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ISBN 978-0-7277-6500-0
https://doi.org/10.1680/icehge.65000.353
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Chapter 18
Hydraulic and transport tunnels, and shafts

D. Cazzuffi*, A. Scuero† and G. Vaschetti‡
*CESI, Milano, Italy, ORCID: 0000-0003-2384-7880
†Carpi Tech, Balerna, Switzerland
‡Carpi Tech, Balerna, Switzerland

Abstract
The main function of hydraulic tunnels is to convey water, under pressure or in free flow, for power and/or water supply works. Hydraulic tunnels are usually lined with steel, cast in situ concrete or sprayed concrete. The most common concrete linings are rarely free from defects such as voids and cracks. During operation, when the concrete linings are exposed to the dynamic action of water, they suffer from deterioration, resulting in the formation of fissures/cracks, increased permeability through the body and joints, and increased roughness. The use of geomembranes allows the combination of continuous watertightness and improved friction properties with the strength of the concrete lining at a much lower cost. Geomembrane systems have reached a high degree of refinement and reliability, and, when adequately designed and installed, they are durable and reliable under high water heads and demanding environments. This chapter provides a complete description of the engineering aspects of geosynthetic-based lining systems for new and old hydraulic tunnels. Geomembrane waterproofing systems for transport tunnels, and for shafts, are also addressed.

18.1. Introduction

Hydraulic tunnels are mainly used as means to convey water, under pressure or in free flow, to be used for power and/or water supply works. Except for old tunnels excavated in competent self-supporting rock, hydraulic tunnels are usually lined with steel, cast in situ concrete or sprayed concrete. In unstable ground, the lining provides structural stability by supporting the excavation. Another important requisite of hydraulic tunnel lining is to provide a waterproofing function by preventing water from seeping out, or water and other deleterious chemicals from entering the tunnel. A further requirement is to improve the hydraulic performance of the excavation by reducing friction losses. Similar considerations on the need for a liner, and on the type and functions of the liner, apply to surge shafts and pressure shafts.

Traditional linings for hydraulic tunnels and shafts have been steel or concrete. Steel addresses all the above criteria; however, the lining thickness required to achieve the criteria often makes it an economically unattractive solution, being both more expensive as a material and more time consuming in its installation. On the other hand, concrete linings are rarely free from defects such as voids and cracks that generally arise because of thermal stresses or poor construction. In addition, during operation, when the concrete linings are exposed to the dynamic action of water, they suffer from deterioration, resulting in the formation of fissures/cracks, increased permeability through the body and joints, and increased roughness leading to increased friction losses that reduce power generation and water supply (Scuero *et al.*, 1999). Movement in the slopes, due to loose or fractured soil, faults and folds, the presence of water, etc., and the quality of flowing water (pH), could also further aggravate the deterioration of the concrete lining (Figure 18.1).

The loss of water into the surrounding ground is extremely serious as it may jeopardise the stability of the ground and that of the structure itself. This is particularly true in areas of low horizontal or vertical overburden. In steep mountain areas, and in areas of unfavourable geology, escaped water can erode the soil, and eventually start landslides or cause collapse of the subgrade on which the tunnel is founded. Exceptionally dangerous is the situation in high-pressurised concrete (reinforced and unreinforced) tunnels and shafts in rock, where leaks are usually very small; however, they can cause large failures because of the full or nearly full static head that may develop and is transferred through cracks or joints in the rock even over great distances. The flow of water through the cracks can be close to zero, but full static pressure can be transmitted to the surrounding ground. Leakages can also cause weakening of the ground (gypsum or salt), resulting in movements affecting the tunnel. Furthermore, cracks and joints in the concrete lining allow groundwater to act as a hydraulic jack and affect the durability of the reinforcement.

The unexpected deterioration of concrete lining systems, even if stability is not at stake, entails high maintenance costs of dewatering and periods of loss of service. In the case of leaking wastewater tunnels, a further threat is posed by potentially deleterious substances coming into contact with the groundwater. It is therefore advisable to line newly built concrete tunnels and shafts with an impervious geomembrane during construction. Geomembrane waterproofing systems are a cost-effective and efficient solution to prevent design and construction delays, and minimise outage loss and repair and maintenance costs, and other consequences of a failure that could be caused by a minor leak.

The development of manufacturing and installation techniques, since the late 1950s, has established the use of prefabricated

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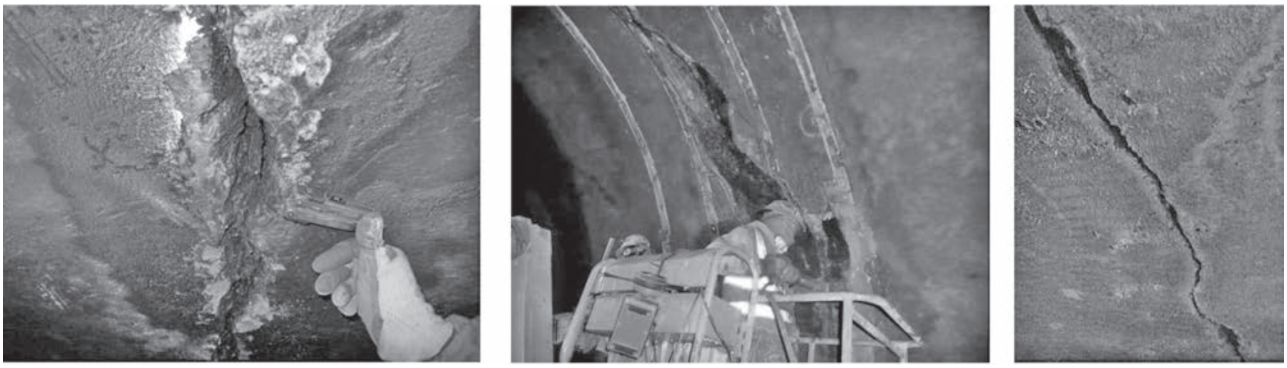
Figure 18.1 Defects in pressure tunnels caused by ground movement/settlement: (a, b) crack development and (c) fissure opening



(a) (b) (c)

synthetic geomembranes as dependable, long-term waterproofing liners for hydraulic structures. A membrane liner can be formed by one single material (geomembrane), or be a composite material (composite geomembrane), the latter consisting of a geomembrane (providing barrier properties) heat coupled during manufacturing to a nonwoven geotextile that increases mechanical resistance and dimensional stability in respect to temperature variations, and provides some drainage capability. The first underground application of a synthetic geomembrane dates back to 1969, when it was used in a subway station in Vienna, Austria. In hydraulic tunnels and shafts, considerable experience has been acquired since the 1970s. Some Austrian applications in hydraulic tunnels and shafts with polyvinylchloride (PVC) geomembranes account for static and dynamic pressures up to about 500 and 740 m, respectively (Heigerth *et al.*, 1979; Laufer, 1985; Scuero and Vaschetti, 1997; Seeber, 1982, 1985).

