

Comparative Evaluation of Waterproofing Systems Used in Railway Tunnel Construction: Performance, Durability, and Engineering Applications

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Abstract

Groundwater ingress is one of the most significant challenges affecting the durability, safety, and service life of railway tunnels. Effective waterproofing systems are therefore essential to prevent seepage, reduce hydrostatic pressure, and protect tunnel linings from deterioration. This review comparatively evaluates the major waterproofing systems used in railway tunnel construction, including polyvinyl chloride (PVC) membranes, spray-applied waterproofing membranes, drainage systems, and grouting techniques. Their material characteristics, installation methods, durability, engineering performance, and suitability under different geological conditions are critically examined. The review also discusses common causes of waterproofing failure and highlights the importance of integrating waterproofing with efficient drainage and quality control measures. Based on the comparative assessment, recommendations are provided to support the selection of appropriate waterproofing systems, thereby improving the long-term performance, reliability, and sustainability of railway tunnel infrastructure.

Keywords: Railway tunnels; Waterproofing systems; Groundwater ingress; PVC membrane; Spray-applied waterproofing; Drainage systems; Grouting; Tunnel durability

Introduction

The rapid expansion of railway transportation networks has become a fundamental component of sustainable economic development, enabling efficient movement of passengers and freight while reducing travel time and environmental impacts (Cazzuffi et al., 2023). As railway corridors increasingly traverse mountainous terrains, densely populated urban areas, and environmentally sensitive regions, tunnel construction has become an indispensable engineering solution for maintaining optimal alignment, minimizing gradients, and overcoming topographical constraints (Dammyr et al., 2014). Modern railway tunnels are expected to provide uninterrupted service for more than a century under complex geological and hydrogeological conditions, making their long-term structural integrity a critical aspect of infrastructure sustainability.

Among the various challenges encountered during tunnel construction and operation, groundwater ingress remains one of the most persistent and technically demanding problems (Du et al., 2022). Excavation disturbs the natural

hydrogeological equilibrium, creating preferential pathways for groundwater to flow toward the tunnel cavity. Continuous water infiltration can generate hydrostatic pressure behind tunnel linings, promote corrosion of reinforcement, accelerate concrete deterioration, induce cracking, and increase maintenance requirements throughout the service life of the structure. Furthermore, excessive seepage may compromise operational safety by affecting railway equipment, electrical installations, and track stability. Consequently, effective waterproofing has evolved from a supplementary construction practice into a fundamental design requirement for ensuring tunnel durability, safety, and operational reliability (Li et al., 2018).

Modern tunnel waterproofing relies on integrated systems comprising impermeable membranes, drainage layers, geotextiles, grouting materials, and protective concrete linings. Among these technologies, polyvinyl chloride (PVC) waterproofing membranes have become the most widely adopted solution due to their excellent flexibility, chemical resistance, low permeability, and long service life. Spray-applied waterproofing membranes have also gained considerable attention because they form seamless bonded barriers capable of accommodating complex tunnel geometries and irregular excavation profiles. In addition, sodium bentonite waterproofing systems, high-density polyethylene (HDPE) membranes, crystalline waterproofing materials, and advanced chemical grouting techniques are increasingly employed to address diverse geological and groundwater conditions. However, the effectiveness of these systems depends not only on material properties but also on installation quality, seam integrity, drainage efficiency, and compatibility with the surrounding geological environment (Wang et al., 2025).

Recent advances in tunnel engineering have emphasized the importance of integrating waterproofing with comprehensive groundwater management strategies. Rather than relying solely on impermeable barriers, modern tunnel designs incorporate drainage networks consisting of geotextile filters, drainage composites, and perforated pipelines to relieve hydrostatic pressure and safely discharge infiltrating groundwater. Such integrated waterproofing–drainage systems significantly reduce mechanical stresses acting on tunnel linings and improve long-term structural performance (Pelz et al., 2022). Nevertheless, field experience demonstrates that waterproofing failures continue to occur in many railway tunnels due to inadequate material selection, poor installation practices, defective welding, insufficient quality control, drainage clogging, and unfavourable geological conditions. These failures frequently result in costly repair operations, service interruptions, and reduced infrastructure durability (Zhang et al., 2023). Numerous researchers have investigated individual waterproofing materials and drainage technologies for underground structures. Previous studies have reported the superior permeability and durability of PVC membrane systems, the adaptability of spray-applied waterproofing in complex geometries, and the effectiveness of drainage systems in reducing groundwater pressure acting on tunnel linings (Zhou et al., 2020). Other investigations have highlighted the importance of proper joint sealing, grouting techniques, and quality assurance during construction for minimizing leakage-related failures. Despite these significant developments, existing literature primarily evaluates individual waterproofing technologies

under laboratory conditions or focuses on specific engineering applications. Comprehensive comparative assessments considering material performance, installation requirements, durability, maintenance, cost-effectiveness, and field applicability under actual railway tunnel construction conditions remain relatively limited (Su et al., 2019).

