum grain size below 2 mm and comply with NP EN 13139:2005, with angular and rough-surfaced grains free of organic matter. The bentonite is added at the specified dosage to prevent premature sedimentation of cement particles during pumping and injection without introducing excessive viscosity. The elevated water-to-cement ratio of 1 was selected to ensure adequate fluidity for pumping and penetration through the masonry into the irregularly shaped voids and must comply with NP EN 1008:2003.

The project specification documents frame the pre-injection laboratory study as fixing the dosage of the three components present in the baseline formulation in addition to admixtures. A dedicated section of the specification documents regulates the potential use of chemical admixtures, referencing the NP EN 934 (parts 1 to 6) and classifying admixture types by primary function:

- Water-reducing plasticizers.
- High-range water-reducing superplasticizers.
- Water retainers.
- Air-entrainers.
- Set accelerators.
- Set retarders.
- Hardening accelerators.
- Water repellents.

Any admixture used is limited to 5% of cement mass, chloride-based products are explicitly excluded and prior approval by the site supervision, supported by laboratory test results, is required.

Although bentonite performs a stabilising function with a purpose comparable to certain admixtures, it does not fall under the EN 934 framework. The baseline formulation therefore contains no admixture, even though the quality-control clause names admixtures as part of the material categories subject to verification, indicating that admixture use was anticipated as a possibility within the adaptive process described below.

The project specifications recognise that this formulation is a starting point requiring laboratory validation before the injection works begin, covering compressive strength, density, viscosity and volumetric variation to determine the most appropriate mix proportions for each case, potentially incorporating the admixtures described above, considering the characteristics of the receiving medium, the function of the treatment and the estimated void volume.

The density of the injected grout may be progressively increased during the injection of a section to optimise the process and mix for each case. If large absorption volumes are detected in a borehole, an increase in the sand dosage may be authorised by the site supervision. The mix design is therefore treated as an empirical and adaptive process, in which the initial formulation is progressively adjusted to the observed behaviour of the injection.

The injection process (Figure 25) is carried out at low pressure, not exceeding 0.2 MPa (value based on similar treatments of other projects) through 51 mm boreholes drilled in a quincunx 1.5 x 2.0 m grid by rotary process to minimise vibration and avoid opening masonry joints. Injection proceeded symmetrically per section and bottom-to-top, beginning at the lowest horizontal row and finishing at the crown, so that ascending grout progressively filled outer lining voids without inducing uncontrolled lateral pressure on the lining. Where grout migration between the lining and the terrain was detected, an indication that cavities were connected, transverse plugs were created before continuing or grouts adjusted consistency to improve efficiency.

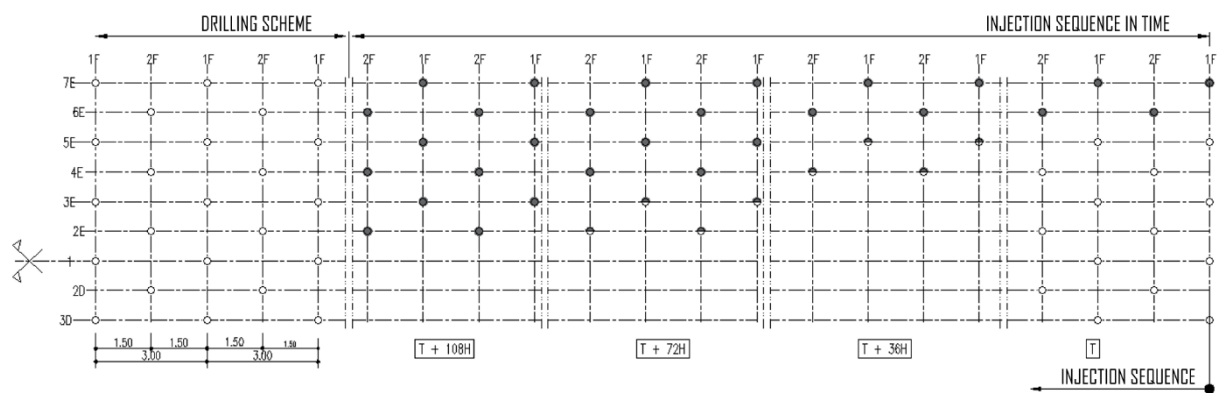


Figure 25 - Injection process

The following criteria were adopted for stopping injection in each borehole:

- Maintenance of pressure at 0.2 MPa with an instantaneous flow rate of 500 L/h or less, for 15 seconds.
- Absorption exceeding 1,000 L. In this case, the borehole will be re-drilled and then injected again after 24 hours.
- Resurgence of grout in a borehole on a upper line.

At the Loureiro and Má Passada tunnels, drainage and waterproofing treatments were executed according to the severity of observed moisture across three different levels of moisture content:

1. Where no visible moisture was present, intervention was limited to void injection, cleaning and joint repointing.

2. Where traces of humidity were detected, a three-layer system was applied, consisting of a 4 cm primary shotcrete base coat, a 3 mm sprayed waterproof membrane and a 5 cm polypropylene fibre-reinforced shotcrete finishing layer with a 1 cm thick layer of sprayed concrete.
3. Where active dripping or seepage was present, perimetral openings of 10 x 8 cm² were cut into the masonry walls not exceeding 2 m from one another. Then, 2 m boreholes were drilled at approximately 30° alternately to either side and U-section PVC drains of 100 mm width were inserted, fixed and sealed with waterproof mortar, discharging into the longitudinal drainage at the invert.

PVC geodrains of 50 mm diameter were additionally drilled and installed in the masonry and rock to intercept hillside groundwater before it reached the inner wall surface.

The drainage and waterproofing solution across the other tunnels of the Marco – Régua section follows a three-step approach:

1. Platform drainage is provided by permeable concrete blanket laid over the track subgrade, working in combination with the ballast layer to capture infiltrating water and direct it to a central longitudinal HDPE corrugated drain pipe, perforated in the upper half and wrapped in geotextile, that runs the full tunnel length and discharges to the exterior drainage network through junction boxes.
2. Rock mass and lining drainage addresses zones of active seepage or groundwater exfiltration. In these sections (Figure 26), deep transverse drains are inserted into the enclosing rock mass, in a quincunx 3.0 x 4.0 m grid, to lower the local water table around the tunnel. The captured water is directed to a semi-drain embedded in the lining, which discharges at ballast level to the central longitudinal drain. Where ingress is localised, 35 cm wide geocomposite drainage bands (Figure 27) are fixed to the lining surface and directed to the base of the wall.

In the Régua tunnel, given the poor geomechanical quality of the enclosing at the western portal approach and the low overburden above the vault in its urban setting, reinforced concrete toe beams with inclined rock bolts were constructed at the base of each wall over the first 106 m from the western portal to control decompression during subgrade excavation.

After drainage and waterproofing, boreholes at different sections of the tunnels are executed in order to verify the proper filling of the outside lining of the tunnel walls.

3.3.2 Slope stabilisation works

The stabilisation of railway embankments and rock slopes is a key component of the modernisation programme, with forty slopes identified for intervention along the Marco – Régua section (Infraestruturas de Portugal, 2025).

The stabilisation works were organised into distinct intervention zones (T3 – T8, T0 – T2, T23 – T39 and T89) each corresponded to a specific section of the line, with its own geotechnical characteristics, access constraints and scope of works. During the internship it was possible to follow all active slope stabilisation work fronts, namely T6 and T7, T3, T4, T5 and T8.

The first operation at each slope front was the establishment of site facilities, including the provision of access routes, temporary fencing and the positioning of equipment and materials. This was followed by general vegetation clearance, involving the mechanical and manual removal of scrub, trees and invasive species from the slope face and immediate surroundings. The removal of vegetation exposed the underlying rock or soil surface, allowing for detailed inspection and identification of unstable zones. Where necessary, loose or potentially unstable rock blocks were identified and removed by mechanical means or manual scaling.

The principal structural stabilisation technique employed across the slope fronts was the installation of soil nails, following a standard sequence:

1. Drilling of holes to the required depth and inclination.
2. Insertion of a steel rebar.
3. Grouting of the space between the bar and the drilled hole with cement grout, pictured in Figure 29.
4. Installation of bearing plates and nuts at the exposed end.

Following the completion of the nailing works, flexible protective mesh systems were installed over the slope face (Figure 30).



Figure 29 - Grouted soil nail



Figure 30 - Unfastened protective mesh system

The programme acknowledged that several fronts would extend beyond the suspension end date, with certain work fronts expected to continue into the second season.

3.3.3 Railway track works

Railway track works during the first suspension period were concentrated primarily at the stations and halts where platform construction, track renewal and the relaying of turnouts (AMV) were planned. The principal locations addressed within the suspension window included Marco de Canaveses, Mosteiró, Aregos, Barqueiros and Régua.

Track removal was the first operation carried out wherever new track was to be laid. This process involved the mechanical extraction of rails and sleepers, followed by the removal of the existing ballast layer and, in some cases, the sub-ballast and formation material beneath. At Mosteiró and Aregos stations, track removal was preceded by earthwork and drainage operations associated with the new platform construction.

Track laying was categorised across four article types: main line ballasted track with concrete twin-block sleepers for open-line sections, main line ballasted track with monoblock sleepers, secondary line ballasted track with monoblock sleepers and tunnel track with timber sleepers.

Regularisation attacks were programmed at the beginning and end of each zone of new track, at all stations, tunnel portals and zones of rail expansion joints and derailment devices, to ensure a correct geometric transition between the new alignment and the existing track. The definitive tamping and dynamic stabilisation were then applied across the full extent of the new track, consolidating the ballast bed to the required load-bearing capacity and geometric precision.

