GEOTECHNICAL ASPECTS IN TUNNEL AND UNDERGROUND WORKS

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Long term durable membrane solutions for waterproofing in drained and undrained tunnels – relevance of design and planning, different membrane materials and influence of the quality of installation

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Summary:

Modern traffic tunnels are increasingly planned for a functional service life time of more than 100 years. For this reason they must be protected extensively against the effects of groundwater and water penetrating through rock fissures. The design and planning of the waterproofing should be correspondingly strict, especially with respect to the required service life. This paper will show how to achieve a long term trouble-free tunnel operation with low operating and maintenance costs with a professionally installed waterproofing system with long term durable membrane materials.

1. Introduction

Modern traffic tunnels are increasingly planned for a functional service life of more than 100 years. For this reason they must be protected extensively against the effects of groundwater and water penetrating through rock fissures. The construction and sealing specifications are strict, especially in respect of the required service life. The level of hydrostatic pressure and the aggressiveness of the water determine the scope of the protection required for the construction. Also, for ecological reasons, here is an increasing desire to limit the drainage of mountain water. There are a broad range of opportunities, technical as well as economic, for selecting the most suitable protection system. Each tunnel requires a specific solution; depending on construction systems, such as cut and cove projects, varying water aggressiveness, transition sections of in-situ water under pressure and seepage water. Sealing does more than just protect important structures against corrosion. The tunnel functions (e. g. prevention of icing) as well as the stability itself require a protection against moisture. In comparison to the total costs of constructing a tunnel, the costs of providing a functional waterproofing is minor – but the advantage to be gained is major. Sealing protects and safeguards the structure. It reduces maintenance costs. Therefore waterproofing is an important part of any tunnel construction. A long-term, trouble-free tunnel operation with low operating and maintenance costs can be achieved with a professionally installed waterproofing system. In addition, a tunnel's sealing system will actively contribute to environmental protection, despite the need for the construction of the tunnel, by avoiding interference with the mountain's hydrological water balance. The sealing system will also prevent environmental damage from oils or chemicals which may occur due to traffic accidents. These important requirements are satisfied reliably and economically with a waterproof sealing system. Basically, sealing systems have two functions in the construction of modern traffic tunnels. They divert the mountain water away from the tunnel and they protect the supporting structure from the potentially aggressive particles in the water. This sealing and protection function must remain intact over the service life of the tunnel. To reach this, geomembranes, particularly those manufactured from flexible polyolefin, are being used in thicknesses up to 3 mm. The type of waterproofing depends on factors such as geology, hydrology and stress on the sealing system. This stress factors will be caused by the pressure of the water or the seeping water and/or the aggressiveness of the mountain water. Geomembranes must be protected against potential mechanical damage. Without a protection layer the geomembranes can be damaged by the rough shotcrete surface of the sealing carrier layer or by careless installation of the concrete steel reinforcement layer. Nonwoven geotextiles are used as a protection layer between the support and the geomembranes. An additional 3 mm thick tunnel geomembranes can also be used as protection for the installed sealing system in the floor area. The advantage that the protection geomembrane has compared to concrete is that it can be installed economically and systematically as the waterproofing progresses. There is also the potential for full area damage quality assurance with a light-coloured signal layer of the tunnel geomembrane. Reinforced concrete, however, must be used if the floor area will support traffic. For tunnel structures that are designed for drainage, the drainage element must survive the tunnel service life. Geosynthetic tunnel drainage mats that are installed over the entire area will divert mountain water flowing towards the tunnel in such a way that the operation of the tunnel is not disturbed. The collection and drainage of the water must remain intact over the service life of the tunnel. Nonwoven geotextiles with a drainage function, drainage nets and mats are most suitable for this requirement as they also provide the protection as well as the drainage function. In order to ensure that accidental damage to the geomembranes becomes visible during construction, the geomembranes are provided with a top-sided signal layer that is approximately 0.1 mm thick (≤0,2mm). This signal layer provides a control of the sealing geomembrane and, at the same time, provides a clear improvement of the lighting conditions in the tunnel.

2. Long term durability of different membrane materials

In tunnel constructions will usually installed thermoplastic membranes which can be connected by the use of hot wedge welding process. The tunnel membranes usually based on plasticized Polyvinyl chloride (PVC-P) or on thermoplastic polyolefin (TPO) like very low density polyethylene (VLDPE).

2.1 Thermoplastic polyolefin (TPO)

A polyolefin is a polymer produced from a simple olefin (also called an alkene with the general formula C_nH_{2n}) as a monomer. For example, polyethylene is the polyolefin produced by polymerizing the olefin ethylene. Polyolefins are impossible to join by solvent cementing because they have excellent chemical resistance and can only be adhesively bonded after surface treatment because they have very low surface energies. They are also extremely inert chemically and exhibit decreased strength at lower temperatures. Waterproofing membranes in tunneling are mostly based on Polyethylene (Very low density polyethylene – VLDPE). They have a natural flexibility and will be produced without any plasticizer. TPO geomembranes for tunnel construction are highly resistant to chemicals and ecologically safe to the environment. The expected service time life of these kinds of tunnel membranes is more than 100 years. For the long term durability of Polyethylene membranes the German official institute BAM (Bundesanstalt für Materialforschung) has approved testing methods to test and calculate the time life of PE-membranes. The tests will be done by an autoclave testing method. Therefore it is scientifically proven that PE membranes can easily meet the requirement of minimum 100 years full service life time.

