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Waterproofing in tunnels – principles, application and quality control

Denijal Sikira
Independent researcher, BSc., denijal.sikira@gmail.com

Abstract: The issue of waterproofing in tunnels represents one of the key challenges of modern underground construction. The continuous action of groundwater and rock water requires systemic solutions that ensure long-term protection of the structure and stability of the facility throughout its service life. In this context, waterproofing systems are not regarded merely as an additional protective layer, but rather as an integral component of the tunnel structure. Their efficiency depends on the interconnection of design requirements, proper substrate preparation, and technical execution in accordance with applicable standards. Particular importance is given to the role of waterproofing in preserving the mechanical and durability properties of the final concrete lining, as well as in reducing the risk of structural degradation caused by the long-term effects of aggressive groundwater.

Key words: waterproofing membrane, geotextile, drainage system, tunnel, primary support, secondary lining, membrane welding, quality control

Hidroizolacija u tunelima – principi, ugradnja i kontrola kvaliteta

Sažetak: Problematika hidroizolacije u tunelima predstavlja jedno od ključnih pitanja savremenog podzemnog građenja. Neprekidno djelovanje podzemnih i stijenskih voda zahtijeva sistemska rješenja koja osiguravaju trajnu zaštitu konstrukcije i stabilnost objekta tokom njegovog eksploatacionog vijeka. Hidroizolacioni sistemi u ovom kontekstu ne tretiraju se isključivo kao dodatni zaštitni sloj, već kao integralna komponenta konstruktivnog sklopa tunela. Njihova efikasnost zavisi od međusobne povezanosti projektantskih zahtjeva, pravilne pripreme podloge i tehničke izvedbe u skladu sa važećim standardima. Poseban značaj pridaje se ulozi hidroizolacije u očuvanju mehaničkih i trajnosnih svojstava završne betonske obloge, kao i u smanjenju rizika od degradacije konstrukcije usljed dugotrajnog uticaja agresivnih podzemnih voda.

Ključne riječi: hidroizolaciona membrana, geotekstil, drenažna odvodnja, tunel, primarna podgrada, sekundarna obloga, zavarivanje membrane, kontrola kvaliteta

1.INTRODUCTION

The purpose of installing waterproofing systems in underground structures, especially in tunnels, is to prevent the penetration of groundwater and rock water into the tunnel interior, as well as to protect the final concrete lining from degradation. In addition to the primary function of preserving the structure, waterproofing also has a wider significance - it ensures the durability, stability, and safety of the tunnel during its operation, and reduces maintenance costs during the service life of the facility.

Water in tunnels is a common occurrence. The tunnel is drained in two ways [9]:

1. During construction,
2. During operation.

Consistent with modern engineering practices, the waterproofing membrane is always installed between the tunnel's primary lining (which usually includes a support made of shotcrete, anchors, and other support elements) and the secondary concrete lining. In this way, the membrane functions as an impermeable barrier that resists hydrogeological pressures and prevents the harmful effects of water on the structure.

The complete waterproofing system in tunnels consists of two basic layers [6]:

1. Protective layer (felt or geotextile) - is placed directly on the shotcrete surface, and its primary role is to protect the waterproofing membrane from possible damage. Such damage may result from irregularities on the shotcrete surface, including sharp aggregate, protruding reinforcement, anchors, or local unevenness. In this way, the geotextile significantly contributes to extending the durability and preserving the functionality of the waterproofing system.
2. Waterproofing membrane – the key element of the system, installed above the protective layer. Its primary function is to ensure complete watertightness, thus protecting the structure from the adverse effects of groundwater, and also extending its service life.

The waterproofing system, as an integral part is the drainage system, serves to collect and control the discharge of groundwater that reaches the zone between the primary lining and the waterproofing.

2. PRINCIPLES AND INSTALLATION OF THE WATERPROOFING SYSTEM

Groundwater is one of the most significant risk factors in tunnel construction. Its ingress can cause a number of serious problems: degradation of the concrete lining, reinforcement corrosion, reduction of the structure's load-bearing capacity, and difficult operating conditions. These processes directly compromise the durability, safety, and functionality of the tunnel structure. For this reason, the application of an adequate waterproofing system emerges as a key element in the design and construction of underground structures, since it provides fundamental protection of the structure against the adverse effects of water and moisture.

In modern tunneling practice, waterproofing systems are most commonly constructed from waterproof PVC membranes, which are installed and welded on site.