Aluminothermic welding was carried out to join individual rail bars into long welded rail. The welding programme covered junctions between new rail bars, transitions to existing track at intervention limits and connections between new AMVs and their collateral bars. Long welded rail regularisation, comprising cuts and associated welds, were included as a separate item for a standard 150 m extent at the contract limits.

Additional track works included:

- Supply and installation of 5 new kilometre posts and 99 new hectometre markers along the full Marco – Bagaúste corridor.
- Definitive survey staking on renewed Lines I and II at each station.
- Supply and installation of insulated rail joints, with two per AMV at each diverging arm.
- Substitution of twin-block sleepers by special monoblock check-rail sleepers and monoblock sleepers in ballasted bridge sections requiring check rail.
- Installation of check rail and check rail supports on the ballasted and metallic bridges.

The lifting and laying of turnouts was treated as a series of specific consequent actions: AMV lifting for each existing switch removed, AMV laying for each new switch installed and AMV for the definitive tamping of each switch. Expansion joints were addressed through specific lifting, installation and definitive tamping.

At the Régua station, the track works were the most complex of the entire programme, structured across eight major phases. However, during this suspension period, three phases set the conditions for all subsequent stages of the Régua station reconfiguration:

- Phase 1A involved the establishment of provisional lines XVII and XVIII and the provisional switch AMV_Prov2, together with the renewal of Line X between AMV_Prov3 and existing AMV24, future AMV_REG2.

- Phase 1B involved the lifting of existing switches AMV23, AMV24 and AMV13 and the installation of new switches AMV2, AMV10 and AMV_Prov3.
- Phase 1C involved the lifting of Line X between the new AMV_REG10 and existing AMV26 and of Lines VI, VII and the narrow-gauge tracks, together with the installation of provisional station facilities and commencement of the fuel depot relocation.

This chapter outlines the operational and technological context for the subsequent chapters.

1. The investigation campaigns determine what was known about the voids before injection began and through which methods.
2. The intervention methodology defines the grout composition and the stop criteria that regulated the injection process.

In this context, chapter 4 assesses the NDT methods for void detection and characterisation, while chapter 5 examines the grout mix design principles that influence the effectiveness of the filling intervention.

4

NON-DESTRUCTIVE TESTING

The detection of hidden voids behind tunnel linings is a recurring problem in the maintenance and rehabilitation of railway tunnels. The anomaly is usually inaccessible from outside the tunnel walls, while inspection in service is restricted to the inside of the tunnel. As a result, the state of contact between lining and surrounding ground must be established through investigation. Invasive methods, such as, trial pits, core drillings and inspection windows, confirm conditions at selected locations, while non-destructive methods, which allow continuous or distributed assessment without disrupting the lining, provide the spatial coverage and continuity that point-based methods alone cannot offer (Harseno *et al.*, 2022; Lei *et al.*, 2023; Poncetti *et al.*, 2025). These two approaches act as complementary rather than alternative approaches.

In older masonry tunnels, the problem is made harder by three facts (McCormick, 2010):

- Heterogeneity of the lining system.
- Short inspection windows under the railway operation.
- Variety of hidden anomalies (void, loosened fill, poor contact, water accumulation, detached lining zones or loss of support at the back of the lining), that may exist behind the lining.

The rehabilitation of old railway tunnels raises two linked questions: how hidden voids behind the lining should be detected and how filling works should later be interpreted and verified. For this reason, NDT and grouting are best understood as parts of a single diagnostic and intervention framework, in which inspection informs injection design, injection parameters guide execution and post-treatment assessment helps to evaluate the result (Peng *et al.*, 2021; Vargemezis *et al.*, 2019).

Most of the method-specific evidence retrieved for hidden-void detection, grouting evaluation and post-treatment verification comes from concrete, segmental, composite or otherwise generic tunnel linings rather than from old masonry railway tunnels (Aggelis, Shiotani e Kasai, 2008; Jorne, Henriques e Baltazar, 2014; Poncetti *et al.*, 2025). The descriptions of the methods below and the functional roles later assigned to them should therefore be read mainly as an interpretation of that broader tunnel literature, transferred cautiously to the present masonry-lined case study. Direct masonry-tunnel evidence within the retrieved literature is clearest for GPR, while most other methods are better treated as cautious transfers from broader tunnel literature (Llanca, Breul e Bacconnet, 2017; McCormick, 2010).

4.1 BASIS OF COMPARISON

The methods explored in this chapter do not all perform the same task. Some can detect hidden anomalies behind the lining directly, whilst others provide more indirect evidence or support the geometric and surface assessment of the tunnel rather than the direct detection of voids. The most useful basis for comparison is based on function. The key questions are whether a method is suited to prospecting, local confirmation, post-treatment verification or surface support and how well it fits the constraints of old railway tunnels (Peng *et al.*, 2021; Poncetti *et al.*, 2025).

It is useful to distinguish between methods that relate directly to the topic of hidden void detection, methods that are relevant mainly as complementary inspection tools and other supplementary verification methods. Accordingly, the methods are grouped here into three categories (Poncetti *et al.*, 2025; Vargemezis *et al.*, 2019, 2021; Ye *et al.*, 2020):

- Primary methods for void detection and local confirmation
 - Ground-penetrating radar
 - Impact-echo
 - Ultrasonic tomography
- Complementary inspection methods
 - Infrared thermography
 - Laser scanning
 - Photogrammetry
 - Laser vibrometry
- Supplementary verification methods

- Electrical resistivity tomography
- Seismic methods
- Transient electromagnetic radar

This hierarchy is used as the functional basis of comparison in the present chapter and is derived mainly from broader tunnel literature (Poncetti *et al.*, 2025; Vargemzis *et al.*, 2019, 2021; Ye *et al.*, 2020).

4.1.1 Ground-penetrating radar

Ground-penetrating radar works by transmitting electromagnetic waves into the lining and recording the reflections from interfaces where dielectric properties change, illustrated in Figure 31 (Lei *et al.*, 2023; Peng *et al.*, 2021). In practice, the antenna is moved along the tunnel surface and the reflected signal is processed into radargrams from which voids, poor contact, moisture-related contrasts and thickness changes may be inferred (Peng *et al.*, 2021).

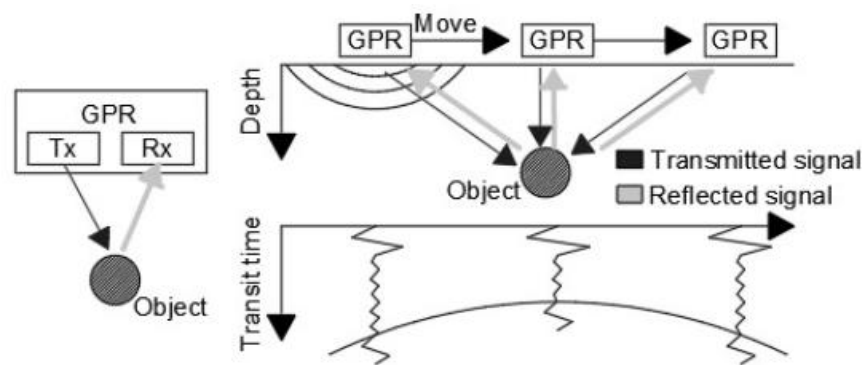


Figure 31 - Schematic GPR functionality (Poncetti *et al.*, 2025)

This is the only method that repeatedly combines operational coverage with useful depth of investigation for hidden anomalies behind the lining. Its principal strength is that it can provide continuous information along the tunnel surface, allowing the detection of void indicators, debonding, moisture-related contrasts and changes in lining thickness over substantial lengths (Karlovišek, Scheuermann e J Willimas, 2012; Peng *et al.*, 2021; Prego *et al.*, 2016). This makes radar the most suitable first-line method for renewed prospecting where older investigations are incomplete or outdated.

A practical distinction should be made between two deployment forms:

1. Ground-coupled radar (Figure 32) is better suited to detailed prospecting because proximity to the lining generally improves resolution and signal quality (Karlovič, Scheuermann e J Willimas, 2012; Prego et al., 2016).
2. Air-coupled or train-mounted radar (Figure 33), by contrast, is more useful for rapid screening and network-scale inspection, particularly in railway environments where possessions are short and contact with the lining is not always feasible (Lei et al., 2023; Xiong et al., 2020).



Figure 32 - Ground-coupled radar (Geng, Ye e Wang, 2022)



Figure 33 - Air-coupled radar (Lei *et al.*, 2023)

For old masonry-lined tunnels, the distinction between ground-coupled and air-coupled or train-mounted deployment remains operationally useful but the evidence for the latter is drawn from generic and concrete tunnel studies rather than from direct masonry tunnel-validation (Lei et al., 2023; Peng et al., 2021; Xiong et al., 2020).

A further functional differentiation concerns antenna frequency, which applies to both deployment methods. General tunnel and concrete-based studies show a trade-off between penetration and resolution (Harseno *et al.*, 2022; Qin *et al.*, 2020):

- Lower-frequency antennas provide greater penetration but lower resolution.
- Higher-frequency antennas improve the detection of thinner defects but with reduced penetration depth.

In old masonry tunnels, however, the practical choice of frequency is likely to be more site-specific because heterogeneity, mortar joints, moisture variation and irregular backing may reduce signal interpretability (Llanca, Breul e Bacconnet, 2017; McCormick, 2010).

GPR also presents well established limitations. Its performance is degraded by water, metallic elements, low dielectric contrast and heterogenous lining conditions (Harseno *et al.*, 2022; Peng *et al.*, 2021). These constraints are especially important in masonry tunnels, where the hidden condition may include poor contact, loose fill, moisture or degraded backing rather than a simple clean void system (Llanca, Breul e Bacconnet, 2017).