This chapter describes in detail the engineering aspects of geosynthetic-based lining systems, especially geomembrane systems for waterproofing of hydraulic tunnels and shafts in new construction as well as in rehabilitating old ones. The design of geomembrane systems for transport tunnels, which is another application of geomembrane liners within their broad range, is also part of the chapter.

18.2. Geomembrane systems in hydraulic tunnels

18.2.1 Applications

Geomembrane systems can be installed as a waterproofing layer for new construction, typically as a covered solution, or on rehabilitation projects as a repair measure for deteriorated leaking linings, typically as an exposed solution.

The exposed solution can be adopted in rehabilitation, as well as in new construction, for water velocities of several metres per second and uplift pressures of several megapascals. In an exposed solution, the geomembrane is generally bonded to a geotextile to form a composite geomembrane (Figure 18.2) and applied to the existing lining.

The covered solution is typically adopted for new tunnels, but it can also be used in rehabilitation in the case of particularly severe service conditions. In a covered solution, the geomembrane is not bonded to the geotextile but is placed over an independent anti-puncturing layer of geotextile. It is typically located between the outer sprayed concrete and the inner concrete lining (Figure 18.3).

The waterproofing layer can be applied to the entire tunnel cross-section (pressure tunnels) or specifically to the problematic areas (free-flow tunnels), as shown in Figures 18.4–18.8.

Figure 18.2 Layering of a drained exposed system

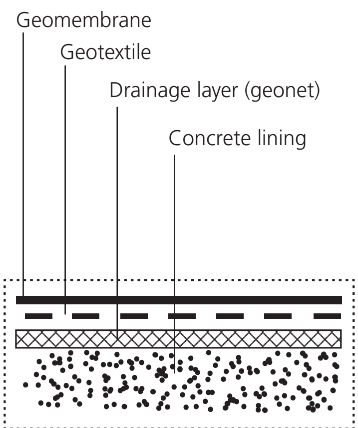


Figure 18.3 Layering of a fully covered system

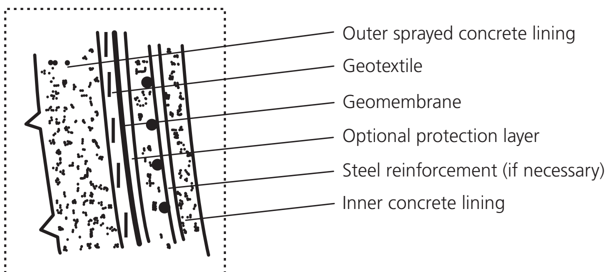


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Figure 18.4 A typical pressure tunnel cross-section, where the geomembrane system is placed all around the tunnel cross-section and covered with a structural inner concrete lining

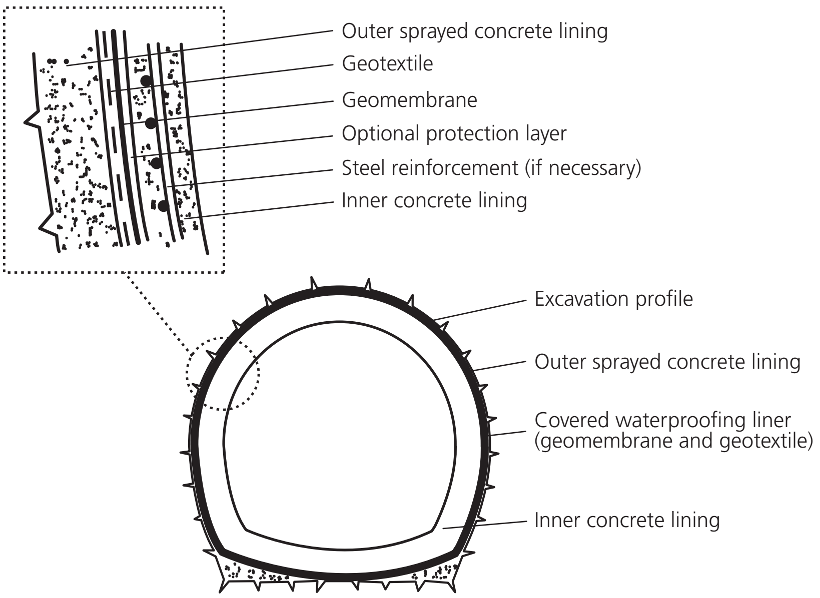

Figure 18.5 A typical pressure tunnel cross-section where the composite geomembrane is exposed

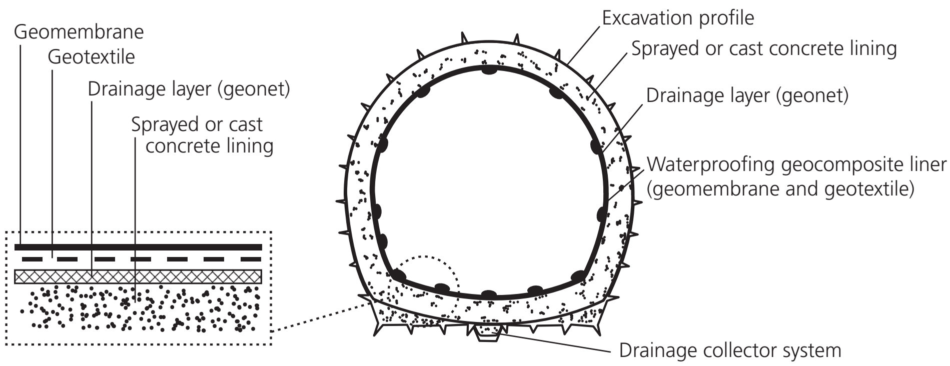

Figure 18.6 A typical free-flow tunnel cross-section where the geomembrane is placed over the walls and invert, and left exposed