Considering these limitations, a systematic evaluation of commonly used tunnel waterproofing systems is essential for improving engineering decision-making during railway tunnel construction. Comparative assessment of available technologies can assist engineers in selecting appropriate waterproofing solutions according to geological conditions, groundwater characteristics, construction methods, and long-term operational requirements. Such evaluations also contribute to identifying practical challenges encountered during installation and provide guidance for improving construction quality and maintenance strategies.

Therefore, the present study aims to comparatively evaluate the waterproofing systems commonly employed in railway tunnel construction, with particular emphasis on PVC waterproofing membranes, spray-applied waterproofing systems, drainage networks, and grouting techniques. The study critically examines their material characteristics, installation procedures, engineering performance, durability, maintenance requirements, and suitability under different underground conditions. Furthermore, the study identifies current challenges associated with tunnel waterproofing and proposes recommendations for enhancing groundwater control, improving structural durability, and ensuring the long-term operational reliability of railway tunnel infrastructure.

Material and methods

Review Methodology

This study employed a comprehensive narrative review approach to critically evaluate waterproofing systems used in railway tunnel construction. The review aimed to synthesize current knowledge on waterproofing materials, installation techniques, drainage systems, performance characteristics, durability, and engineering challenges associated with groundwater control in underground railway infrastructure. Rather than relying on a single technology, this review comparatively assessed the most commonly adopted waterproofing systems to identify their advantages, limitations, and suitability under varying geological and hydrogeological conditions.

A systematic literature search was conducted using internationally recognized scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, and publications from the International Tunnelling and Underground Space Association (ITA-AITES). Peer-reviewed journal articles, conference proceedings, technical reports, engineering manuals, and international standards published between 2000 and 2025 were considered, with particular emphasis on recent publications (2015–2025) to capture the latest

developments in tunnel waterproofing technologies. The literature search was performed using combinations of the following keywords: railway tunnel, tunnel waterproofing, PVC waterproofing membrane, HDPE geomembrane, spray-applied waterproofing membrane, bentonite waterproofing, tunnel drainage system, groundwater control, chemical grouting, tunnel lining, water ingress, waterproofing durability, and underground infrastructure. Boolean operators (AND, OR) were used to refine the search and improve retrieval of relevant publications.

Selection Criteria

The collected literature was screened based on relevance to railway and transportation tunnel waterproofing. Studies were included if they provided information on waterproofing materials, installation procedures, drainage technologies, waterproofing performance, failure mechanisms, durability, maintenance strategies, or field applications in underground infrastructure. Publications focusing on unrelated underground structures, duplicate reports, or studies lacking sufficient technical information were excluded from the review.

Data Extraction and Comparative Analysis

Relevant information was extracted from the selected studies, including waterproofing material type, installation methodology, mechanical and hydraulic properties, durability, groundwater resistance, maintenance requirements, construction challenges, and reported field performance. The extracted data were organized and comparatively analysed to evaluate the strengths and limitations of different waterproofing systems. Particular attention was given to polyvinyl chloride (PVC) membranes, high-density polyethylene (HDPE) membranes, spray-applied waterproofing membranes, bentonite-based systems, drainage composites, and grouting technologies. Comparative evaluation considered engineering performance, ease of installation, adaptability to varying geological conditions, long-term durability, maintenance requirements, and overall suitability for railway tunnel construction.

Scope

The scope of this review was limited to waterproofing systems used in railway tunnels and associated underground transportation infrastructure. The discussion focuses on engineering aspects of waterproofing design, construction practices, groundwater management, drainage systems, and long-term performance. Emerging waterproofing technologies, recent material developments, and future research directions were also examined to identify knowledge gaps and provide recommendations for improving the durability and service life of railway tunnels.

RESULTS AND DISCUSSION

Comparative Performance of Tunnel Waterproofing Systems

The reviewed literature demonstrates that no single waterproofing system is universally suitable for all railway tunnel projects. The effectiveness of a waterproofing system depends primarily on geological conditions, groundwater pressure, tunnel geometry, construction practices, and long-term maintenance requirements. Among the available technologies, PVC waterproofing membranes remain the most widely adopted because of their excellent permeability, high tensile strength, flexibility, and chemical resistance. Their ability to accommodate minor deformations while maintaining water tightness has made them the preferred choice for tunnels constructed using the New Austrian Tunnelling Method (NATM). However, their performance is strongly influenced by installation quality, particularly membrane welding, joint sealing, and protection against mechanical damage during concrete lining placement.

Spray-applied waterproofing membranes have emerged as an attractive alternative where complex tunnel geometries or irregular excavation surfaces make conventional sheet membrane installation difficult. Unlike prefabricated membranes, spray-applied systems produce a seamless waterproof barrier that adheres directly to the substrate, minimizing potential leakage pathways at joints. Their excellent bonding characteristics also improve crack-bridging capacity and reduce the likelihood of localized seepage. Nevertheless, successful application requires strict control of substrate preparation, membrane thickness, curing conditions, and environmental factors such as temperature and humidity. Variability in field application remains one of the principal limitations of these systems.