In this way, a continuous and reliable protective barrier is formed, capable of ensuring complete watertightness along the entire structure. Protective felt (geotextile) is placed between the primary support and the PVC membrane.

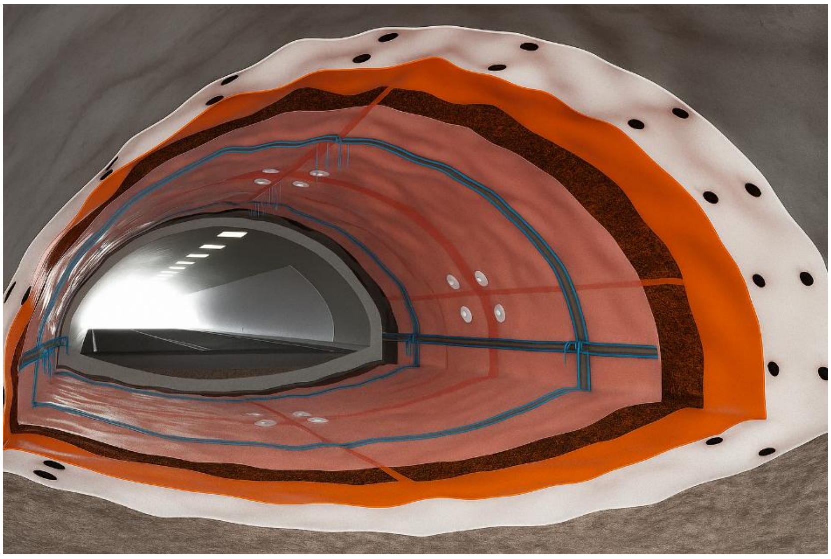

Figure 1. Cross-sectional view of the waterproofing system in tunnels [4]

2.1 Protective felt

Protective felt (geotextile) is a key element of the waterproofing system, because it directly protects the most sensitive and important layer— the PVC waterproofing membrane. Its proper installation is essential for the long-term durability and reliability of the tunnel structure. In addition to its primary function of protecting the membrane from mechanical damage during the execution of works and in the operation phase, the felt plays a significant role in the even distribution of pressure on the waterproofing. This reduces the risk of point loads and perforations that could compromise the watertightness of the system. Furthermore, thanks to its permeable structure, the felt allows any residual water to reach the drainage system, thereby ensuring the proper functioning of the entire waterproofing system.

The felt is installed between the primary support, i.e., shotcrete, and the PVC waterproofing membrane. It is placed continuously, with mandatory overlapping of edges, to ensure complete surface coverage and prevent the formation of unprotected zones. The overlaps are additionally secured by mechanical means—the so-called PVC discs—which, together with special nails, are fixed to the concrete surface using a gas gun. This method of fastening ensures the stability and durability of the protective layer, without damaging the substrate or impairing the functionality of the waterproofing system.

The felt is attached to the shotcrete surface with appropriate fixing elements, and the number of fasteners depends on site conditions. As a rule, between two and four elements are used per square meter of surface [6].

Proper distribution of these points ensures firm adhesion of the felt to the substrate, prevents displacement and contributes to the overall stability of the waterproofing system. High-quality, carefully planned, and technically coordinated installation of protective felt is crucial for the long-term functionality of the waterproofing, the preservation of the PVC membrane, and the reliability of the structure as a whole.

Figure 2. Illustration of the attachment of the protective felt and the waterproofing membrane [3]

2.2 Waterproofing membrane

In tunnel construction, the waterproofing membrane must be made of high-quality and technically proven materials, such as ECB (ethylene copolymer bitumen) or PVC (polyvinyl chloride) [6]. PVC membranes are most commonly used due to their elasticity, durability, and resistance to moisture and chemical effects. The membrane is laid over a previously installed layer of protective felt, which prevents mechanical damage and provides stable support on the substrate. The fastening is carried out on preset fixing elements, exclusively by thermal welding to discs, thereby ensuring stability and complete watertightness of the joints. Throughout the installation process, any puncturing or perforation of the membrane is strictly prohibited, as even minor damage can compromise the system and lead to water ingress.

Special attention is paid to joining adjacent sheets of PVC membrane. Joints are made by double thermal welding using specialized hot air machines (Figure 3). Depending on the type and thickness of the membrane, and site conditions, the usual welding temperature ranges from 450 °C to

600 °C. A double weld consists of two parallel seams, between which a control channel 2 to 3 cm wide is left. This channel enables simple and reliable quality control of the welded joint, most commonly through compressed-air testing under pressure, which facilitates the detection of possible irregularities and defects. In this way, additional safety is ensured regarding the watertightness of the joints, which is crucial for the long-term functionality of the waterproofing system.