2.2 Polyvinyl chloride plasticized (PVC-P)

PVC was accidentally discovered at least twice in the 19th century, first in 1835 by Henri Victor Regnault and then in 1872 by Eugen Baumann. On both occasions the polymer appeared as a white solid inside flasks of vinyl chloride that had been left exposed to sunlight. In the early 20th century the Russian chemist Ivan Ostromislensky and Fritz Klatte of the German chemical company Griesheim-Elektron both attempted to use PVC in commercial products, but difficulties in processing the rigid, sometimes brittle polymer blocked their efforts. Waldo Semon and the B.F. Goodrich Company developed a method in 1926 to plasticize PVC by blending it with various additives. The result was a more flexible and more easily processed material that soon achieved widespread commercial use. Plasticizers are used to make PVC-P flexible so it can be used as a geomembrane for containment purposes. Plasticizer can migrate from PVC-P geomembranes over time because of contact with air, liquid, and an absorbent solid material. Plasticizer migration can reduce the flexibility of PVC geomembranes in brittle behavior. One of the limitations in using plasticized PVC in practice is the possibility of plasticizer migration over time for various service conditions. Plasticizers loss reduces the flexibility of PVC membranes and in extreme cases results in noticeable shrinkage. Plasticizer retention is controlled by many external and internal factors. The external or environmental factors such as temperature, chemicals, microorganism, and the characteristic of the contact material such air, liquid, and a solid, are related to the site-specific condition. These external factors should be considered in design and construction quality control for the liner and cover system that use PVC geomembranes as a barrier. In contrast to the external factors, the internal factors controlling plasticizer retention include the molecular weight and linearity of the plasticizer. These internal factors should be considered by the manufacturer because the type of plasticizer can influence the process ability. For the waterproofing in tunnel projects will be used normally monomer plasticizer (e.g. Dioctylphtalate – DOP). To increase the membrane time life it is possible to produce the PVC-P membranes with polymer plasticizer or high-molecular additives but there for the cost increase extremely.
The expected time life of PVC-P membranes will be strongly influenced from the used kind of plasticizer and the surrounding tunnel conditions.

2.3 Recommendation for the application of PVC-P and TPO (VLDPE) in view to the permanence

The following recommendation shows that the usage of TPO (VLDPE) is in every surrounding condition better than PVC-P, especially in view to the main requirement for tunnel construction with a full service time life of 100 years. The recommendations based on the following parameters:

- Constant temperatures in °C in the structure
- Constant pressure on the waterproofing membrane
- Composition of the surrounding groundwater
- Water flow intensity over the surface of the tunnel membrane

2.3.1 Constant temperatures in °C in the structure

With the increasing of the temperature, the aging process for tunnel waterproofing membranes will speed up accordingly. For PVC-P membranes means that a strongly increase of the migration of plasticizer from a temperature of 23°C.

Recommendation:	<23 °C	PVC-P and TPO (VLDPE)
	>23 °C	only TPO (VLDPE)

2.3.2 Constant pressure on the waterproofing membrane

High constant pressure loads on the waterproofing membrane effects a reduction of the thickness. Especially for PVC-P membranes cause a permanent pressure a relevant decreasing of the thickness. For a pressure load of 5 N/mm^2 the decrease of the PVC-P membrane thickness is more than 25% in a permanent process. In opposite therefore the TPO (VLDPE) decrease in the thickness about 3% only during the first 7 days, after then the membrane is already stable. In view to a further reduction in thickness of the membrane the ratio of 1:5 results in a limiting pressure for PVC-P membranes with 1 N/mm^2

Recommendation:	<1 N/mm^2	PVC-P and TPO (VLDPE)
	>1 N/mm^2	only TPO (VLDPE)

2.3.3 Composition of the surrounding groundwater

Increasing properties of sulphates, chlorides, magnesium, sodium and calcium in the surrounding groundwater can speed up the ageing behaviour of tunnel waterproofing membranes. An increasing concentration of e.g. sulphates caused a growing migration of plasticizer. For TPO (VLDPE) is no influence to the durability noticeable .

Recommendation:	Sulphates	<1500 mg/l	PVC-P and TPO (VLDPE)
		>1500 mg/l	only TPO (VLDPE)
	Sodium	<100 mg/l	PVC-P and TPO (VLDPE)
		>100 mg/l	only TPO (VLDPE)
	Chloride	<50 mg/l	PVC-P and TPO (VLDPE)
		>50 mg/l	only TPO (VLDPE)

2.3.4 Water flow intensity over the surface of the tunnel membrane

With increasing speed of the water flow the quantity of soluble components which will be washed out are also increase. During immersion tests it was established that the migration of plasticizer speed up directly after replacing the water in the testing baths. The following recommendation based on surrounding water without aggressive additives.