4.1.2 Impact-echo

Impact-echo (IE) is a local stress-wave method that identifies discontinuities through changes in the lining response after a controlled impact. It works by applying a short mechanical impact to the lining surface, creating P-waves (primary), S-waves (secondary) and R-waves (surface) and recording the returning stress-wave response with a nearby sensor (Cao *et al.*, 2019; Poncetti *et al.*, 2025). A scheme demonstrating how this method works is illustrated in Figure 34.

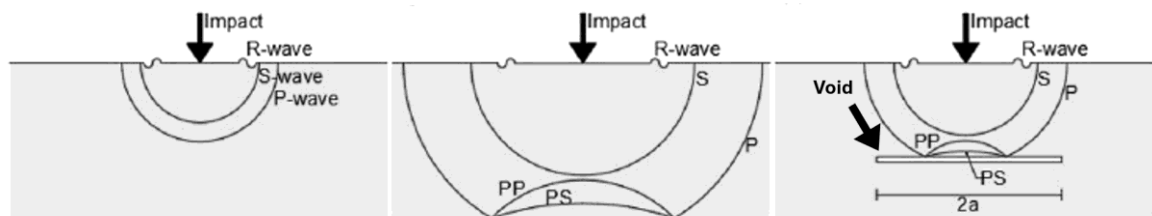


Figure 34 - Schematic IE functionality, adapted from (Poncetti *et al.*, 2025)

Voids behind the lining can be distinguished through amplitude, duration, energy distribution and dynamic stiffness even if the dominant resonance frequency associated with the lining thickness does not by itself diagnose the defect (Cao *et al.*, 2019). This makes IE useful where radar indicates a suspicious zone but the intervention decision requires greater local confidence.

It is point-based, relatively slow and sensitive to the location of the test point relative to the hidden void, so it is not well suited to tunnel-wide prospecting under railway operating constraints (Aggelis, Shiotani e Kasai, 2008; Cao *et al.*, 2019).

4.1.3 Ultrasonic tomography

Ultrasonic tomography (UST) works by introducing acoustic or ultrasonic waves into the lining and recording transmitted or reflected signals at multiple locations (Figure 35). These measurements are then combined into scans (A-Scan is the basic waveform registered by one probe, B-Scan, C-Scan and D-Scan are images that display a matrix derived from the data obtained by the probes), depicted in Figure 36, that indicate internal boundaries, defects, debonding or the quality of contact and filling behind the lining (Poncetti *et al.*, 2025).

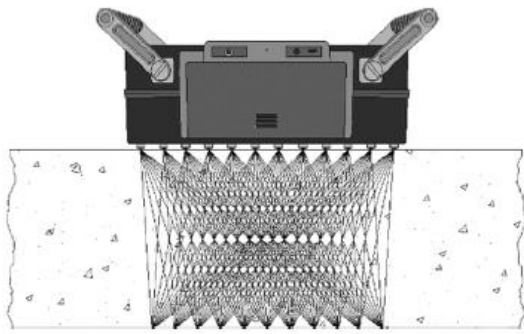


Figure 35 - UST operational sketch (White *et al.*, 2014)

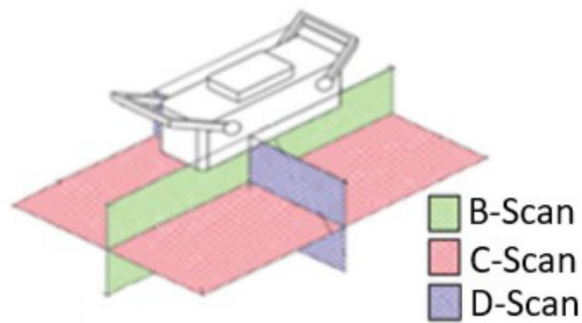


Figure 36 - Types of scans (Poncetti *et al.*, 2025)

UST provides richer local information because it aims to reconstruct the internal condition of the lining or the contact state behind it from wave propagation data, presenting as one of the strongest methods for local clarification and post-grouting assessment (Jorne, Henriques e Baltazar, 2014; Lu *et al.*, 2018; White *et al.*, 2014).

Its main limitation is that this method requires contact, good coupling and slower execution than radar, making it more suitable for selected sections than for extensive inspection campaigns (Poncetti *et al.*, 2025). For old masonry-lined tunnels, it is presented as a plausible local method whose post-injection role is supported mainly by broader tunnel and adjacent masonry literature rather than by strong direct validation on masonry railway tunnels (Llanca, Breul e Bacconnet, 2017; Poncetti *et al.*, 2025).

4.1.4 Electrical resistivity tomography

Electrical resistivity tomography works by placing electrodes along a profile, injecting electrical current, measuring resulting potential differences and inverting the apparent resistivity data into an image of subsurface resistivity contrast (Putiška *et al.*, 2012). It is based on contrasts in electrical resistivity and is therefore sensitive to changes in moisture, air content, grout presence and ground condition.

Its main value in tunnel rehabilitation lies in comparison of measurements obtained before-and-after grouting (Vargemezis *et al.*, 2019, 2021). Where filling changes the physical state of the treated zone, resistivity methods may show a clearer response than methods that depend on precise geometric imaging alone. For this reason, ERT is best regarded as a verification method rather than a first-line prospecting tool.

4.1.5 Seismic methods

Seismic methods work by measuring the propagation of mechanical waves or, in some cases, ambient vibration, through the lining and surrounding medium. Changes in travel behaviour, stiffness-related response or dominant vibration frequencies are then interpreted as signs of discontinuity, loss of continuity or voiding (Gao, Jiang e Li, 2014).

These methods occupy a similar position to ERT, because both methods are more useful for complementary assessment of physical change rather than primary hidden-void mapping. They are secondary methods whose main value lies in post-treatment verification or complementary investigation (Vargemezis *et al.*, 2019, 2021).

4.1.6 Infrared thermography

Infrared thermography works by recording the thermal radiation emitted from the tunnel surface with an infrared camera. Defects are inferred where voids, moisture or debonding change local heat transfer and create temperature patterns that differ from those of sound material (Poncetti *et al.*, 2025).

In tunnel inspection it is relevant because it is fast and non-contact, however, its effectiveness depends heavily on environmental and thermal boundary conditions, which makes it less reliable as a primary hidden-void detection method than radar or wave-based methods (Poncetti *et al.*, 2025). Therefore, thermography is best treated as an indirect support method.

4.1.7 Laser scanning and photogrammetry

Laser scanning works by sending laser pulses to the tunnel surface and calculating 3D coordinates from the returned signal, thereby producing a dense point cloud of the lining geometry. Photogrammetry reconstructs the visible surface from overlapping images processed into 2D or 3D models (Poncetti *et al.*, 2025; Sjölander *et al.*, 2023).

Their main role is surface and geometric documentation rather than hidden-void detection. Their value lies in accurate documentation of geometry, surface deformation, cracking, leakage and visible tunnel condition (Poncetti *et al.*, 2025). If radar suggests an anomaly behind the crown and laser scanning or photogrammetry shows coincident distortion or cracking, the combined interpretation is stronger than either dataset alone.

4.1.8 Laser vibrometry

Laser vibrometry works by measuring surface vibration remotely through the Doppler response of a laser reflected from the lining while the surface is excited by sound or impact (Poncetti *et al.*, 2025). Internal defects are inferred from changes in displacement or velocity response associated with detachment, altered stiffness or abnormal dynamic behaviour (Poncetti *et al.*, 2025).

It is a contactless technique capable of assessing vibration response and surface detachment, whose main feature is that it can be applied remotely, a useful characteristic for difficult or hazardous locations. Even so, it is not one of the principal methods for detecting hidden voids behind the lining (Poncetti *et al.*, 2025).

4.1.9 Transient electromagnetic radar

Transient electromagnetic radar (TER) works by using electromagnetic induction to sense contrasts in apparent resistivity and related electrical properties behind the lining. In practice, defects are inferred from anomalies associated with poor contact, thickness variation or hidden voids (Poncetti *et al.*, 2025).

Its main role is specialised supplementary detection or verification. It has been applied to the detection of voids, insufficient lining thickness and poor contact behind tunnel linings (Geng, Ye e Wang, 2022; Ye *et al.*, 2020) but it is not generally treated as a standard first-line inspection method. Its value lies mainly in specific lining-evaluation contexts where apparent resistivity contrasts help to distinguish defective zones (Geng, Ye e Wang, 2022; Ye *et al.*, 2020).

Taken together, the methods reviewed above can be compared more clearly in functional terms, as shown in Table 3.