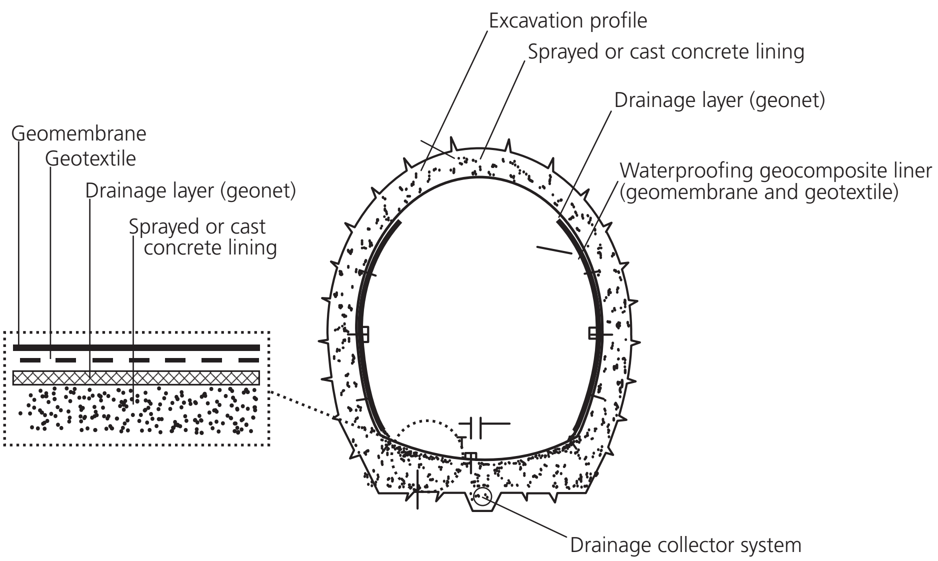

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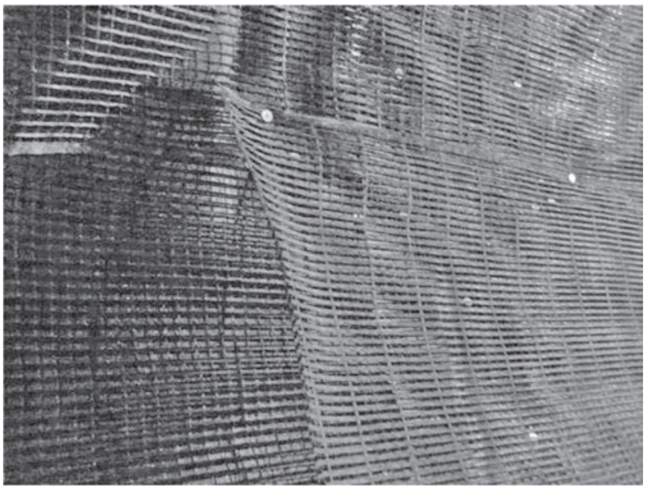
Figure 18.7 Large cracks injected with acrylic resins or cementitious grout prior to the installation of the waterproofing composite geomembrane system

Figure 18.8 A geogrid being installed on active cracks, generally done in addition to or as an alternative to injection of large cracks



The selection of the solution depends on the physical and operational characteristics of the tunnel, and on the scope of the lining. Physical and operational characteristics to consider are the water head, the static and dynamic pressure inside the tunnel, the water velocity, the negative pressure inside the tunnel due to suction during closing and opening of turbine valves, the negative pressure outside the tunnel when the tunnel is empty (elevation of the water table in the soil surrounding the tunnel), the tunnel operation (always full or mostly empty) and the presence of chemicals aggressive to concrete.

18.2.2 Types of geomembranes

The experience in hydraulic tunnels consists mainly of PVC geomembranes and composite PVC geomembranes. Some applications of polyethylene (PE) and polypropylene (PP) geomembranes have also been reported.

Extensive experience with PVC geomembranes in underground tunnels goes back for over 30 years. Since then, according to the International Tunnelling Association, PVC geomembranes have been employed in over 92% of lined tunnels all over the world. The reasons for such an impressive record are the following.

- Geomembranes possess very low permeability ($k = 10^{-12}$ m/s), at least three orders of magnitude lower than new concrete.
- Geomembranes possess greater than 200% elongation, which allows the bridging of old and new cracks, and for considerable movements that can occur in the slopes.
- Geomembranes are a thin (of the order of a few millimetres) lining that does not reduce the cross-section of the tunnel.
- Geomembranes possess a Manning (Gauckler–Strickler) coefficient n of less than 0.0115, which is not affected by operation. If left in contact with flowing water, they will increase the water flow compared with a concrete lining.
- Geomembranes possess excellent chemical resistance.
- Geomembranes possess excellent flexibility over a wide range of temperatures.
- Geomembranes have very good weldability even in a wet environment, and a wide weldability temperature range, about three times that acceptable, for example, for PE and PP membranes.
- Technologically advanced methods of welding and testing are available.
- A wide range of compatible accessories are available (waterstops, disks, grouting hoses, grouting profiles, etc.).
- Geomembranes are easy to handle to optimise installation.
- Geomembranes have performed outstandingly. Several million square metres of laid PVC geomembrane in tunnels can confirm the effectiveness of the material and of the system.

18.2.3 Benefits

The scope of the waterproofing liner is not necessarily only watertightness: other possible objectives are, for example, to decrease friction losses or to provide an elastic barrier to water infiltration in the event of excavations performed in expansive soil. Some of the major benefits of geomembrane systems are listed below.

- *Durability*: Installations dating from the 1960s and early 1970s are still in service (Cazzuffi and Venesia, 1989). Tests have been performed on PVC geomembrane systems that indicate that the geomembrane will last more than 50 years when directly exposed to an outside environment. Geomembrane formulations have been upgraded since the early 1970s and, additionally, the thickness of the geomembrane has been increased, so that it can be safely assumed that geomembranes installed today will have an even longer service life. Considering the underground environment of hydraulic tunnels, the composite geomembrane will never be exposed to ultraviolet rays, and PVC geomembranes and composite geomembranes show no reduction in performance even over extremely long periods of immersion in water. The durability of the composite geomembrane is thus several decades, without the need for maintenance.