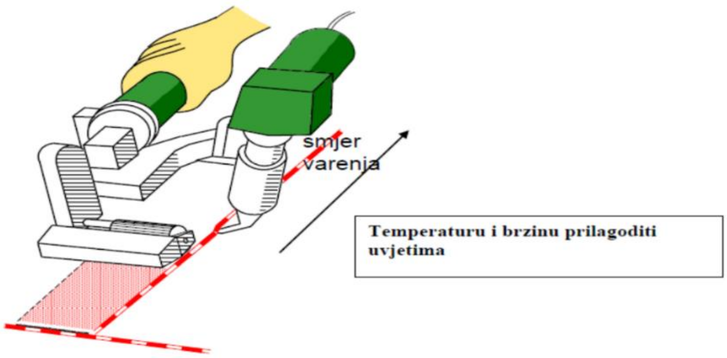

Figure 3. Illustration of the waterproofing membrane welding procedure [7]

The use of double welding with control channels is a modern standard in tunnel waterproofing, as it guarantees high reliability, a long service life of the system, and a reduced risk of water ingress into the structure. Properly selected materials, careful execution of works, and technical control of joints together form the basis of a successful and durable waterproofing solution.

Figure 4. Illustration of a double weld [4]

Protective felt and waterproofing membrane are installed exclusively from steel tunnel scaffolding of modular removable design, which allows quick assembly, phase-specific adjustment, and efficient dismantling without delays in construction. Scaffolding provides a stable and safe working platform. It is assembled and inspected in compliance with applicable occupational safety regulations, with verification of load-bearing capacity, leveling, and protective elements. The material is distributed evenly within the allowable load, and all works are carried out with mandatory use of prescribed personal protective equipment and regular monitoring of the integrity of the scaffold structure until completion of the works.

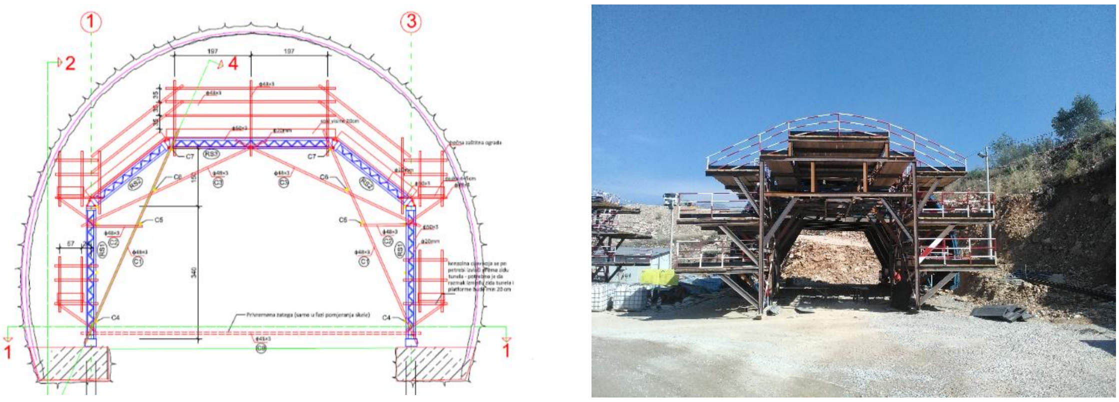

Figure 5. View of steel tunnel scaffolding, Vjeternik Tunnel, Montenegro [2]

2.3 Drainage system

Side drainage is an indispensable and functionally crucial element of tunnel waterproofing systems. Its primary role is to constantly collect and drain groundwater and rock water penetrating through the primary lining, as well as water that may appear or accumulate behind the waterproofing membrane. Efficient drainage prevents hydrostatic pressure on the waterproofing system and tunnel structure, thus extending its service life and ensuring the stability of the structure.

The side drainage system usually consists of perforated drainage pipes of circular cross section, which are installed on both sides of the tunnel, immediately above the foundation. HDPE pipes, known for their high resistance to deformations and chemicals, as well as long duration in underground construction conditions, are used for these purposes. To ensure sufficient water intake and transport capacity, the total perforation area must be at least 200 cm^2 per meter of pipe [6].