Table 3 - Comparative NDT framework

Method	Physical basis	Directness for void detection	Main strength	Main limitation	Role in railway tunnels
Ground-penetrating radar	Electromagnetic wave reflection	High	Continuous prospecting over long lengths (Karlovšek, Scheuermann e J Willimas, 2012; Peng <i>et al.</i> , 2021; Prego <i>et al.</i> , 2016)	Sensitive to moisture, reinforcement, low dielectric contrast and interpretation uncertainty (Harseno <i>et al.</i> , 2022; Qin <i>et al.</i> , 2020)	Primary prospecting tool
Impact-echo	Stress-wave response to impact	High at local scale	Local detection of stiffness change and debonding (Aggelis, Shiotani e Kasai, 2008; Cao <i>et al.</i> , 2019)	Point-based and slow. Sensitive to test position (Cao <i>et al.</i> , 2019; Poncetti <i>et al.</i> , 2025)	Local confirmation

Method	Physical basis	Directness for void detection	Main strength	Main limitation	Role in railway tunnels
Ultrasonic tomography	Elastic-wave transmission and imaging	High at local scale	Strong local evidence of internal condition or filling quality (Jorne, Henriques e Baltazar, 2014; Lu <i>et al.</i> , 2018)	Contact method with slower application and coupling requirements (Poncetti <i>et al.</i> , 2025)	Local confirmation and post-treatment verification
Infrared thermography	Surface thermal contrast	Low to moderate	Rapid-noncontact screening (Poncetti <i>et al.</i> , 2025)	Strongly dependent on thermal and moisture conditions	Indirect support
Laser scanning and photogrammetry	Active geometric capture and image-based reconstruction	Low	High-quality geometric and surface documentation (Poncetti <i>et al.</i> , 2025; Sjölander <i>et al.</i> , 2023)	Does not detect hidden voids directly	Geometric and surface support
Laser vibrometry	Remote measurement of vibration response	Low to moderate	Contactless assessment of surface detachment or dynamic response (Poncetti <i>et al.</i> , 2025)	Specialised and less established for void mapping and can be sensitive to field noise (Poncetti <i>et al.</i> , 2025)	Specialised support

Method	Physical basis	Directness for void detection	Main strength	Main limitation	Role in railway tunnels
Electrical resistivity tomography	Electrical resistivity contrast	Moderate	Good before-and-after change detection where filling alters physical properties (Vargemezis <i>et al.</i> , 2019, 2021)	Lower geometric sharpness and more complex logistics	Post-treatment verification
Seismic methods	Propagation of mechanical waves through materials	Moderate	Complementary evidence on change in treated zones (Vargemezis <i>et al.</i> , 2019, 2021)	Indirect and usually less precise for small void geometry	Post-treatment verification
Transient electromagnetic radar	Electromagnetic response interpreted through apparent resistivity contrast	Moderate	Useful for voids, poor contact and thickness anomalies in some tunnel lining studies (Geng, Ye e Wang, 2022; Ye <i>et al.</i> , 2020)	More specialised and less established than GPR (Ye <i>et al.</i> , 2020; Ye e Ye, 2019)	Specialised supplementary detection and verification

4.2 INTERPRETATION FOR OLD MASONRY-LINED RAILWAY TUNNELS

The comparative framework above is useful but it should not be interpreted as if all methods had been equally demonstrated on old masonry railway tunnels. Most of the evidence underlying these functional roles comes from concrete, segmental or generic tunnel studies. For masonry-lined tunnels, the main question is therefore not only which method is strongest in principle but also which methods have direct support and which must be transferred more cautiously from adjacent literature. The difference between the broader tunnel literature and the masonry-specific evidence can be summarised in Table 4.

Table 4 - Strength of evidence for transfer to the masonry case study

Method	Main role in concrete or generic tunnel literature	Direct support in masonry tunnels	Position for the present case study
GPR	Primary prospecting and, in some studies, post-grouting verification (Peng <i>et al.</i> , 2021; Zhang, Liu e Gong, 2008)	Clearest direct support, including old masonry diagnosis and brick-lined tunnel applications (Llanca, Breul e Bacconnet, 2017; McCormick, 2010)	Strongest masonry-supported method
Impact-based methods	Local confirmation and, in generic tunnel studies, local grouting evaluation (Aggelis, Shiotani e Kasai, 2008; Cao <i>et al.</i> , 2019)	Limited direct support. Brick-tunnel or masonry use appears but the evidence base is thinner than for GPR (Llanca, Breul e Bacconnet, 2017; McCormick, 2010)	Cautious transferred local method
UST	Local clarification and post-treatment verification (Jorne, Henriques e Baltazar, 2014; Lu <i>et al.</i> , 2018)	No clear direct old masonry railway tunnels validation retrieved. Support comes mainly from adjacent masonry studies (Jorne, Henriques e Baltazar, 2014; Zigler, 2019)	Plausible transferred method
Thermography, laser scanning, photogrammetry, laser vibrometry	Complementary inspection and surface-support roles (Poncetti <i>et al.</i> , 2025)	Little masonry-tunnel evidence for hidden-void or grout verification	Complementary tools only
ERT, seismic methods, TER	Supplementary before-and-after verification or specialised detection (Poncetti <i>et al.</i> , 2025; Vargemezis <i>et al.</i> , 2019, 2021; Ye <i>et al.</i> , 2020)	No direct masonry-tunnel validation retrieved	Cautious transfer only

For the present case study, this means that the use of GPR was technically reasonable and also the method with the clearest direct support for masonry tunnels (Llanca, Breul e Bacconnet, 2017). A more complete investigation framework could still have combined GPR with local confirmation methods but those additions should be presented as plausible transfers from non-masonry literature rather than as masonry-specific proven solutions.

The literature also supports a complementary relation between NDT and invasive investigation. In old masonry tunnels, NDT is useful for rapid prospecting and anomaly localization, while invasive methods remain necessary where direct confirmation or design-grade evidence is required (Llanca, Breul e Bacconnet, 2017).

4.3 NDT, GROUTING AND VERIFICATION

4.3.1 NDT and grout mix design

NDT does not determine grout composition directly but it helps define the geometry and likely condition of the void system to be filled. A better prospecting stage therefore strengthens the engineering basis for grout selection, especially where water condition, continuity and probable void influence the choice of mix (Axelsson, Gustafson e Fransson, 2009; Chuaqui e Bruce, 2003).

4.3.2 NDT and stop criteria

The literature on stop criteria makes clear that fixed pressure or volume limits alone do not by themselves prove adequate filling. Their interpretation depends on grout spread, flow behaviour and the response of the receiving medium. This means that the more the void system is understood beforehand, the more adequate the stop criteria are (Rafi e Stille, 2021; Stille *et al.*, 2009). NDT does not directly justify stop criteria but it helps define the physical context in which those criteria are interpreted. A more robust prospecting stage therefore strengthens the basis on which the filling criteria are later discussed.

4.3.3 NDT and verification of filling quality

A second and more direct connection relates to post-injection verification, since stop criteria mainly regulates the process of injection rather than proving the final state achieved, it is reasonable to question whether NDT could be used to support verification of proper filling.

- GPR has been used to evaluate grout distribution and identify insufficiently filled zones behind tunnel linings (Xie *et al.*, 2007; Yu *et al.*, 2016).
- UST has been used to assess grout consolidation, continuity or filling quality in treated areas (Jorne, Henriques e Baltazar, 2014; Lu *et al.*, 2018).
- Combined geophysical methods using ERT, GPR and seismic refraction have also shown that before-and-after treatment measurements can provide evidence of successful filling where anomalies disappear after injection (Vargemezis *et al.*, 2019, 2021).

For old masonry-lined tunnels, however, the retrieved evidence is more limited. The masonry literature supports NDT clearly for diagnosis before intervention and more broadly for before-and-after assessment of rehabilitation but not as strongly for direct validation of post-injection filling quality itself (Llanca, Breul e Bacconnet, 2017; McCormick, 2010). The safest conclusion is therefore that post-injection verification by UST or another NDT technique is technically plausible and supported by general tunnel literature but not equally demonstrated for old masonry railway tunnels (Jorne, Henriques e Baltazar, 2014; Zigler, 2019).

4.4 IMPLICATIONS FOR THE CASE STUDY

When the defined framework from the preceding sections is applied to the Douro Line project, three implications emerge that are relevant both to the assessment of the current works and to the design of future campaigns on comparable infrastructure.

1. The first concern relates to the 2008 inspection campaign that characterised the outer wall void geometry at the Douro Line tunnels using GPR predated the current electrification project by over a decade. The immediate pre-rehabilitation baseline was therefore built on direct invasive methods which provide reliable point-specific evidence but not spatial continuity across full tunnel lengths. A new GPR resurvey would have provided a continuous spatial picture within the operational constraints of the line, linking the confirmed invasive data points into a coherent void distribution map across the full lengths of all six tunnels (Lei *et al.*, 2023; Llanca, Breul e Bacconnet, 2017; Peng *et al.*, 2021).

2. The second implication concerns the interpretation of the defined stop criteria, namely maintained pressure at 0.2 MPa with an instantaneous flow rate below 500 L/h for fifteen seconds or a total absorption exceeding 1,000 L. These are operational controls whose meaning depends on what is known about the void system beforehand (Rafi e Stille, 2021; Stille *et al.*, 2009). Void mapping by continuous GPR would have reduced this ambiguity by indicating whether the treated section represented an isolated void or part of a more extensive interconnected system, thereby helping to interpret whether refusal response at a given borehole was evidence of completion or a signal for further investigation (Llanca, Breul e Bacconnet, 2017; Peng *et al.*, 2021).
3. The third implication concerns post-injection verification. The control drillings carried out at representative sections after grouting confirm filling condition at those locations, however, they remain localised and cannot provide spatial continuity between drilled points (Llanca, Breul e Bacconnet, 2017). A complementary post-injection GPR resurvey could provide coverage of those intervals and close the detect-inject-verify cycle with greater spatial confidence than control drillings alone can offer (Llanca, Breul e Bacconnet, 2017; Poncetti *et al.*, 2025; Zhang, Liu e Gong, 2008). UST could be considered in selected structurally important sections as a caution local verification method. This suggestion is based mainly on generic and concrete lining tunnel literature rather than on direct validation in old masonry railway tunnels (Jorne, Henriques e Baltazar, 2014; Lu *et al.*, 2018; Poncetti *et al.*, 2025).