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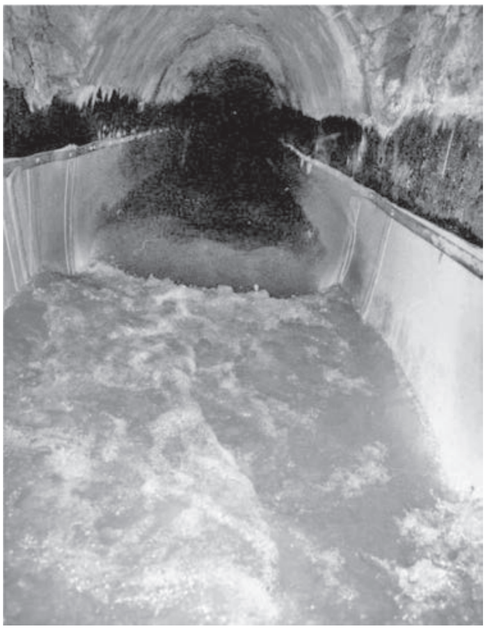
- *Waterproofing*: This refers to the elimination of inward and outward leakages. The measurement of leakage after an installation is typically so low as to be statistically insignificant. The system has no discrete joints, and forms a bridge over new cracks.
- *Hydraulic efficiency*: When left exposed, the smoothness of a PVC geomembrane can increase the velocity of water and the flow capacity of the tunnel, decreasing the maximum water level (Figure 18.9).
- *Geometry*: When left exposed, a geomembrane system does not reduce the tunnel envelope.
- *Maintenance*: In hydraulic tunnels, the reliability of the seal is of particular significance, since once in operation it is not easily accessible for subsequent repairs. Exposed geomembrane systems require no planned, routine or preventive maintenance. Removal of sediments that will deposit on the geomembrane is required for the hydraulic performance of the tunnel, not for the integrity or the performance of the geomembrane. Furthermore, the installed and exposed geomembrane allows for much easier control of future performance and cheaper maintenance during the years to come.
- *Installation costs*: The installation cost of a geomembrane system is lower compared with other lining systems. The long service life of the system further reduces the life-cycle costs. The installation of the geomembrane requires only simple hand tools that can operate in various weather or environmental conditions. This prevents weather from being a factor affecting the quoted price, and assures consistent quality of the final installation. Geomembranes do not have many environmental or mechanical systems that can prevent or delay the work. Additionally, an exposed geomembrane reduces the quantity of construction material to be transported inside the tunnel and the need for preparation works when compared with steel lining. Because mobilisation does not require the movement of large equipment, the job can be undertaken over several years, with the main requirement being only the remobilisation of personnel.
- *Programme*: The possibility of the modular installation of the geomembrane system allows installation in sections based on the customer's operating requirements, thereby saving the customer money by reducing the downtime during installation.

The use of flexible PVC geomembranes provides a combination of continuous watertightness and improved friction properties of a steel liner with the strength of a (reinforced) concrete lining, but at a much lower cost.

18.3. The exposed liner system

As already stated, exposed solutions, which can be adopted in rehabilitation and in new construction, for water velocities of several metres per second, and uplift pressures of several megapascals, are most frequently used for rehabilitation (Cazzuffi, 1995). In pressure tunnels, prefabricated synthetic geomembrane sheets are used to cover the entire inner surface of the tunnel, bridging existing cracks, fissures and construction joints. Underground water is usually collected in the invert or haunches by means of a drainage system (see Figure 18.5). In free-flow tunnels, the exposed composite geomembrane waterproofing system is typically applied to the lower section of the tunnel, which in existing tunnels coincides with the wet damaged area (see Figure 18.6).

Figure 18.9 Increased water flow, due to the presence of a geomembrane, resulting in a decrease in the overall water level



18.3.1 Support system

The substrate, particularly in rehabilitation work, needs to be prepared. Where large cracks and joints are present, they should be treated and covered with a support geogrid prior to the installation of the drainage and waterproofing layers. This layer is intended to improve the efficiency of the system by spanning large openings, and preventing the geomembrane from collapsing into the gap and getting damaged in the process (see Figure 18.8).

The waterproofing system must ensure that imperviousness is provided and maintained, notwithstanding movements at joints and opening cracks. In the case of rehabilitation work, the substrate needs to be prepared, and large cracks and joints are treated (see Figure 18.7) and covered with a geogrid (see Figure 18.8) prior to the installation of the waterproofing system. The efficiency of the system to accommodate displacements, rotations and opening of fissures without rupturing has been proven by over 30 years of field performance.

18.3.2 Drainage system

Inward external pressure caused by the hydrostatic load, applied by the groundwater entering the tunnel structure from behind the composite geomembrane, since the composite geomembrane forms an impermeable barrier, can build up. If not discharged, the built-up pressure can, in some circumstances, destroy the installation. For this reason, a method to drain behind the composite geomembrane is provided: the build-up of pressure due to groundwater is negated by the presence of a drainage system (Yoo, 2015).

The drainage system consists of a draining layer and of a drainage discharge system. The draining layer is a highly permeable

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material, typically a geonet, installed over the substrate and fastened by means of impact anchors (Figure 18.10). The geonet is covered by the waterproofing composite geomembrane. The drainage system provided behind the composite geomembrane collects the water and discharges it outside the tunnel when possible; if outside discharge is not possible, patented one-way valves, made of the same composite geomembrane material, operated by pressure differentials and discharging inside the tunnel, are available. The relief valves will open only when the pressure inside the tunnel is less than the pressure from the surrounding soil, usually when the tunnel is empty. The valves discharge inside the tunnel the water conveyed by the drainage layer. Other types of geosynthetics are also used as drainage in underground applications as described by Cazzuffi *et al.* (1986).

18.3.3 Waterproofing liner

The waterproofing layer used in the state-of-the-art projects is a very low-permeability composite geomembrane, composed of a PVC geomembrane, a few millimetres thick, bonded during fabrication to a geotextile that enhances its anti-puncture resistance, placed over the substrate/support/drainage layers (Figure 18.11).

Figure 18.10 A geonet fastened to the substrate by means of impact nails

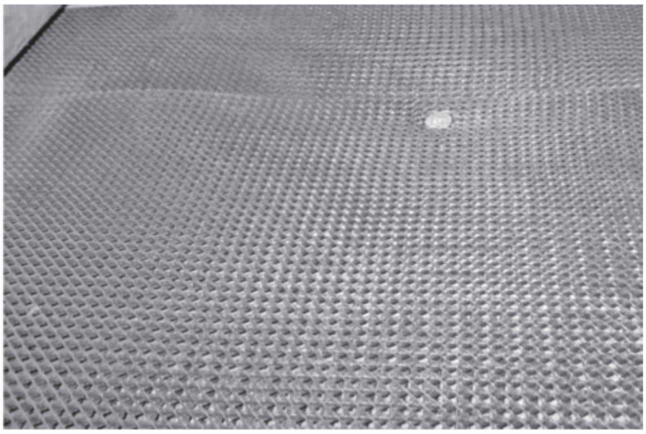


Figure 18.11 Placing of the composite geomembrane inside a pressure tunnel in the Czech Republic