Recommendation:	No water flow	PVC-P and TPO (VLDPE)
	Medium water flow	PVC-P and TPO (VLDPE)
	Strong water flow	only TPO (VLDPE)

2.3.5 Summing up recommendation

In tunnel projects worldwide both materials PVC-P and TPO (VLDPE) will be used. The advantage of PVC-P is the higher flexibility in the installation stage and also the easier weldability for hot air hand welding.
In view to the common requirement of a service time life of more than 100 years for tunnel constructions and in view to the fact that the membrane waterproofing system cannot easily changed or repaired after finishing the main concrete construction the TPO (VLDPE) membranes have much better technical arguments. Based to the long term durability and resistance against external influences which are showed above for tunnel constructions with a concrete inner shell should be used only TPO (VLDPE) tunnel membranes.
In many project in the past the argument for PVC-P membranes was the price. But the cost difference for tunnel membranes between PVC-P and TPO (VLDPE) is slightly. The percentage of the membrane waterproofing system in reference to the complete budget of a tunnel construction is only around 3 %. Therefore the influence of the selected material is less than 0.5 % of the total budget. On the opposite side are the refurbishment costs of a failed membrane system which could be easily a multiple of the complete costs of the waterproofing system.
Finally it is a question of investment in the future to use long term durable and high resistance waterproofing membranes. A very important issue for that is also the quality of installation. Only the use of TPO (VLDPE) membranes alone don´t assured the desired result for the waterproofing system. It is also very important that only qualified and experienced tunnel sealing companies are ordered for the waterproofing works.

3. Design basics of membrane waterproofing systems

In principle, there are distinctions in tunnel construction between a sealing against water pressure and against seepage water. For seeping water, a tunnel geomembrane that is 2mm thick can be used as an umbrella seal. For occurring hydrostatic water the use of an all-around sealing (360°) with a separation system is the required solution. All kind of tunnel waterproofing membranes should be delivered with a light coloured (e.g. white) signal layer.

This results in the following sealing systems:

Seepage water sealing system - "Drained tunnel"
The structure is protected against water by a tunnel geomembrane with an umbrella sealing system. This system discharges the incoming seepage water without pressure over the longitudinal drainage at the bottom of the structure. If the seepage water corresponds to

class XA3 (“highly aggressive“), 360° single-layer geomembrane must be installed for corrosion protection reasons.

Hydrostatic pressure sealing system - “360° sealing with segmental waterstops“

When hydrostatic water pressure is present, it is recommended to use a water-impermeable concrete that is protected with a tunnel geomembrane, especially if the classification of the seepage water corresponds to exposition class XA3 (”highly aggressive“) (3). In order to limit potential damage and to confine the damaged area, the concrete segments are additionally sealed with external waterstops.

Hydrostatic pressure sealing system with integrated injection system “360° sealing with segmental separation including injection devices for injection after concreting the concrete inner shell“

For hydrostatic pressures in excess of a 10 m water column, an integrated injection system for possible repair option is planned. The sealing system otherwise corresponds to the construction of the hydrostatic pressure system.

4.1. Seepage water sealing system - Drained tunnel

The seepage water sealing system is carried out with a 2 mm thick tunnel geomembrane with a light coloured (e.g. white) signal layer according to the cross-section (from the inside out – Figure below):

- o Interior shell
- o Tunnel geomembrane 2 mm with signal layer
- o Geotextile (>900 g/m²)
- o Shotcrete