4.5 CONCLUSION

The comparison supports a staged interpretation of NDT in railway tunnel rehabilitation but the evidential basis is unbalanced across lining types. Most of the functional hierarchy discussed in this chapter is derived from concrete and generic tunnel literature, where a broader range of methods has been tested for prospecting, local confirmation and post-treatment verification (Aggelis, Shiotani e Kasai, 2008; Jorne, Henriques e Baltazar, 2014; Poncetti *et al.*, 2025; Vargemezis *et al.*, 2019). For old masonry-lined tunnels, by contrast, direct support in the retrieved literature is clearest for GPR, while most other methods are better understood as cautious transferred options rather than masonry-specific proven solutions (Llanca, Breul e Bacconnet, 2017; McCormick, 2010; Poncetti *et al.*, 2025).

5

GROUT MIX DESIGN AND STOP CRITERIA

5.1 GROUT MIX DESIGN IN RAILWAY TUNNEL FOR VOID FILLING

In railway tunnel rehabilitation, the grout must move through hoses and boreholes, enter an irregular and often poorly known void system, resist washout where water is present, remain stable during pumping and then develop enough stiffness and strength to improve support or reduce leakage. A blend that performs well in one of these tasks may perform poorly in another. For that reason, grout selection is a design problem in which composition is matched to the geometry of the void, the state of the lining, the presence of water, the pumping distance and the intended function of the treatment (Chuaqui e Bruce, 2003; Wannenmacher, Entfellner e Hauer, 2022; Wright *et al.*, 2015).

However, in old railway tunnels the grout is often required to perform more than one function, as part of a wider rehabilitation package, involving (Kovačević, Bačić e Jurić Kaćunić, 2018; Mangabhai e Witchurch, 1999; Wright *et al.*, 2015):

- Drainage.
- Waterproofing.
- Local repair.
- Strengthening of the lining.

The pressure reached during injection, the rate at which grout take declines and the apparent refusal of the ground or void system are shaped not only by the geometry of the receiving space but also by water-to-cement ratio, rheology, filtration tendency and time dependent changes caused by hydration (Axelsson, Gustafson e Fransson, 2009; Draganović e Stille, 2011; Eklund e Stille, 2008; Rahman, Håkansson e Wiklund, 2015). In practice, this means that stopping parameters cannot be treated as universal values transferred unchanged from one grout to another. Initial pressure and volume limits may be informed by the known condition of the lining and the expected void system but their interpretation during the works must also take account of the selected grout, the injection records and the observed response of the treated tunnel zone.

Although the present case concerns a masonry-lined tunnel, most of the mix-design arguments are not confined to masonry linings. The broader grouting literature gives lining-independent evidence on rheology, filtration, bleeding, washout resistance, setting and temperature sensitivity (Bohloli *et al.*, 2019; Chuaqui e Bruce, 2003; Eklund e Stille, 2008).

Masonry-specific railway rehabilitation papers remain important for framing the practical context but much of the arguments also applies to concrete-lined and segmental tunnels (Cavalaro e Aguado, 2013; Kovačević, Bačić e Jurić Kaćunić, 2018; Mangabhai e Witchurch, 1999; Wright *et al.*, 2015).

5.2 FUNCTIONAL FAMILIES OF GROUT USED IN TUNNEL REHABILITATION

The tunnel rehabilitation literature does not point to a single preferred grout family, instead, it shows a recurring functional division between blends used for bulk filling, blends used for sealing or waterproofing and blends used for repair or strengthening, one blend is not expected to do everything equally well. The different grout families and their main characteristics are presented in Table 5.

Table 5 - Grout families characteristics

Grout family	Typical function	Main strengths	Main risks or limits
Plain cement suspension	Sealing, waterproofing, moderate filling (Chuaqui e Bruce, 2003; Wang <i>et al.</i> , 2024)	Simple and can be adapted by changing water-to-cement ratio	May bleed, filter, segregate or wash out if poorly designed (Draganovic, 2009; Gustin, Karim e Brouwers, 2007)
Cement, bentonite and sand mixes	Repair, void filling, support restoration (Cavalaro e Aguado, 2013; Chuaqui e Bruce, 2003)	Better stability and bulk than plain suspension. Can improve suspension behaviour	Higher viscosity can reduce penetrability. Sand segregation must be controlled (Cavalaro e Aguado, 2013; Chuaqui e Bruce, 2003)
Microfine cement grouts	Penetration into finer discontinuities or tighter pathways (Håkansson, Hässler e Stille, 1992)	Better entry into small apertures due to finer particles	Rheology and cost can be demanding. Performance still depends on filtration control (Eklund e Stille, 2008; Håkansson, Hässler e Stille, 1992)
Lightweight or plastic backfill materials	Large irregular void systems and long pumping distances (Cavalaro e Aguado, 2013; Khodaei <i>et al.</i> , 2025; Weiwei, Xiaoguo e Lujia, 2020)	Good pumpability over long distances. Useful where voids require bulk filling with controlled density	Final mechanical properties and quality retention during transport must be managed (Cavalaro e Aguado, 2013; Khodaei <i>et al.</i> , 2025; Weiwei, Xiaoguo e Lujia, 2020)
High mobility cement-based grouts with admixtures	Tailored injection where stability, anti-washout and controlled set are needed (Chuaqui e Bruce, 2003)	Can be engineered for low bleed, high filtration resistance and controlled rheology	Require more rigorous testing and quality control (Chuaqui e Bruce, 2003)

These families overlap but they clarify an important design principle: grout composition follows function. The key question is not which grout is strongest in the abstract but which grout best suits the void geometry, water regime, access conditions and rehabilitation objective.

5.3 FORMULATION VARIABLES IN GROUT DESIGN

5.3.1 Water and the water-to-cement ratio

Among all mix parameters, water content has the widest influence on grout behaviour. The water-to-cement ratio affects viscosity, yield stress, penetrability, bleeding, setting and final strength (Bohloli *et al.*, 2019; Rahman, Håkansson e Wiklund, 2015). A lower ratio usually produces a denser and stronger set material but it also raises viscosity and cohesion, which can make pumping and penetration more difficult, whereas a higher ratio improves fluidity, yet it tends to increase bleeding, reduce stability and lower final strength.

If the void system is broad and accessible, a relatively fluid mix may be acceptable or even advantageous. If the aim is to penetrate narrow pathways behind the lining or to follow complex routes, the grout must remain mobile without filtering prematurely.

This ratio also affects the stopping behaviour of cementitious grouts, which means that pressure development, grout take decline and apparent refusal cannot be interpreted independently of the chosen blend (Axelsson, Gustafson e Fransson, 2009). The same nominal mix does not behave the same way throughout the stages of pumping because hydration alters rheology with time, as illustrated in Figure 37 (Rahman, Håkansson e Wiklund, 2015).

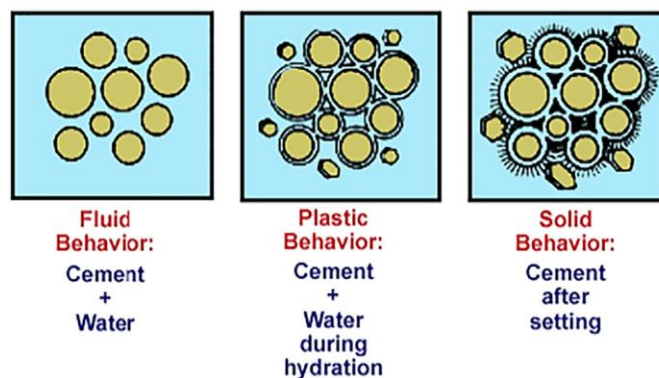


Figure 37 - Properties of cement grout during different stages of development (Bohloli *et al.*, 2019)

This is one reason why site practice in railway tunnels often remains observational, the pump pressure and grout intake observed on site are responses not only to the ground and void geometry but also to the evolving rheology of the injected mix (Wright *et al.*, 2015).

5.3.2 Cement type and grain size

Grain size distribution, specific surface area, mineralogy and hydration behaviour all influence rheology, bleed, setting time and strength development (Bohloli *et al.*, 2019; Håkansson, Hässler e Stille, 1992). Finer cements and microfine cements are especially important where the grout must enter small openings or tighter discontinuities. Their advantage lies not simply in lower apparent viscosity but in improved ability to pass through small openings before filter cake formation (Figure 38), that is, the accumulation of particle layer at a constriction that progressively blocks further flow, stops penetration (Draganović e Stille, 2011; Eklund e Stille, 2008; Håkansson, Hässler e Stille, 1992).

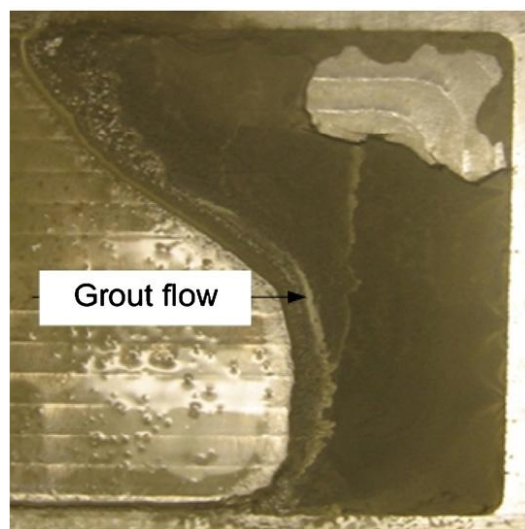


Figure 38 - Filter cake (Draganović e Stille, 2011)

The importance of cement choice also appears in temperature dependent behaviour. Different cements can behave very differently at tunnel temperatures, even when tested over the same water-to-cement ratios (Bohloli *et al.*, 2019). In railway tunnels, this can affect set time, bleeding and early strength in ways that matter directly for the rehabilitation works.

5.3.3 Bentonite, fillers and bulk stability

Bentonite and mineral fillers are introduced to change the suspension behaviour of the grout rather than merely to reduce cost. Bentonite can improve stability, reduce sedimentation and help keep particles in suspension, which is useful when the grout must remain uniform during pumping or while occupying larger void systems (Chuaqui e Bruce, 2003; Gustin, Karim e Brouwers, 2007).