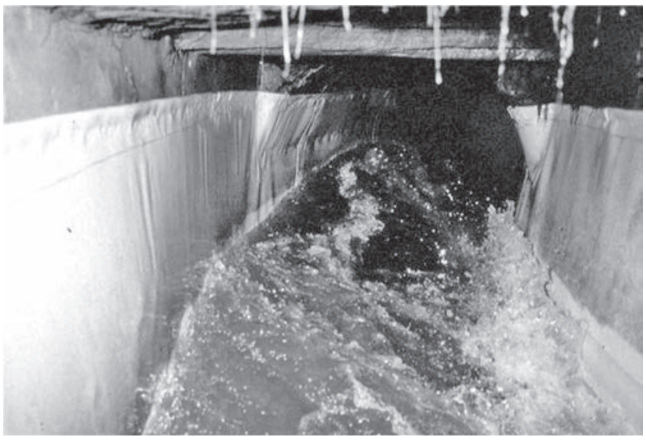
Particular provisions, such as an additional layer of geotextile, must be made to avoid the intrusion of the waterproofing liner into possible cracks in the substrate, in presence of high-water heads. The composite geomembrane is left exposed to contact with the water flowing inside the tunnel, and is designed to withstand mechanical actions (abrasion, impact and tear) due to flowing water (Figures 18.12 and 18.13), and transported materials and sediments.

18.3.4 Fastening system

The fastening system consists of lines of stainless-steel profiles, anchoring the composite geomembrane to the substrate, be it

Figure 18.12 Exposed composite geomembrane in a free-flow tunnel

Fig. 18.13 Exposed composite geomembranes to resist high water velocities and turbulence



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concrete or natural ground, and keeping it independent from it. The elastic geomembrane can thus freely deform over it when the tunnel is dewatered. They are typically placed along the longitudinal axis of the tunnel. There are two types of linear fastening available: tensioning profiles (originally developed and used in the rehabilitation of dams, and later adopted in water conveyance structures due to their efficiency) and flat profiles (Figures 18.14 and 18.15). If both types are used, they are generally arranged in alternate lines, with the spacing depending on the foreseen operation conditions of the tunnel. When the tunnel is in operation, the composite geomembrane will be pushed against the existing surface of the concrete lining by the water pressure; when the tunnel is empty, the composite geomembrane will be subject to minimum deflections.

Tensioning profiles are made of two parts, the internal and the external profiles. The internal profile is anchored to the concrete structure by means of chemical anchors, whereas the external profile is installed over the PVC composite geomembrane and clamped to the internal one. The tensioning profiles, in addition to anchoring the waterproofing liner to the existing tunnel liner, also pretension the geomembrane to eliminate wrinkles and slack areas (Figures 18.16 and 18.17), improving the hydraulic efficiency. Tensioning will result in the most effective adherence of the composite geomembrane to the existing surface. In the event of a tear in the composite geomembrane, the tensioning profiles will maintain the composite geomembrane in place, preventing it being carried away by the water flow towards, for example, the turbines. Negative pressure due to suction is taken into account

Figure 18.14 Tensioning profiles

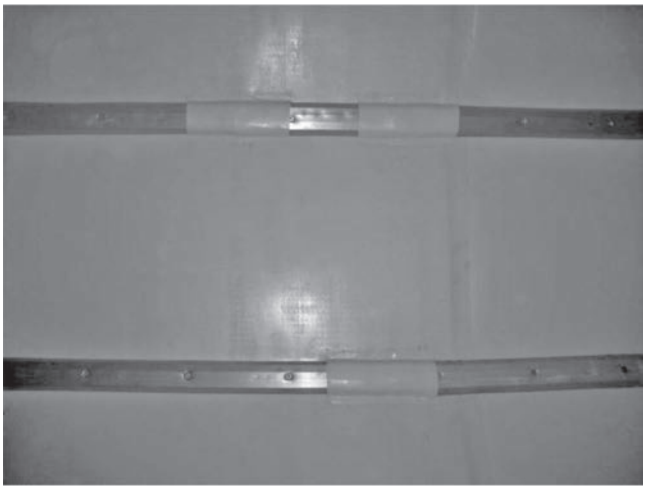

Figure 18.15 Flat and tensioning profiles arranged across a tunnel perimeter

Figure 18.16 External tensioning profiles installed over a composite geomembrane to remove any slack in a pressure tunnel in Greece

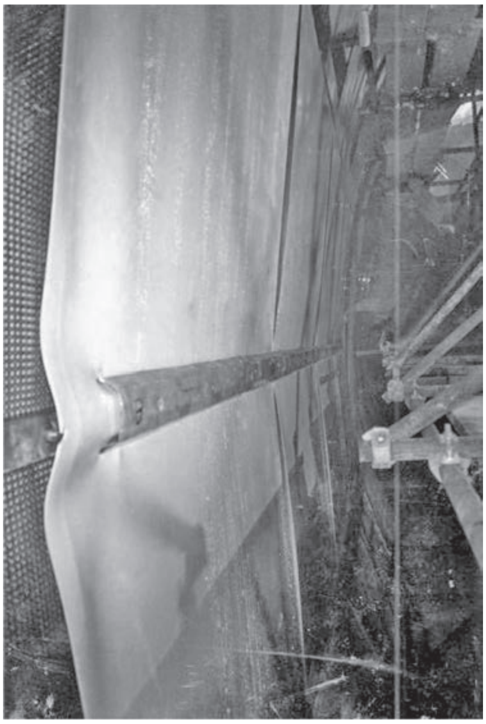

Figure 18.17 Stretching of the composite geomembrane through tightening of the external tensioning profile

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when designing the fastening system. The operational conditions dictate the positioning of the fastening lines, the type of anchorage method, and the need for particular provisions at sections influenced by the peak suction areas, also due to transients. The number, type and position of the fastening anchorage profiles are designed as a function of the inward pressure caused by groundwater in the case of dewatering, of suction occurring during the operation of the tunnel, and of the dynamic action of water that would result from a tear in the geomembrane.

The flat profiles are fastened by mechanical anchors. All profiles are covered by waterproofing PVC geomembrane strips. Additional steel plates are used in the areas affected by suction due to transients, to provide support against the detaching action of the suction. In a few recent projects, profiles that are intrinsically watertight and do not require waterproofing strips have been adopted.

If in-service conditions (high uplift, high water velocity or suction) require very closely spaced anchorages for the geomembrane, a covered solution may become more cost-effective.

18.3.5 Perimeter seals

The waterproofing system is sealed at the perimeter (the beginning and end of the waterproofed section, and any other submersible periphery) by means of stainless-steel profiles compressing the composite geomembrane against the existing surface. The distribution of compression forces is made by layers of resin bedding mortar and neoprene gaskets of adequate consistency (Figure 18.18).