Importance of Integrated Drainage Systems

The literature consistently highlights that waterproofing alone cannot ensure complete groundwater protection in railway tunnels. Modern tunnel design increasingly incorporates integrated drainage systems consisting of geotextiles, drainage composites, collector pipes, and longitudinal drainage channels. These systems reduce hydrostatic pressure behind the tunnel lining by safely collecting and discharging infiltrated groundwater. Studies indicate that the combined waterproofing–drainage approach significantly reduces stress on tunnel linings, limits crack development, and extends structural service life compared with impermeable barrier systems alone. However, drainage efficiency decreases when drainage channels become clogged by fine particles, mineral deposits, or biological growth. Long-term maintenance and regular inspection are therefore essential for preserving drainage performance throughout the operational life of the tunnel.

Role of Grouting in Groundwater Control

Chemical and cementitious grouting techniques continue to play an important role in controlling groundwater inflow, particularly in fractured rock masses and highly permeable formations. Pre-excavation grouting effectively seals rock discontinuities before tunnel advancement, whereas post-excavation grouting is commonly employed to repair localized leakage. The effectiveness of grouting depends on grout composition, injection pressure, fracture characteristics, and surrounding geological conditions. Although grouting substantially reduces groundwater inflow, it is generally most effective when used as a complementary measure rather than as a standalone waterproofing solution.

Common Causes of Waterproofing Failure

Despite considerable advances in waterproofing technology, leakage remains a common operational problem in railway tunnels. The reviewed studies identify several recurring causes of waterproofing failure, including defective membrane welding, inadequate overlap of waterproofing sheets, mechanical damage during reinforcement and concrete placement, poor workmanship, insufficient quality control, drainage blockage, and unsuitable material selection for site-specific geological conditions. Groundwater chemistry and cyclic loading may further accelerate membrane ageing and deterioration, increasing maintenance requirements over time. These observations emphasize that waterproofing performance depends as much on construction quality as on material properties. Comprehensive inspection during installation, non-destructive testing of welded joints, and strict adherence to construction specifications are therefore essential to achieve long-term waterproofing performance.

Comparative evaluation

Among the reviewed technologies, PVC membrane systems provide the highest reliability for long-term waterproofing under a wide range of geological conditions, provided installation quality is carefully controlled. Spray-applied membranes offer superior adaptability and seamless coverage for complex tunnel geometries but require highly skilled application. Drainage systems play a critical supporting role by reducing hydrostatic pressure, while grouting serves as an effective supplementary technique for controlling groundwater inflow in fractured or highly permeable rock masses. Consequently, integrated waterproofing systems combining membranes, drainage, and grouting provide the most effective solution for ensuring long-term tunnel durability and operational safety. Overall, the reviewed evidence indicates that successful railway tunnel waterproofing depends on an integrated engineering approach involving appropriate material selection, site-specific design, high-quality construction practices, and regular maintenance. Future developments should focus on improving membrane durability, developing smart monitoring systems for early leakage detection, and optimizing waterproofing solutions for increasingly challenging geological environments.

CONCLUSION AND RECOMMENDATIONS

Effective waterproofing is fundamental to ensuring the long-term durability, safety, and operational reliability of railway tunnels. The reviewed literature indicates that groundwater ingress remains one of the primary factors contributing to tunnel deterioration, resulting in concrete degradation, reinforcement corrosion, increased maintenance requirements, and reduced service life. Among the available technologies, PVC waterproofing membranes offer excellent permeability, durability, and flexibility, making them the most widely adopted solution for railway tunnels. Spray-applied waterproofing membranes provide seamless protection and are particularly suitable for tunnels with complex geometries, whereas drainage systems effectively reduce hydrostatic pressure and enhance the overall performance of waterproofing installations. Grouting techniques further improve groundwater control by sealing fractures and reducing water inflow in challenging geological conditions. However, the long-term effectiveness of all waterproofing systems depends not only on material properties but also on proper installation, quality control, regular inspection, and maintenance. An integrated waterproofing strategy combining membranes, drainage, and grouting offers the most reliable solution for achieving durable and sustainable railway tunnel infrastructure.

RECOMMENDATIONS

- Select waterproofing systems based on detailed geological and hydrogeological investigations rather than adopting a single solution for all tunnel projects.
- Integrate waterproofing membranes with efficient drainage networks to minimize hydrostatic pressure and improve long-term structural performance.
- Implement stringent quality assurance and quality control measures during membrane installation, seam welding, and grouting operations.
- Conduct regular inspection and maintenance of drainage systems to prevent clogging and maintain effective groundwater discharge.
- Utilize advanced monitoring technologies for early detection of seepage and waterproofing defects to reduce maintenance costs and prevent structural damage.
- Promote the development and application of innovative waterproofing materials with improved durability, chemical resistance, and environmental sustainability.
- Future research should emphasize long-term field performance, life-cycle cost analysis, and the evaluation of waterproofing systems under diverse geological and climatic conditions to support more reliable engineering decision-making.

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