Sand and other fillers may be used to increase bulk, modify stiffness or support a more economical filling of larger voids (Cavalaro e Aguado, 2013; Chuaqui e Bruce, 2003).

The grain size of fillers also matters. Coarser mixes may be better suited to bulk filling but larger particles reduce penetrability through narrow access paths and increase the risk of segregation or premature blockage (Cavalaro e Aguado, 2013; Chuaqui e Bruce, 2003; Eklund e Stille, 2008).

These benefits come with limits:

1. Bentonite generally increases viscosity and can lower ultimate strength if used excessively (Chuaqui e Bruce, 2003).
2. Sanded mixes can segregate if the suspension is not well designed, leading either to blockage during pumping or to a non-uniform final fill (Chuaqui e Bruce, 2003).
3. Bleeding in cement and cement-bentonite grouts is not a minor side issue. Water expulsion changes the effective fill and can reduce the ability of the grout to occupy the full target volume. In void filling behind tunnel linings, that is especially important because any settlement or bleed may leave residual unfilled space within the treated void, reducing the effectiveness of the filling operation (Gustin, Karim e Brouwers, 2007).

The railway literature therefore supports a simple but important principle: where larger crown voids or irregular chambers are present, bulk stability may matter more than maximising nominal strength. A slightly weaker but more stable fill can be more effective than a stronger mix that bleeds, filters or segregates before it has fully occupied the space.

5.3.4 Admixtures and rheology control

Chemical admixtures provide a further way to improve grout behaviour when water content and solid composition alone do not give the required balance. Much of the detailed evidence on these effects comes from broader cement-grout literature rather than only from direct tunnel case studies but the underlying mechanisms are relevant to tunnel void filling because they act on dispersion, cohesion, washout resistance, setting and permeability (Håkansson, Hässler e Stille, 1992; Liang *et al.*, 2025; Saric-Coric, Khayat e Tagnit-Hamou, 2003; Wang *et al.*, 2024). The most relevant admixtures functions are summarised in Table 6.

Table 6 - Admixtures functions, effects on grout behaviour and relevance to void filling

Admixture function	Main effect in grout behaviour	Relevance to void filling
Plasticizers and superplasticizers	Improve particle dispersion and mobility at lower water demand (Håkansson, Hässler e Stille, 1992; Saric-Coric, Khayat e Tagnit-Hamou, 2003)	Useful where pumpability and penetrability are limiting
Viscosity modifiers and cohesion-enhancing admixtures	Increase cohesion, reduce washout and reduce forced bleeding (Saric-Coric, Khayat e Tagnit-Hamou, 2003)	Useful in wet conditions or where stability after placement is critical
Set accelerators	Shorten setting time and may improve early hardening (Chuaqui e Bruce, 2003; Wang <i>et al.</i> , 2024)	Useful where faster stabilisation or water control is needed
Retarders	Extend workable time during pumping (Chuaqui e Bruce, 2003)	Useful where transport distance or injection duration is long
Waterproofing or permeability-reducing admixtures	Improve sealing and reduce permeability (Wang <i>et al.</i> , 2024)	More relevant where seepage reduction is a major objective

This classification is more useful than treating admixtures as a single group. Some are intended mainly to improve mobility, whereas others are used to increase cohesion, limit washout, control set or improve sealing performance (Chuaqui e Bruce, 2003; Liang *et al.*, 2025; Saric-Coric, Khayat e Tagnit-Hamou, 2003; Wang *et al.*, 2024). A workable grout is not simply the one with the lowest viscosity but the one with the right balance of mobility, stability and time-dependent behaviour for the receiving void system (Chuaqui e Bruce, 2003).

5.4 RESULTING GROUT BEHAVIOUR

5.4.1 Filtration resistance and penetrability

One of the strongest themes in the broader grouting literature is that grout movement is often limited less by nominal viscosity than by filtration. When solid particles accumulate and form a filter cake, the grout may stop penetrating even though it still appears fluid in bulk tests (Draganović e Stille, 2011; Eklund e Stille, 2008). This is crucial for filling in irregular tunnel voids systems. A grout that filters early may create the illusion of refusal while leaving parts of the void system untreated.

Penetrability is therefore a function of both grout properties and the geometry of the receiving paths (Draganović e Stille, 2011; Eklund e Stille, 2008; Jorne e Henriques, 2016). The key problem is not simply getting grout into a visible cavity but getting it through the narrower access paths that connect the borehole to the wider hidden void system.

This also clarifies why microfine cements or well dispersed high mobility grouts can be valuable in some rehabilitation settings. Their advantage lies not merely in being more fluid but in being less prone to premature blockage when the access routes are narrow.

5.4.2 Bleeding, segregation and anti-washout behaviour

Stability after pumping is as important as mobility during pumping. Bleeding reduces effective filling and may leave residual voids at the top of the treated zone (Draganovic, 2009; Gustin, Karim e Brouwers, 2007).

Segregation changes the local composition of the grout, producing a non-uniform fill with uncertain mechanical properties (Chuaqui e Bruce, 2003). In tunnels with active water ingress, the risk is even greater because moving water can erode or dilute the fresh grout before setting.

These issues are directly relevant to old railway tunnels affected by seepage where water ingress is a central driver of masonry deterioration, freeze thaw risk and broader serviceability problems (Mangabhai e Witchurch, 1999). More recent grout studies treat injection partly as a waterproofing and anti-seepage problem in water-affected tunnel environments. In this context, a grout blend must be judged partly by its resistance to washout and its ability to remain in place after placement (Chuaqui e Bruce, 2003; Wang *et al.*, 2024). A thixotropic grout that flows under pumping but gains cohesion rapidly once flow ceases may be better suited to water affected voids than a highly fluid grout that continues to run away from the intended zone.

5.4.3 Setting behaviour, strength development and compatibility with the lining system

Set time is often treated as a secondary parameter but the literature suggests that it has direct practical importance (Bohloli *et al.*, 2019; Chuaqui e Bruce, 2003):

- If the grout sets too slowly, it may bleed, migrate or remain unable to provide timely support.
- If it sets too quickly, pumping and distribution become difficult, particularly over long transport distances.

Final strength also has to be interpreted in context. Some void-filling operations mainly require the grout to remain in place and restore contact behind the lining, whereas others also require it to harden into a stronger repair material (Chuaqui e Bruce, 2003; Wang *et al.*, 2024; Weiwei, Xiaoguo e Lujia, 2020).

Compatibility with the lining system matters for the same reason. The grout should suit not only the void geometry but also the mechanical role it is expected to play within the lining system. In an old masonry tunnel, a grout that is excessively strong, brittle or unstable may be less suitable than a weaker but more stable material that achieves better contact and volume retention. More broadly, tunnel grout studies show that formulation affects both filling quality and the way loads may later be transferred to the lining (Bezuijen e Talmon, 2006).

5.5 HOW RAILWAY REHABILITATION EVIDENCE FITS THE MECHANICS

The railway case literature becomes easier to interpret once these mechanics are made explicit. Existing cases describe a strongly observational approach to void grouting, in which mix behaviour, water conditions, pumping response and grout intake are read together rather than through fixed universal rules. In the practical literature, mix design is often presented empirically, through case experience and adjustments during the works, rather than through a shared formal design framework (Kovačević, Bačić e Jurić Kaćunić, 2018; Wannenmacher, Entfellner e Hauer, 2022; Wright *et al.*, 2015). This does not make mix design secondary. It reflects the fact that field performance depends on the interaction between formulation, void geometry, seepage and injection procedure.

The practical literature also supports a functional division between blends used mainly for bulk filling, blends used mainly for sealing or waterproofing and blends used where improved repair or contact is required (Cavalaro e Aguado, 2013; Chuaqui e Bruce, 2003; Wang *et al.*, 2024; Weiwei, Xiaoguo e Lujia, 2020). The same grout may contribute to more than one outcome but the design starting point remains the primary function of the intervention.

5.6 IMPLICATIONS FOR THE DOURO LINE CASE STUDY

1. The project documentation presents the intervention primarily as void filling behind the masonry lining. At the same time, filling those voids may also help restore contact, reduce seepage pathways and provide local support benefits where conditions allow. The main design purpose is therefore described as void filling, while recognising that the operation may also serve related sealing and support functions.
2. The baseline formulation consists of cement, fine sand, bentonite and water, with cement-to-sand and water-to-cement ratios of 1 and a bentonite dosage of 6 kg per 100 kg of cement, belonging most closely to the cement, bentonite and sand family associated with void filling, repair and support restoration. This points to a design logic closer to stable bulk void filling than to very fine fissure permeation. The inclusion of sand suggests volume filling, while the bentonite dosage suggests a concern with suspension stability during pumping and placement (Cavalaro e Aguado, 2013; Chuaqui e Bruce, 2003).
3. The specified water-to-cement ratio of 1 suggests that fluidity and pumpability were given substantial weight which is consistent with the need to pass through masonry access paths and reach irregular void systems under a maximum injection pressure of 0.2 MPa. At the same time, such ratio raises concerns regarding bleeding, segregation and lower final strength if not controlled by the rest of the formulation and by site quality control (Bohloli *et al.*, 2019; Gustin, Karim e Brouwers, 2007; Rahman, Håkansson e Wiklund, 2015).