18.4. The covered liner system

The covered geomembrane system described combines Austrian and Italian expertise, and construction of hydraulic tunnels with waterproofing geomembranes. In the 1960s, the so-called new Austrian tunnelling method was developed, which is now used all over the world. The covered solution is mostly adopted for new pressure tunnels, and can be used in rehabilitation in the case of particularly severe service conditions. The covered solution is adopted when high external pressure is exerted by groundwater on the geomembrane at dewatering of the tunnel, due to water present in the slopes. The covered geomembrane system provides stability of the liner under very high piezometric heads, as the inner concrete lining constitutes the permanent support of the geomembrane. This makes it necessary for the geomembrane system and inner concrete lining to be designed to cope with the groundwater pressure.

In this solution, the flexible PVC waterproofing geomembrane is sandwiched between the natural excavation, the smoothing shotcrete layer, the outer concrete lining or the existing structure (depending if new construction or rehabilitation), as described for the exposed solution, and the inner concrete (reinforced or unreinforced, according to the structural design) lining that supports the geomembrane.

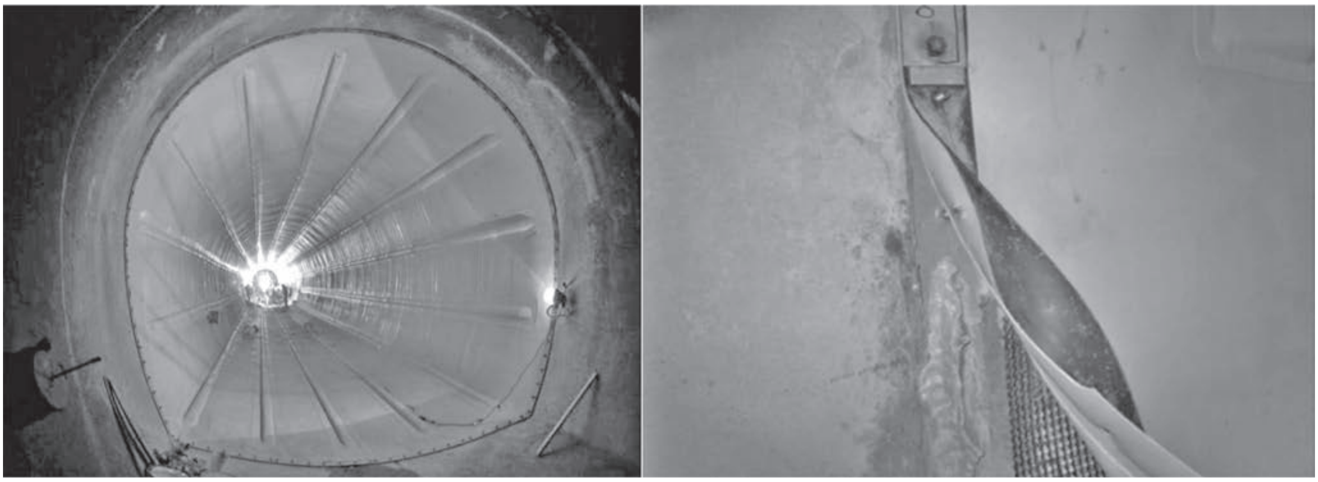
The same system is adopted in shafts and in transport tunnels, as discussed in the related sections. According to Austrian experience, the covered geomembrane system is extremely suitable for application in pressure shafts up to a medium head (30–500 m). Tests have also been performed successfully up to 900 m (Heigerth, 1982). The resulting layering of the tunnel and of its waterproofing system is as follows

(*a*) natural excavation line
(*b*) structural/smoothing shotcrete (outer shotcrete lining)
(*c*) anti-puncture geotextile layer
(*d*) waterproofing composite geomembrane layer
(*e*) protection layer (optional)
(*f*) inner concrete lining.

18.4.1 Protective anti-puncture geotextile

The protective anti-puncture layer under the geomembrane is typically made from a material such as a geotextile, resistant to the aggression of fresh shotcrete and that can further regularise the substrate for installation of the waterproofing geomembrane.

Figure 18.18 The perimeter seal



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This layer is secured to the outer shotcrete ring by shot nails equipped with PVC roundels, specially designed to provide temporary anchorage of the PVC geomembrane while at the same time avoiding excessive stresses being applied to it before concreting of the inner ring occurs (Figure 18.19).

18.4.2 PVC waterproofing geomembrane

The PVC waterproofing geomembrane provides a barrier to aggression of the underground environment both in the short term, to allow construction of the inner concrete ring (placement of fresh concrete), and in the long term, when it will protect the structure of the tunnel from deterioration due to infiltration of aggressive water. It will also stop any water loss through fissures that should form in the concrete. The waterproofing liner is typically a PVC geomembrane, at least 2 mm thick, placed over the geotextile and heat welded to the back surface of the roundels (Figure 18.20). The roundels are made in a colour different from that of the waterproofing liner (Figure 18.21). The geomembrane is often composed of two layers, to improve the detection of any damage: the upper signal layer is usually of a light colour, and the lower layer is a darker colour. Any damage affecting the integrity of the composite geomembrane will be easily detected by sight by the appearance of the darker colour of the lower layer.

18.4.3 Protective layer (optional)

The optional protection layer, which could be either a geotextile or another sacrificial sheet geomembrane of reduced properties, is installed on the waterproofing liner before the inner concrete ring is cast, to protect the geomembrane against potential mechanical damage caused by construction of the inner concrete lining, including the placement of reinforcement. It is good practice to install a sacrificial geomembrane layer over the waterproofing geomembrane at those zones that can be affected by the steel reinforcement, the invert (Figure 18.22), or by the stop ends of the formworks, or where construction of the concrete lining poses a particular risk of damaging the PVC geomembrane, such as in correspondence of the joints. A heavy-duty PVC protection geomembrane 1.5 mm thick, of the same type as the waterproofing liner, is placed as a sacrificial 0.50 m-wide

Figure 18.19 Geotextile applied and secured by shot nails and PVC roundels in the foreground

Figure 18.20 Geomembrane heat welded to the roundels

Figure 18.21 Close up of a roundel

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Figure 18.22 Geomembrane installed in the crown, walls and invert, and a protective sacrificial layer of geomembrane (black) in the invert

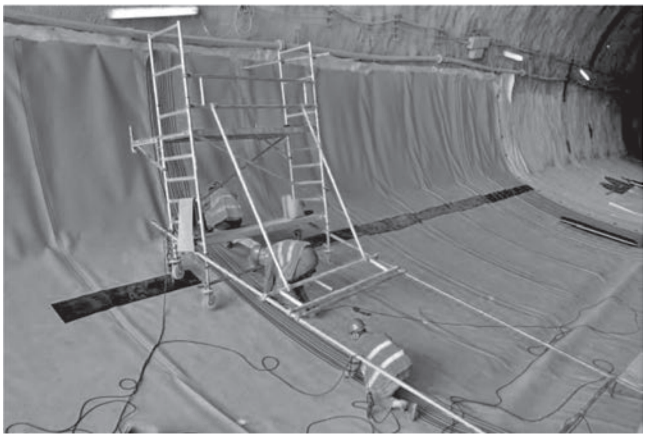
band over the joints. An additional sacrificial geomembrane layer will be placed on the invert to avoid possible damage during the invert concreting working phases.