Installation of the drainage system begins with preparation of the waterproofing membrane, which is laid on the tunnel foundation surface. The membrane roll is cut to the required width, in accordance with the overlap on the adjacent membrane. As a rule, the initial width of the cut sheet is about 1.05 m. After cutting, the membrane is unrolled and carefully laid on the previously cleaned foundation surface. At the bottom of the vertical wall of the drainage channel, the membrane is fixed using nails and a special tool (an explosive-charge fastening gun) or by manual fastening, depending on site conditions.

This is followed by installation of the drainage pipes. Their placement must be precise, adhering to the designed alignment, gradient, and tunnel level line to ensure uninterrupted gravitational water transport. To direct inflow towards the pipe perforations, a bedding layer of fine-grained concrete based on Portland cement is first placed. This concrete forms the bedding and channel profile, routing water directly to the pipe perforations.

After positioning and leveling the pipe, rough porous concrete is placed in two phases. In the first phase, concreting is carried out up to half the pipe height to stabilize it in the bedding and prevent movement. In the second phase, porous concrete is placed up to the top of the drainage channel, forming a slope according to the previously marked height on the tunnel perimeter.

This layer enables filtration and unhindered groundwater flow into the perforated openings of the drainage system. Through this procedure, the durability, functionality, and safety of the waterproofing system are ensured, while minimizing the risk of water ingress and structural stress.

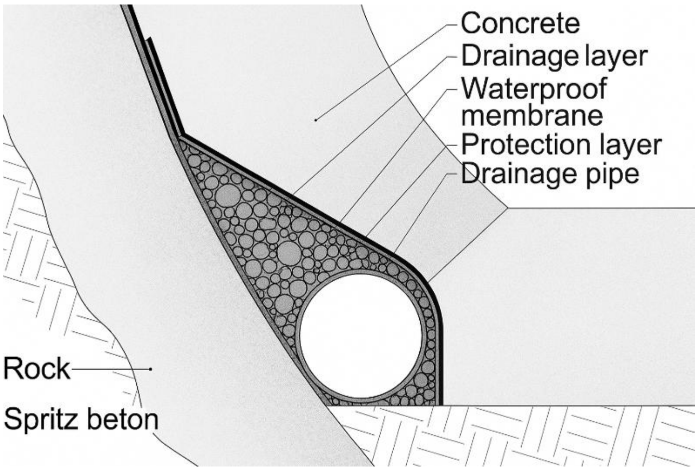

Figure 6. Detail of side drainage [3]

2.4 Waterproofing in tunnel niches

Road tunnels contain niches that play an important safety and functional role. They serve as spaces for storing equipment for emergency situations, such as fire extinguishers, hydrant network, emergency telephones, and cabinets with electronic and signaling equipment. In addition, some niches are designed as safety shelters for road users in the event of a vehicle breakdown, traffic accident, or fire.

Inspection niches are used for inspection and maintenance of tunnel installations, such as drainage systems. Since tunnels are susceptible to the ingress of groundwater and seepage water, inspection niches must be waterproofed. Inspection niches are designed so that technical personnel can access the installations for regular inspection, functionality testing, and repairs.

The remaining niches, such as electrical, fire protection and SOS niches, are designed and constructed in compliance with applicable technical regulations and standards, while meeting the specific functional requirements of each particular installation. Their design must ensure unobstructed access to equipment, adequate protection of installations against mechanical damage and the effects of moisture, and permanent integration with the waterproofing system of the tunnel structure.

At niche locations, the previously installed foil around the tunnel perimeter is cut diagonally. Full attention is given to ensure that the cut begins at least 10 cm from the edge of the niche, thereby providing a longitudinal weld overlap on the flat surface of the niche on one side, as well as the necessary looseness of the waterproofing to prevent overloading during construction of the secondary lining.

On the inner surface of the niche, waterproofing is made by installing segments of waterproofing material prepared according to the niche's dimensions. The waterproofing segments are attached to the porous concrete in the usual manner, while the ends overlapping the vertical membrane are welded with a longitudinal seam, thus ensuring continuity and watertightness of the system.

Figure 7. Waterproofing within the inspection niche, Kobilja Glava Tunnel [5]

3. QUALITY CONTROL

The waterproofing PVC membrane is tested to verify the quality of the joints and to ensure complete watertightness. There are two standard control methods, namely seam testing with compressed air and seam testing with vacuum equipment [6].

For seams between adjacent sheets of waterproofing PVC membrane, the testing for tightness shall be carried out by means of compressed air pumped into the test channel, which is formed by the double welded joint.