4. The cement requirements on fineness and setting time fit the same logic. Fineness limits support dispersion and movement through restricted paths, while a setting time of not less than three hours suggests that premature loss of workability during pumping was to be avoided (Bohloli *et al.*, 2019; Håkansson, Hässler e Stille, 1992). The project documents also make clear that the baseline formulation was only a starting point. Laboratory validation was intended to fix the most suitable proportions for each case based on compressive strength, density, viscosity and volumetric variation, with provision for chemical admixtures if justified by testing and approved by supervision, however, the reviewed documentation does not establish whether any specific product or dosage was actually adopted in the executed works.
5. The possibility of progressively increasing grout density during injection and of increasing sand dosage where high absorption volumes were detected, shows that the project treated mix design as an adaptive field process rather than as a fixed recipe. This is closely aligned with the observational logic described in railway grouting practice (Chuaqui e Bruce, 2003; Wright *et al.*, 2015).

No fresh or hardened state test results for the executed Douro Line blend were available for review and no injectability trial records or post-injection laboratory results were available within the scope of this dissertation. The assessment of the formulation is therefore qualitative. Even so, the specification logic is coherent with the literature: the selected baseline mix prioritises pumpability, bulk occupancy and suspension stability in a masonry void-filling context, while retaining scope for empirical adjustment during the works.

5.7 CONCLUSION

The significance of grout mix design in railway tunnel void filling is that the grout serves not only as a vessel for cement into an empty space, it is the medium through which the intervention succeeds or fails. Water content, cement fineness, fillers, bentonite, admixtures and temperature all influence mobility, stability, penetrability, set and structural effect (Bohloli *et al.*, 2019; Eklund e Stille, 2008; Rahman, Håkansson e Wiklund, 2015).

Railway rehabilitation evidence adds that these properties must be interpreted in relation to uncertain void geometry, seepage and observational field control (Kovačević, Bačić e Jurić Kaćunić, 2018; Mangabhai e Witchurch, 1999; Wright *et al.*, 2015).

For the present masonry-lined case, the strongest conclusion is not that one universal grout mix exists but that the selected formulation should be read against the function of the intervention, whether that being improving sealing performance, limiting washout, stabilising larger voided zones or maintaining pumpability and quality over the course of injection (Cavalaro e Aguado, 2013; Wang *et al.*, 2024; Wannenmacher, Entfellner e Hauer, 2022; Wright *et al.*, 2015).

In the Douro Line project documentation that function is defined primarily as void filling. The specified baseline mix is consistent with that aim and with the wider literature on stable cementitious filling grouts, even though the absence of project-specific test results limits the assessment to a qualitative one.

The chapter's central claim therefore remains that grout design is a primary engineering decision in railway tunnel rehabilitation and that its suitability depends on how well it matches the void system, water regime, lining condition and operational purpose of the works.

6

CONCLUSIONS AND FUTURE PERSPECTIVES

6.1 CONCLUSIONS ON GROUT MIX DESIGN

The grout mix design literature reviewed in this dissertation leads to a consistent conclusion: the grout is the primary medium determining the success of the intervention. The composition of the mix determines whether the grout can enter the void system, remain stable during placement, resist washout where water is present and develop adequate hardened properties to fulfil its structural function.

Among all mix parameters, the water-to-cement ratio has the widest influence on performance because it affects viscosity, penetrability, bleeding, setting and final strength at the same time. In old masonry railway tunnels, where void geometry is irregular and access paths may be narrow and uncertain, this interdependence means that workability cannot be adjusted simply by adding water without potentially increasing bleeding and reducing stability and strength. A more defensible approach is to treat workability as a balance between water content, cement fineness, suspension stability and, where appropriate, admixture use.

Cement type and particle size also influence the grout's ability to pass through restricted openings behind the lining. Where access conditions are relatively open, ordinary cement suspensions may be adequate, whereas finer or microfine cements are more appropriate where narrower flow paths control penetration. The literature also shows that penetrability is often limited less by apparent bulk viscosity than by filtration and filter cake formation, so a grout that appears sufficiently fluid in laboratory tests may still stop penetrating if its particle size is too large relative to the pathway aperture.

Bentonite and fillers mainly affect suspension stability rather than nominal strength. Their value lies in limiting sedimentation, helping to keep solid particles uniformly suspended during pumping and improving the ability of the grout to occupy larger irregular voids. However, excessive bentonite dosage raises viscosity and reduces long-term compressive strength, while any settlement or bleeding may leave residual unfilled space within the treated void, reducing the effectiveness of the filling operation.

Anti-washout resistance is particularly important in old railway tunnels affected by seepage. The masonry tunnels of the Douro Line are excavated through jointed granite in the Douro valley and are associated with seasonal water ingress, so a grout that flows adequately during pumping but lacks sufficient cohesion after placement may be partially displaced or diluted by moving water before it sets. Treating washout resistance as a relevant design consideration is therefore justified for these conditions.

Setting behaviour must be matched to the actual tunnel temperature and the length of the pumping route. Laboratory optimisation at room temperature can underestimate the acceleration of set at the lower in-situ temperatures typical of old railway tunnels or over-predict the available workability time where long delivery distances are involved. This supports the project requirement for laboratory validation of the starting formulation under conditions representative of the works.

The baseline formulation adopted in the Douro Line project (cement-to-sand and water-to-cement ratio of 1 and bentonite at 6 kg per 100 kg of cement) belongs most closely to the cement, bentonite and sand family associated in the literature with void filling, repair and support restoration. In functional terms, it is better interpreted as a grout for stable bulk void filling than for fine fissure permeation. The sand at a 1 to 1 ratio with cement provides bulk fill of larger cavities and limits excessive migration of the grout within connected void systems, while the bentonite dosage supports suspension stability during pumping and placement.

The main tension in the Douro Line baseline formulation lies in the water-to-cement ratio of 1. This ratio ensures adequate fluidity for pumping and distribution through irregular masonry void systems under a maximum injection pressure of 0.2 MPa but it also increases the risk of bleeding and reduced final strength if not balanced through the rest of the mix design and by site validation. The project specifications acknowledge this directly by permitting progressive adjustment of the mix during works, including an increase in sand content where large absorption volumes are observed and by requiring laboratory validation of the starting formulation before injection begins. This adaptive observational approach is consistent with what the literature identifies as the most appropriate framework for void filling in old masonry tunnels.

The reviewed documentation does not show that chemical admixtures were used in the executed grout but it does show that their use was anticipated and regulated within the project specifications. Admixtures therefore formed part of the admissible mix-design framework, even though their actual adoption and performance in the Douro Line works could not be confirmed from the available records. The assessment of the project formulation is therefore necessarily qualitative rather than test based.

The main conclusion is that the Douro Line baseline mix is compatible with a void-filling function in old masonry tunnels, especially where stable occupation of larger hidden voids is the main objective. Its main limitation is not that it contradicts the grouting literature but that the project-specific laboratory and injection records were not available for review within the scope of this dissertation. This prevents a more rigorous assessment of how well the chosen balance between mobility, stability, penetrability and hardened performance was achieved in practice.

6.2 CONCLUSIONS ON NDT METHODS AND THEIR APPLICABILITY

The comparative analysis of non-destructive testing methods shows that no single technique is universally best for all stages of tunnel void assessment. A staged approach is more appropriate, separating prospecting, local confirmation and post-treatment verification and selecting methods according to the purpose of each phase. This conclusion is well supported in concrete and generic tunnel literature, where multimethod NDT frameworks are more developed.

For old masonry-lined tunnels, however, the evidence is scarcer. In the retrieved literature, direct support is clearest for ground-penetrating radar, while most other methods are supported mainly by cautious transfer from concrete, segmental or generic tunnel studies.

GPR therefore remains the most suitable primary prospecting method for hidden void detection in old railway tunnels. Its main advantage is the combination of useful depth of investigation with continuous spatial coverage, making it the only method capable of providing a systematic picture of anomaly distribution over full tunnel lengths within the operational constraints of railway possessions. Even so, interpretation in masonry is more uncertain than in concrete, because the heterogeneous assembly of masonry units, mortar joints, degradation and variable moisture conditions generates complex overlapping reflections. GPR should therefore be understood mainly as a detection and mapping tool rather than as a precise geometric measurement tool.

Impact-echo and ultrasonic tomography offer stronger local evidence where a suspicious zone requires confirmation with greater confidence or where selected treated sections require closer checking. Their value lies in local assessment of stiffness change, discontinuity or internal condition, not in long-length tunnel prospecting. In concrete and generic tunnel literature, these methods are well established as confirmatory or verification tools. In old masonry-lined tunnels, by contrast, they should be recommended more cautiously, as plausible transferred methods rather than as masonry-specific proven solutions.

Electrical resistivity tomography, seismic refraction and related geophysical methods are more suited to before-and-after comparison than to primary prospecting, since their main strength lies in detecting physical change in the treated zone.

Infrared thermography, laser scanning and photogrammetry support condition assessment through surface documentation, geometric control and visible moisture or deterioration mapping but they are not primary methods for hidden void detection.

It should also be noted that GPR did not form part of the immediate preparatory investigation programme of the current rehabilitation project. The execution project relied mainly on direct methods, including visual inspection, trial pits, rotary core drillings, LDP tests, seismic refraction at selected portals, laser scanning and geomechanical classification. These methods provide physically reliable but point-specific information on lining condition, thickness and void geometry at the investigated locations. The earlier 2008 GPR campaign therefore contributed background spatial knowledge but the immediate pre-rehabilitation characterization was based mainly on direct investigation.

Post-injection verification in the project was carried out through rotary core drillings at representative sections. This is a physically reliable direct method for confirming grout presence and bonding at the drilled points but it remains inherently local and cannot provide continuity between those locations or identify residual unfilled zones in the intervals between them.

For future rehabilitation campaigns in old masonry-lined tunnels, the most complete verification strategy would therefore combine direct control drillings with complementary NDT. In that context, repeat GPR is the clearest masonry-supported option for wider interval coverage, while UST may be considered at selected critical sections as a cautious local verification tool supported mainly by broader tunnel literature rather than by strong direct masonry-tunnel validation.