18.4.4 Protective seals and inner (reinforced) concrete lining

End fastenings are generally as described in Section 18.3.4 for the exposed geomembrane solution. The anchor bars providing attachment of the reinforcement for the inner concrete ring are secured directly on the natural rock, and they penetrate the protective anti-puncture geotextile layer, the PVC geomembrane layer and the protection layer, if applicable. The anchors are equipped with watertight fittings to avoid water seepage at crossings of the waterproofing liner. They must be designed for the maximum head to which the system is subject (the water head or grouting pressure). If the reinforcement is self-supported, however, no anchoring is required. New design trends seek to avoid or minimise the penetration of the geomembrane using self-supporting reinforcement cages, which do not require drilling holes in the waterproofing liner, and which should ideally be hole-free.

Compartmentalisation is generally adopted to divide the lined area into shorter sections. Following the installation of the waterproofing geomembrane and before casting of the inner concrete lining, PVC waterstops are heat welded onto the waterproofing geomembrane at the perimeter of each compartment (Figure 18.23). The concrete is then cast, embedding the waterstops. The location of circumferential waterstops is strictly related to the length of the formwork. Longitudinal compartmentalisation will be located at the joint between the invert and the walls.

Figure 18.23 Longitudinal compartment seal made by welding the waterstop to the geomembrane. (Note: the waterstop is then embedded in the concrete lining)

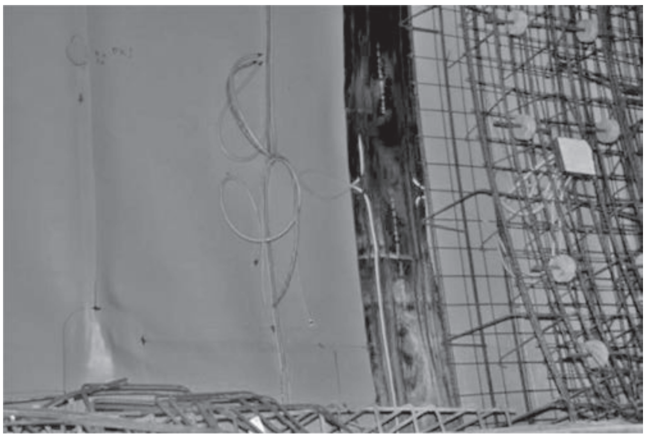


Since, as recognised by international experience, perfect placement of the concrete and filling of all voids in the vault is impossible to achieve in practice, an allowance for grouting is made to prevent faulty concrete arising in the inner lining, particularly in the crown. Grouting is carried out once the concreting is complete, using horizontal injection hoses, previously attached to the geomembrane or placed at the top of the reinforcement (Figure 18.24). The inner concrete lining is usually constructed in two stages: one stage for the invert, and another for the crown and walls.

18.5. Geomembrane systems in transport tunnels

Geomembranes are extensively used in road, railway and metro tunnels as the internal water barrier protecting the inner concrete lining. As in all underground structures, infiltration of water is detrimental to the safe and durable performance of the tunnel. At a high water head, infiltration water may cause fissuring, jacking or washing out effects in the concrete lining, while at a lower head, water seeping through the concrete may cause damage to traffic and

Figure 18.24 Post-grouting arrangement at a waterstop



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equipment inside the tunnel. A geomembrane waterproofing system prevents groundwater from entering the tunnel and compromising the service of the structure, protects the inner concrete lining against deterioration, avoids formation of dangerous ice stalactites inside the tunnel, and eliminates/minimises maintenance.

18.5.1 Applications

In new construction as well as in rehabilitation, the waterproofing geomembrane is always covered. In new construction, the geomembrane system is installed over a smoothing layer of sprayed concrete or over an outer lining. In rehabilitation works, the geomembrane system is installed directly onto the deteriorated lining; the reduction in the cross-section caused by the new inner concrete lining may require local demolition in order to restore the free space needed for traffic.

The layering of the waterproofing system is the same as used in hydraulic tunnels. The geomembrane can be applied to the entire tunnel cross-section (fully tanked solution), or to the crown and walls in an 'umbrella'-type configuration (drained solution), or specifically to the problematic areas.

In tunnels in weak or loose rock and soils, or in urbanised areas where the minimisation of settlement is vital, the fully tanked solution is needed (Figure 18.25), and the lining must be designed to withstand the full water pressure.

For situations where it is necessary to ensure that pressure does not develop behind the lining, the drained solution should be used (Figure 18.26). Water behind the lining is usually collected in the haunches or invert by means of a drainage system that relieves the tunnel from water pressure. To avoid failure of the drainage system due to sintering/clogging, the design should make an allowance for water build-up.

18.5.2 Protective anti-puncture geotextile

The protective anti-puncture layer under the geomembrane is usually a geotextile, laid on the outer ring and secured to it with shot nails equipped with PVC roundels to which the waterproofing liner will then be heat welded (Figure 18.27), as described for hydraulic tunnels.

18.5.3 Waterproofing liner

PVC is the material mostly used for transportation-related applications, followed by chlorinated polyethylene (CPE), and chlorosulfonated polyethylene (CSPE). The use of PE is less common because ease of constructability takes precedence over chemical resistance, which is not usually a compelling criterion in these applications.