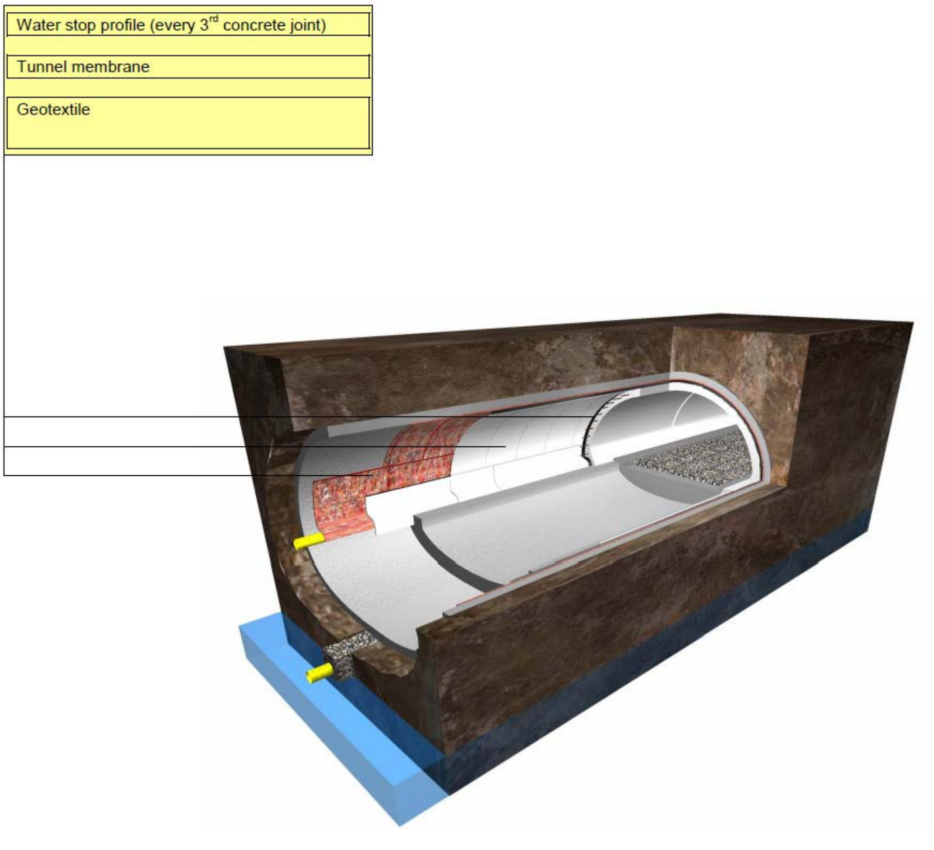

Figure: Drained tunnel waterproofing system

For the connection of the sealing to the drainage area the following is a solution:
Drainage systems are intended to collect any water and to discharge it away from the tunnel structure. Drained tunnel structures are constructed using either cut and cover or mined technique. Water built-up is not expected to occur when the drainage system has been planned and constructed carefully.

The criteria listed below are required for planning a drainage system:

- Minimize the alkaline content in the shotcrete and drainage gravel
- HDPE drainage pipes with a diameter of minimum DN 200, smooth interior surface, sufficient hydraulic discharge capacity
- The drainage pipe must be designed for the pressure resulting from the entire system
- Slot widths in the drainage pipe of 5-6 mm
- Drainage gravel and installation process must be adjusted to the size of the drainage slots
- Revision shafts and drainage pipe system to be acceptable for monitoring by mobile cameras and flushing

It must be mentioned that a tunnel with a seepage waterproofing system influence the surrounding water condition in a long term. This interference to the surrounding water needs usually an authorization by the appropriate authorities.

3.2. Hydrostatic water pressure sealing system with segmental waterstops

Water column

The main component of the sealing system comprises of a 3 mm thick tunnel geomembrane with a light coloured (e.g. white) signal layer, which is installed as a single circumferential layer to resist hydrostatic water pressure. An effective visual, quality assurance of the entire sheet is created by a light reflecting signal layer on the tunnel geomembrane side that is faced to the inside of the tunnel.
To protect against mechanical damage, geotextiles are installed towards the mountain. Needle punched, nonwoven geotextiles are necessary for protection particularly for high-quality, single-layer sealing systems. Depending on the condition of the surface and the water pressure it might also be necessary to install Nonwoven geotextiles that have a higher mass per unit area than recommended in the standards and guidelines.

Construction guidelines recommend the following (from the inside out – Figure below):

- o Concrete inner shell
- o 3 mm tunnel geomembrane
- o Geotextile >900 g/m²
- o Shotcrete