Direct validation evidence for post-injection verification in old masonry-lined tunnels remains limited in the retrieved literature. Even so, taken together, tunnel studies on GPR and UST and masonry studies on grout-consolidation assessment support the view that post-injection verification is technically feasible in masonry-lined tunnels, although it should still be presented as a cautious inference rather than as a firmly established masonry-specific result.

6.3 INTEGRATION OF GROUT DESIGN AND NDT WITHIN A REHABILITATION FRAMEWORK

The main conclusion linking the two analytical chapters of this dissertation is that grout mix design and non-destructive testing are not independent technical domains within tunnel rehabilitation, they are part of a single intervention framework in which the output of each phase informs the quality and appropriateness of the next. The characterisation of the void system shapes the grout selection, grout behaviour during injection informs the interpretation of stop criteria and post-injection verification, whether by invasive drillings or NDT, determines whether the intended change in structural condition has been achieved.

The degree to which the void geometry and continuity are understood before injection directly conditions the formulation for the chosen grout. A well-characterised void system, one in which the size, location, likely interconnection and water regime are known with reasonable confidence, allows the blend to be selected for function. This may mean that a stable high-mobility mix for large connected voids, a low-bleed anti-washout formulation for water-active zones or a more cement-rich or superplasticised blend where narrow access pathways demand lower filtration tendency. In this sense, grout design is better understood not as a fixed recipe chosen once before the works begin but as an adaptive field process constrained by prospecting data, laboratory validation and observed injection response.

The deployment of a substantial multi-method investigation programme as the preparatory basis for the rehabilitation works, together with the grout formulation adopted in the Douro Line project specifications as an empirical starting point requiring laboratory validation before execution and allowing adaptive adjustment during the works, is consistent with the literature's emphasis on linking void diagnosis with adaptive grout design in old masonry tunnels.

The stop criteria used during injection (maintenance of 0.2 MPa with an instantaneous flow rate of less than 500 L/h for 15 seconds or a total absorption of 1,000 L) are operational controls on the injection process, not direct measurements of what has been achieved in the void. Their interpretation depends entirely on the effectiveness of void characterisation: what is known about the size, geometry and connectivity of the void systems being treated.

A limit pressure reached after modest injection may signal successful filling in a small discrete void but the same response in a large or interconnected void system may indicate premature filter cake formation or grout migration away from the target zone. This context is precisely what the pre-injection investigation programme is designed to establish. The documentation of the observed pressure-flow-time history at each borehole, alongside the void characterisation data, is therefore essential for understanding injection behaviour retrospectively and for informing future works in comparable tunnels.

Post-injection verification closes this cycle by providing a physical basis for assessing whether the intended change in condition behind the lining has occurred across the treated zone, complementing the point-specific evidence provided by control drillings.

In the Douro Line project control drillings were executed at representative sections after injection, confirming filling at those locations. The project therefore included a verification stage based on direct physical evidence, even though the corresponding core records were not available for analysis within the scope of this dissertation. A detect-inject-verify logic can thus be identified in the project framework and execution sequence. Future improvement should focus not on replacing the direct drilling checks already carried out but on complementing them with NDT-based spatial verification capable of extending confidence between verification points.

A final qualification is nevertheless needed. This integrated framework is strongly supported at the level of general tunnel rehabilitation but for old masonry railway tunnels the direct evidential base remains unbalanced. Within the retrieved literature, the strongest direct support is attached to GPR, while the use of other post-treatment NDT methods remains more dependent on cautious transfer from broader tunnel evidence. The integration proposed here is therefore well grounded as an engineering framework but some of its verification components remain better supported in generic tunnel literature than in masonry-specific railway case evidence.

The modernisation of the Douro Line is a project of considerable historical and technical significance. The tunnel rehabilitation works carried out during the first suspension period represent a substantial contribution to the preservation of infrastructure whose construction, in the 19th century, reflected the most ambitious civil engineering of its time. The application of a systematic NDT and grout design framework to such works is not merely a technical refinement, it is a means of ensuring that interventions of this scale and cost are executed with the level of diagnostic confidence that the age, complexity and irreplaceability of these structures require.

6.4 LIMITATIONS OF THE PRESENT WORK

Several limitations of this dissertation should be acknowledged so that the conclusions can be understood clearly.

The geotechnical characterisation of the Douro Line tunnels prior to the rehabilitation works was built from multiple investigation campaigns conducted over an extended period. These included a 2008 inspection campaign with GPR surveys and core drillings, a series of IP Asset Management routine inspections and a dedicated execution project investigation programme using visual inspection, trial pits, rotary core drillings, LDP tests, seismic refraction, laser scanning and geomechanical classification.

The primary investigation basis for the execution project was therefore a multimethod direct programme rather than the GPR campaign alone, which predated the current project by over a decade. The GPR scan records were not available for direct analysis within the scope of this dissertation. The conclusions drawn regarding void conditions and their implications for grout selection are therefore based on the project documentation and on the literature reviewed rather than on independent analysis of the investigation records.

A broader limitation concerns the evidential base for NDT methods in old masonry railway tunnels. Much of the retrieved method-specific literature on void detection, grouting assessment and post-treatment verification comes from concrete, segmental or otherwise generic tunnel linings rather than directly from old masonry railway tunnels. Some parts of the interpretive framework developed in this dissertation therefore rely on cautious transfer from adjacent tunnel literature rather than on repeated validation in masonry railway cases.

Post-injection verification by rotary core drillings was carried out on site at representative sections of the treated tunnels, confirming the filling condition at those locations. The drilling records and any associated laboratory testing on recovered cores were not reviewed within the scope of this dissertation. The discussion of post-injection verification quality is therefore qualitative and literature based.

The grout mix design discussion is based on the published literature and on the specification parameters in the project. No laboratory test results from the specific Douro Line blend have been analysed. The assessment of the formulation's suitability relative to the mix design literature is therefore qualitative. A more rigorous comparison would require the actual fresh and hardened state test results from the works, which form part of the injection quality control records supervised by LNEC and were not available for publication.

A related limitation concerns chemical admixtures. The project specification framework allowed for their use and defined the conditions under which they could be evaluated and approved but it did not establish a specific admixture product, type or dosage as part of the baseline void-filling grout.

Admixtures were treated instead as a possible component to be fixed through the pre-injection laboratory study. Whether that study, as executed for the Douro Line tunnels, actually adopted any admixture is not established by the documentation reviewed for this dissertation, since the injectability trial records and associated laboratory reports were not available. The discussion of admixtures in this dissertation is therefore limited to the provision made for them in the specification framework, rather than to their demonstrated use or non-use in the executed works.

For these reasons, the present work should be read as a structured interpretation of the available project documentation and relevant literature, rather than as a full quantitative performance assessment of the executed intervention.

6.5 RECOMMENDATIONS FOR FUTURE WORKS

Based on the findings of this dissertation, four recommendations are offered for future railway tunnel rehabilitation projects with comparable characteristics to the Douro Line electrification works.

1. First, the multi-method investigation framework deployed in the current project of combining visual inspection, trial pits, core drillings, seismic refraction profiling, laser scanning and geomechanical classification provides a strong model for comparable rehabilitation works. Future projects should maintain this range of direct investigation and additionally incorporate ground-penetrating radar as a dedicated non-destructive testing component of the pre-rehabilitation programme. Among the methods reviewed in this dissertation, GPR is the best-supported tool for the systematic detection of hidden voids over extended tunnel lengths and the one with the clearest direct support in old masonry railway tunnels. Its inclusion alongside direct investigation methods would provide continuous spatial coverage that point-based methods alone cannot offer. Where existing GPR surveys are outdated, a targeted resurvey at sections of priority concern should be carried out.
2. Second, at sections identified as critical through the investigation programme, whether it being locations with active water ingress, documented structural deformation or evidence of large or interconnected void systems, selective local complementary testing such as ultrasonic tomography may be considered in addition to core drillings. Within the literature reviewed in this dissertation, this is a more cautious recommendation than that made for GPR, since the support for UST in old masonry railway tunnels remains less direct and depends partly on transfer from broader tunnel literature and adjacent masonry evidence. Even so, at critical sections where uncertainty remains high after the main investigation programme, such local testing may help refine the interpretation of hidden anomalies and strengthen the basis for intervention planning.

3. Third, the control core drillings carried out in the Douro Line project after grouting represent a sound approach to point-specific verification that may be complemented, at selected representative sections, by post-injection spatial verification using GPR. In this role, GPR should not be treated as a substitute for direct verification or as definitive proof of complete filling but rather as a means of improving confidence in the intervals between drilled points and extending the spatial reading of the treated zone. This recommendation should be interpreted with some caution, since the support for post-injection NDT verification in old masonry railway tunnels is less direct than the support for pre-injection prospecting and relies more heavily on broader tunnel literature. Even so, where justified, such a complementary check could strengthen the overall verification framework.
4. Fourth, the systematic documentation of injection records, including pressure-flow-time histories, grout volumes per borehole and records where stop criteria were met, together with fresh and hardened state quality-control test results, is already standard practice in the current project and is being supervised within the quality-control framework of the works. The recommendation for future projects is not simply that these records continue to be collected but that they be used for retrospective integrated technical review at the conclusion of the intervention, linked spatially to the corresponding pre-injection investigation data and post-injection verification results. Such an approach would allow a more rigorous assessment of whether moments where the stop criteria were met were consistent with the void conditions established by the investigation and with the behaviour of the selected grout. It would also produce transferable technical knowledge directly applicable to future rehabilitation works on comparable railway infrastructure.

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