Initial tests are performed under the following conditions:

- pressure of 2 bar for 5 minutes, or
- pressure of 1.5 bar for 10 minutes.

Joints are considered completely watertight if the pressure loss during the test period does not exceed 20% of the initial value. This procedure ensures that seams are properly welded and that there is no leakage through the joints.

Figure 8. Testing of joints with compressed air [8]

For testing smaller areas of the membrane, especially at locations with specific joint configurations or local repairs where patches have been applied, the vacuum method may be used. This method is performed using a vacuum bell placed above the part of membrane being tested. Once the bell is firmly pressed against the surface, the space beneath it is evacuated by pumping, thus creating negative pressure. In this way, any voids, irregularities, or defects in the joints can be detected, or their complete watertightness confirmed.

Figure 9. Testing of the membrane using the vacuum method [1]

The test is based on the use of a specialized device consisting of a rigid, transparent plastic hemisphere with a diameter of 40 cm, with two ergonomically shaped handles positioned along its edges. The device is equipped with a pressure gauge with a measuring range from 0 to –1 bar, as well as a control knob for adjusting the level of negative pressure inside the test chamber [1].

On the lower edge of the hemisphere there is a sealing ring that allows complete sealing on flat surfaces, thus ensuring the creation and maintenance of negative pressure inside the closed space. The test chamber is connected to a small-capacity vacuum pump with a flexible tube approximately 150 cm long. The pump is equipped with a switch that, once activated, enables continuous air extraction from the chamber interior.

The test procedure begins by defining the test point, after which a solution of soap and water is applied to the weld surface for visual detection of any leaks. The vacuum pump is then turned on, and the test cap is set above the selected point. Activation of the pump gradually increases negative pressure inside the chamber, which is registered on the pressure gauge. The pressure level is adjusted to approximately -0.2 bar using the control knob.

Once stable negative pressure is established, the welded joint is visually inspected through the transparent hemisphere. Two outcomes are possible [1]:

a) If no bubbles appear along the welded joint, the test is considered successful, and it is concluded that the weld is watertight.

b) If bubbles appear within the tested zone, a defect in the welded joint is identified. The defect can be further specified using an appropriate weld tester. In this case, the joint does not meet the prescribed criteria and must be repaired by welding a patch of the same geomembrane type, in accordance with applicable technical requirements.

Non-destructive mechanical test of the joints: The test is performed by passing the tip of the weld tester along the welding line exerting enough pressure to detect any weak point (Figure 10). This operation is necessary to check the integrity of the welded joint and has to be performed when the welding has completely cooled.

In case there are discontinuity points or points with insufficient adherence, local repair shall be carried out by welding spot patches of the same type of material, to ensure the continuity of the joint [1].

Figure 10. Manual control using a weld tester [1]

4. CONCLUSION

Waterproofing in tunnels is a structural element of fundamental importance, not merely a secondary protective layer within the lining system. Its function extends beyond serving as a barrier against water ingress, as it directly influences the durability, mechanical resistance, and long-term reliability of the entire tunnel structure. Preventing the ingress of groundwater and seepage rock water minimizes the risk of cracking, chemical degradation of concrete, reinforcement corrosion, and reduction of the load-bearing capacity of the lining, thus extending the service life of the structure and ensuring structural stability under variable hydrogeological conditions.

The efficiency of the waterproofing system depends directly on an integrated approach to design and construction. Proper dimensioning of the system in accordance with the geological and hydrological characteristics of the terrain, adequate substrate preparation, precise installation of the protective geotextile layer (felt), high-quality installation of the PVC membrane, and a functionally solved drainage system represent interdependent phases that determine the overall performance of the system. Double welds with control channels are of particular importance, as they enable pressure testing of joints and timely detection of potential defects, thereby ensuring complete watertightness and minimizing the risk of subsequent repairs.

It must be emphasized that the quality of installation and systematic testing of both the joints and the entire membrane are critical factors for the long-term functionality of the waterproofing. Professional and controlled installation, with continuous supervision and adherence to prescribed welding procedures, directly affects system homogeneity and prevents hidden defects. Testing of welds, controlling pressure in the control channels, conducting visual inspections, and documenting results provide verification of the executed state and enable timely correction of any irregularities. In this way, a high level of system reliability is achieved, the likelihood of water ingress during operation is reduced, and long-term protection of the tunnel structure is ensured.

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