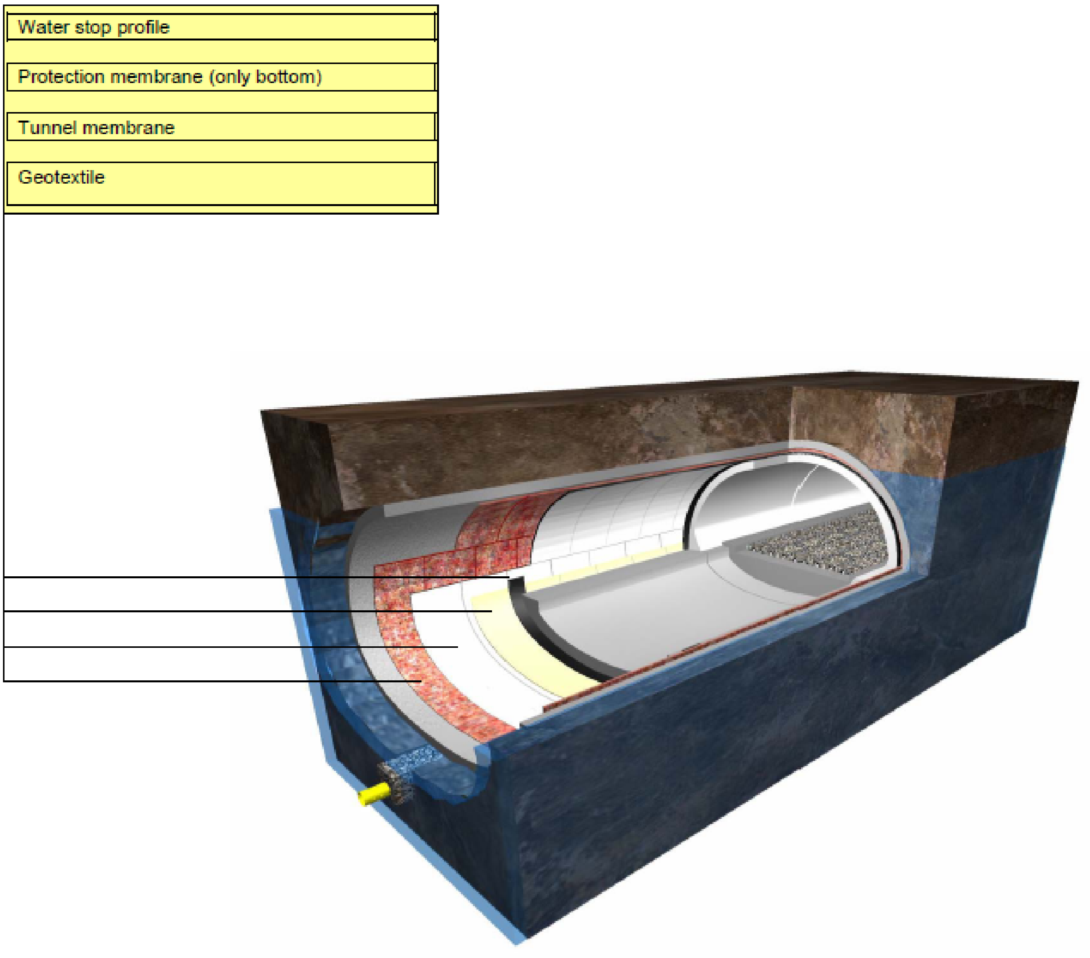

Figure: Undrained waterproofing system

The concrete segment blocks are sealed with six bar waterstops. These will restrict the movement of water to other segments should damage occur in a segment. A 3 mm thick protection geomembrane with a light coloured (e.g. white) signal layer is installed in the floor area to protect the floor sealing

Block joints

The circumferential segmental block waterstops between segments have, essentially, the following functions:

a) Restricting the flow of seepage in the event of leakage
b) Protection of the tunnel geomembranes from the front casing and from pressure from the Concrete edges
c) Limiting the leakage

These functions are fulfilled safely and reliably by the six bar waterstops. A homogeneous welding of the tunnel geomembranes with the waterstops is possible by using the same raw material for both products. The waterstops are provided with an additional injection system for the removal of air during the pouring of the concrete or for retroactive injection possibilities.

3.3 Sealing system against hydrostatic water pressure with integrated injection system

For this system, the basic design is identical to that of the item number 3.2. Additionally, an injection system is integrated, which permits retroactive sealing and repairing. The integrated injection system allows for sealing followings:

- potential damages caused by subsequent construction works (e.g., installation of steel reinforcement) can be easily repaired
- incomplete concreting of inner shell can be completed due to the additional injection system (to avoid exposed steel reinforcement)
- an integrated injection system has also the function of an leakage inspection system

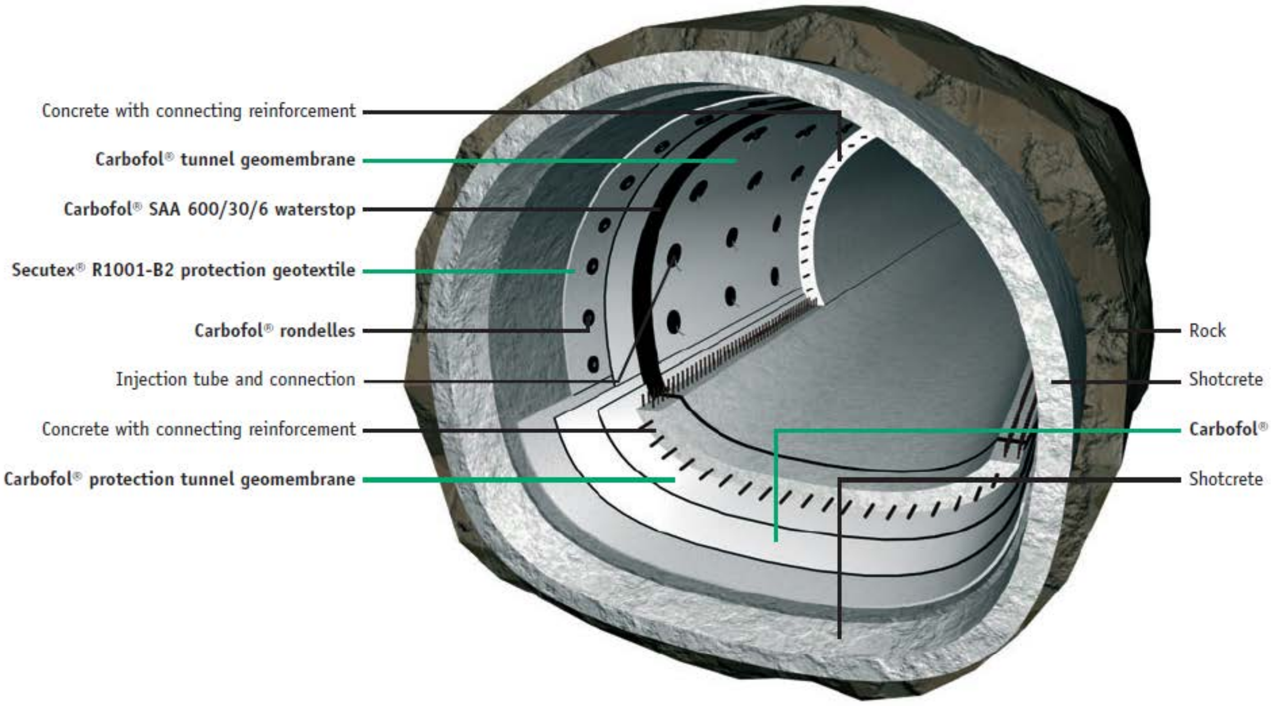

Figure: Undrained waterproofing system with integrated grouting system

3.4. Sealing system and drainage system – cut and cover construction, including portal sealing

In contrast to the mining technique of a tunnel, the cut-and-cover method takes place in the open. The tunnel geomembrane is placed loosely on the protection geotextile, which is installed first onto the sealing carrier layer (construction concrete) and which must be smooth and free of cavities and ridges. A second protection geotextile is placed (also loosely) on top of the tunnel geomembrane.

In a cut and cover construction regulations require that the sealing system is installed on the tunnel outside surface as follows (figure below):

- Concrete shell (sealing carrier system)
- Geotextile protection layer
- Tunnel geomembrane
- On the floor, geotextile protection layer, if required, geosynthetic drainage system
- Fill material

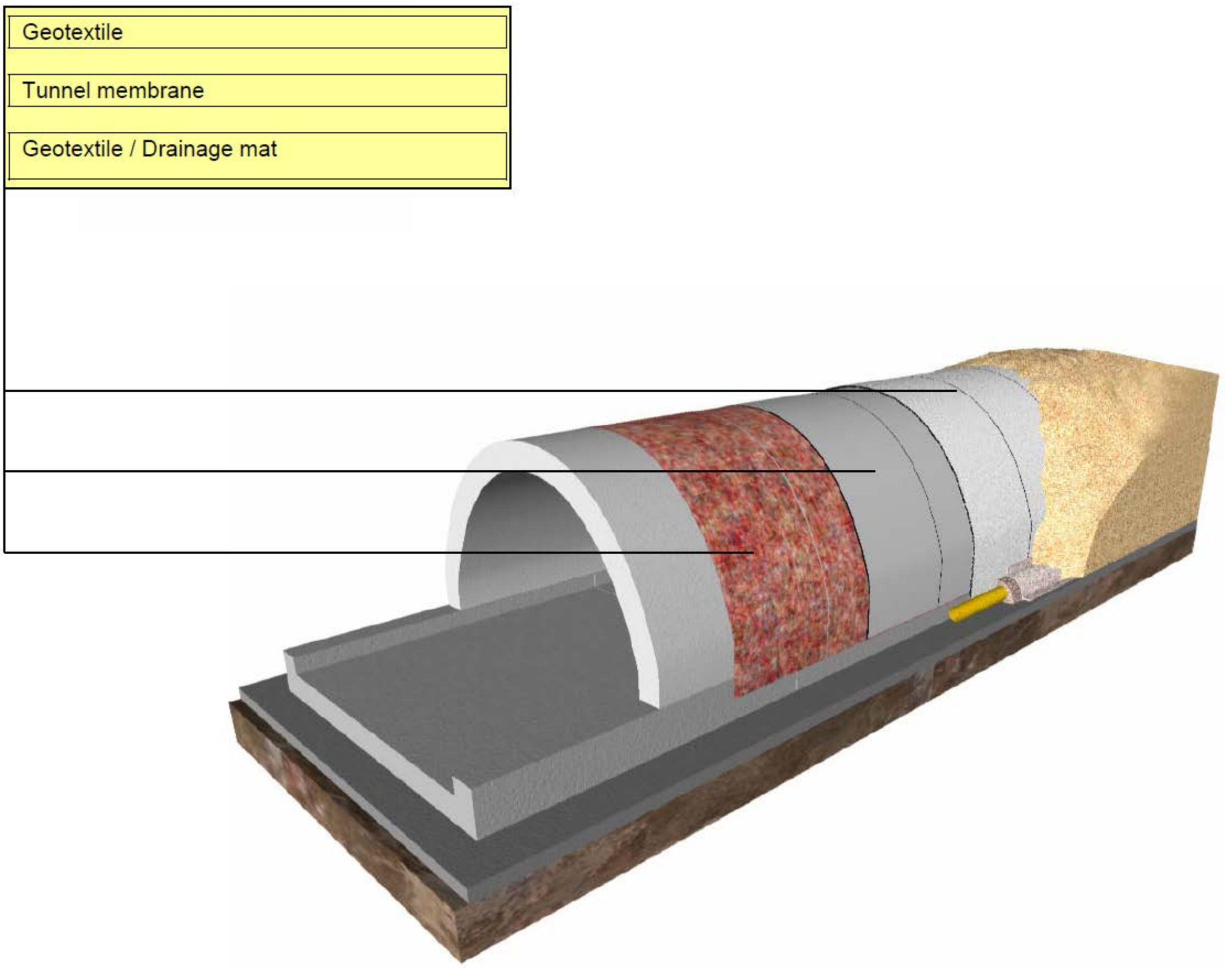

Figure: Drained waterproofing system Cut and Cover

Sealing against seepage water, single layer

A geotextile is installed as a protection layer below the tunnel geomembrane. This avoids any possible damage from the concrete shell. The tunnel geomembrane is a single layer, at least 2 mm thick and is fixed longitudinally to the tunnel structure, using connection profiles. It is recommended a 3 mm thick tunnel geomembrane with signal layer, so that possible damage to the surface of the tunnel geomembrane, such as that might be caused by backfilling operations, can be detected. Backfill work can cause unintended damage to the tunnel geomembrane. For this reason, a 3 mm thick protection tunnel geomembrane will provide excellent protection against the high stresses during backfill operations. The reflective layer is beneficial, so that visual inspections for damaged areas can be carried out immediately. Generally, due to the backfilling, the protection layers should be dimensioned thicker in a cut and cover construction than in a mining technique construction. Alternative systems can be used, such as protection geotextiles, geosynthetics drainage systems or others.

Sealing against water pressure

In this case, the tunnel geomembrane has a thickness of 3 mm. The floor and the arch are welded together and an expansion joint is welded to both of the geomembranes horizontally.

3.5. Requirements for the sealing carrier system (shotcrete shell)

The shotcrete formation layer, which simultaneously serves as the backing and the fixing support for the sealing system is an important criterion for the functioning of the sealing geomembrane in mining technique tunnel construction. The sealing carrier system is to be constructed such that a full-plane interface connection of protection layer and geomembrane is ensured without the geomembrane being overstressed or being folded.
The 5 to 15 cm thick shotcrete shell, which can be far thicker, depending on the geological conditions, ensures that:

- The stability of the mined mountain can be ensured on a temporary basis
- Edges, ridges, bursting, protruding anchor bodies, support arches and suspensions can be covered.

Therefore the following conditions must be met by the shotcrete shell:

- thickness ≥ 5 cm
- maximal particle size 8 mm, gradated in a base layer (0 - 16 mm) and cover layer (0 - 8 mm)
- Rise difference a ≤ 20 cm
- Sufficient dimensional stability
- rounding radius Na ≥ 5a
- Distance low and high point L ≥ 10a

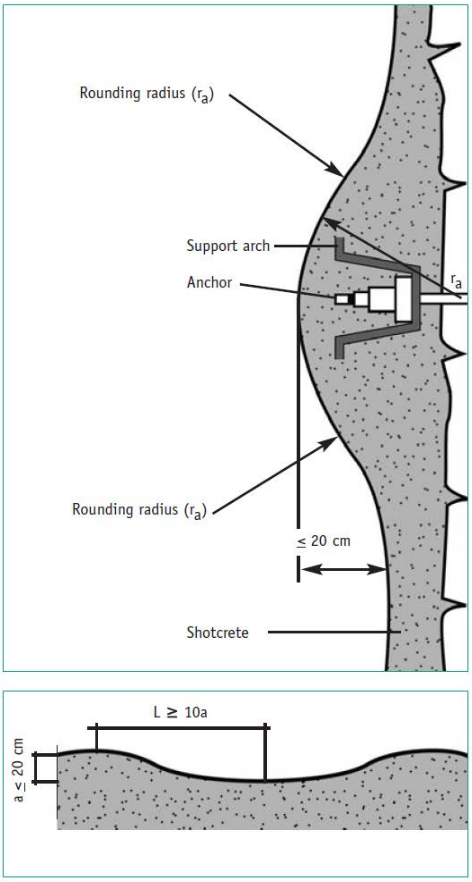

Figure: Surface requirements shotcrete

4. Waterproofing Installation with quality control system

4.1 Quality controlled Installation

The installation of waterproofing systems especially in NATM tunnels required an experienced sealing company. To achieve the optimal result in waterproofing it is necessary that the waterproofing company will be approved as a long term experienced and qualified company for tunnel waterproofing. This approval could be also achieved with a quality certification which is available for example from the tunnel association “Arbeitskreis Tunnelabdichtung e.V.”. For this certification the installation company has to work according to the quality guidelines of the “Arbeitskreis Tunnelabdichtung e.V.”. The frequently external testing will be done from the STUVA e.V.
After the successful test procedure of the STUVA e.V. the waterproofing company get the allowance from the “Arbeitskreis Tunnelabdichtung e.V.” to hold the Certificate as an approved tunnel waterproofing expert.

4.2 Common installation processes

Installation of tunnel waterproofing systems

Sealing the floor level

When using tunnel geomembrane as the floor sealing system (e.g. in hydrostatic water pressure applications), a protection nonwoven geotextile is installed as protection layer to prevent mechanical stress. Geotextile is attached to the carrier construction, using Polyethylene (PE) roundels, to prevent movement and slippage. The tunnel geomembrane is then installed in the slightly curved floor. In order to prevent the tunnel geomembrane from slipping, it is welded against to the PE roundels. It is recommended that the tunnel geomembranes laid in the floor area are installed to approximately 1 m above the top edge of the floor concrete reinforcement bars. This makes it possible to weld the floor sealing correctly to the sealing system of the arch. A further welding of the tunnel geomembrane is carried out between the geomembrane and the waterstops at the segmental block joints. After the quality inspection and acceptance of all welding work, a 3 mm thick protection geomembrane with signal layer is installed and welded. The edge of the floor tunnel geomembrane must also be welded to the protection geomembrane to prevent any cement suspension protruding between the layers.

Figure: Installed waterproofing bottom slab

Sealing arches, Calotte and side wall sealing

The tunnel geomembrane for sealing arches and tunnel side walls is installed radially to the structure’s axis using movable scaffolding and welded to the drainage connection joint or the floor sealing system. During the first working step, the protection geotextile or geosynthetic drainage mats are attached to the shotcrete sealing carrier system with a bolt gun, using steel nails and PE roundels. On average, the numbers of anchoring points (roundels) that are fastened to the shotcrete supports geotextiles with bolt-driven steel nails are approximately 2 until 3 pieces/m². Tunnel geomembranes are installed with sufficient lateral overlapping at the edges. This makes an easy welding of the next tunnel geomembrane. The Tunnel geomembranes are positioned by working from the installation scaffolding and are hot air welded to the roundels. The roundels have a predetermined breaking point, so that in the case of excessive stress the tear will not be within the geomembrane. The thickness of the tunnel geomembrane must not be minimized by such an occurrence.

Figure: Installed waterproofing arch

Welding and testing methods

Welding can be done independent of the state (roughness, waviness) of the sealing carrier system. However, basic requirements are an ambient temperature of at least 5°C and a relative humidity of less than 80 %. One of the installation personnel positions the lightweight welding device between the overlapping tunnel geomembranes to be welded and continuously monitors the required overlap width of the geomembranes. The homogeneous welding of the tunnel geomembrane is carried out with hot wedge welding machines that create a testing channel between two parallel-running welded seams. The created double seam is tested with compressed air. Additional tests for the mechanical strength of these am are also performed. The testing of all the seams is usually done at the end of the working day.

Figure: Installation of waterstops

Figure: Testing with air pressure

Waterstops are used in tunnel construction to seal block joints, create segmental sections and allow connections between geomembranes. Tunnel geomembranes and waterstops are made of similar materials, so that a problem-free and permanent weld is possible between waterstops and a geomembrane.

In order to achieve the flawless encasing of waterstops in concrete, in particular in the arch area, it is absolutely necessary that the use of injection de-airing tubes is allowed for.

Figure: Installed water stops

5. Summery and Conclusion

A successful realisation of a tunnel construction including a waterproofing system based always on the following three columns:

- **Design and planning**
- **Waterproofing materials**
- **Professional and certified installation**

5.1 Influence of the design and planning

With the beginning of the planning a waterproofing specialist should be involved as a consulter for the tunnel design for all waterproofing details. These systems save the right waterproofing design. That means that in the first stage of a tunnel project the main points for waterproofing like the planning of the right membrane materials and the requirements for a professional installation will be fixed.

5.2 Influence of the choice of waterproofing materials

In view to the common requirement of a service time life of more than 100 years for tunnel constructions and in view to the fact that the membrane waterproofing system cannot easily changed or repaired after finishing the main concrete construction the TPO (VLDPE) membranes have much better technical arguments. Based to the long term durability and resistance against external influences which are shown in these paper; for tunnel constructions with a concrete inner shell should be only used TPO (VLDPE) tunnel membranes without any plasticiser.

5.3 Influence of the Quality of installation

It is a very important part to install all components of the waterproofing system in a professional way because all possible mistakes could cause very expensive renovation works. That is the reason that only approved installation companies should be used for waterproofing works. A perfect design and perfect long term durable tunnel waterproofing membranes alone is therefore not enough. A professional waterproofing company should have a long term experiences in these applications and should have a completely quality system (e.g. DIN EN ISO 9001). In the optimal case the waterproofing company has a quality certification as a tunnel waterproofing expert according to the requirements of the association “Arbeitskreis Tunnelabdichtung e.V.” These requirements will be tested and approved from the STUVA e.V.

Summary

The requirement of the expected lifetime for a tunnel construction fixed the expected lifetime for the sealing system too, more than 100 years.
A long term trouble-free tunnel construction with low operating and maintenance costs can be achieved only with a professionally installed waterproofing system and with long term durable waterproofing membrane materials.

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