In traffic tunnels the PVC geomembrane is either a two-layer geomembrane (geomembrane with an upper signal layer), as mentioned for the covered system in hydraulic tunnels, or a transparent geomembrane. The transparent geomembrane has the additional benefits that it allows visual assessment that

- the anchorage of the PVC roundels to the subgrade has been done properly (Cunegatti, 2019)

Figure 18.25 The fully tanked solution. Application of the waterproofing system all around the tunnel cross-section; no drawdown of the groundwater table. The tunnel inner lining is in compression. 1, temporary drainage; 2, sprayed concrete layer; 3, geotextile layer; 4, waterproofing geomembrane over the whole tunnel cross-section; 5, inner concrete lining

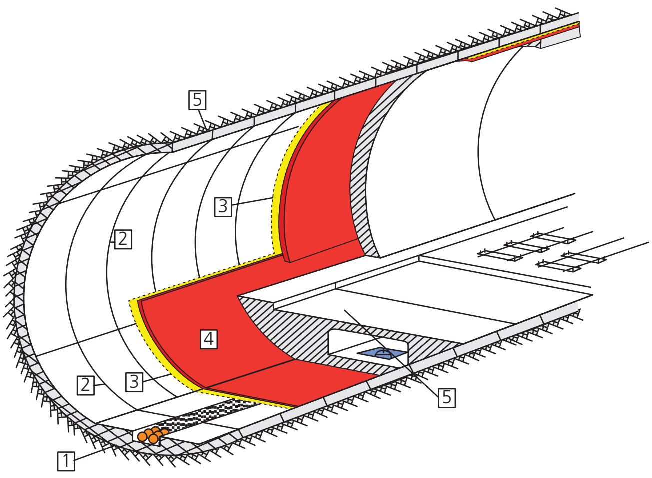
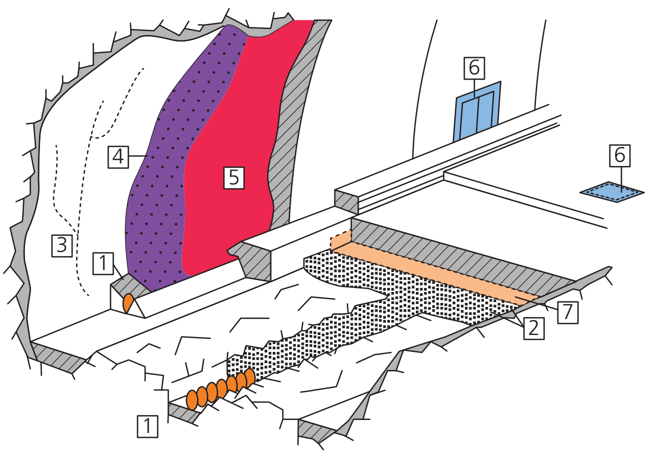


Figure 18.26 The drained solution. Application of the waterproofing system is limited to the crown and tunnel walls; drawdown of the groundwater table. The tunnel inner lining is in slight compression (ground overburden only). 1, drainage system at the haunch; 2, drainage system at the invert; 3, deteriorated lining; 4, drainage layer; 5, waterproofing geomembrane over the crown and walls; 6, inner concrete lining



- the welding of the geomembrane to the roundels has been done in the foreseen percentage, to grant temporary anchorage and at the same time prevent excessive stresses being applied on the geomembrane before the inner concrete lining is cast
- the welds between adjacent panels of a geomembrane do not present fish mouths or burns
- the geomembrane is intact before the inner concrete is cast.

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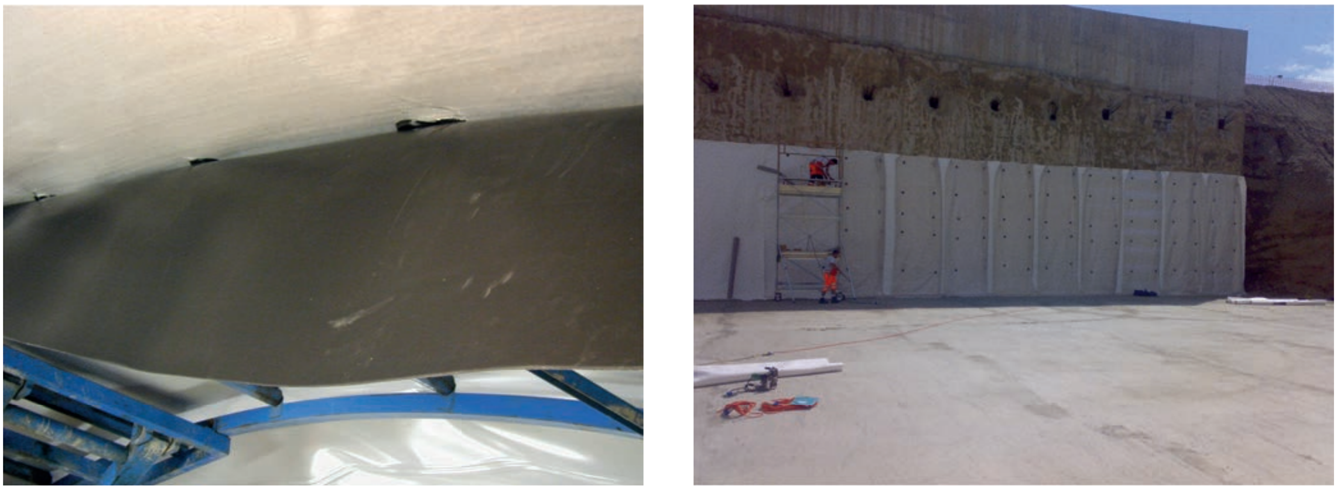
Figure 18.27 PVC geomembranes heat welded to PVC roundels: (a) with the upper signal layer and (b) transparent, with the white anti-puncture geotextile showing underneath the two adjacent sheets of geomembrane not yet welded



(a) (b)

18.5.4 Protective seals and inner (reinforced) concrete lining

End fastenings and compartmentalisation are generally the same as described for the covered solution in hydraulic tunnels. If the excavated tunnel is followed by a cut-and-cover section (Figure 18.28), the waterproofing liners of the two sections are watertight connected by heat welding. In cut-and-cover tunnels, the geomembrane is installed directly over the concrete ring, and then covered by a protection layer and by the overburden.

As for hydraulic tunnels, post-grouting between the geomembrane and the inner concrete lining, allowing potential localised leaks to be addressed and restoring imperviousness to the tunnel, is done in separate compartments (Figure 18.29).

If the inner concrete ring is reinforced and the reinforcement is not self-supported, as for hydraulic tunnels, the design must allow for watertight fittings at the anchor bars supporting the reinforcement (Figure 18.30).

A ‘maximum safety’ solution is the so-called ‘vacuum system’, formed by a double PVC or thermoplastic polyolefin (TPO) geomembrane installed between the outer and inner rings, and divided into separate compartments as in the standard post-grouting system. The key concept of the system is the ability to create a vacuum in the gap between the two geomembranes. The vacuum allows testing of the airtightness, and hence the water-tightness of the welds and of the system, both before concreting, to assure that the waterproofing system is viable, and when the tunnel is in service, to provide effective control and the

Figure 18.28 A cut-and-cover section (a) before and (b) after installation of the PVC geomembrane (the grey material covered by the white protection geotextile)

(a) (b)

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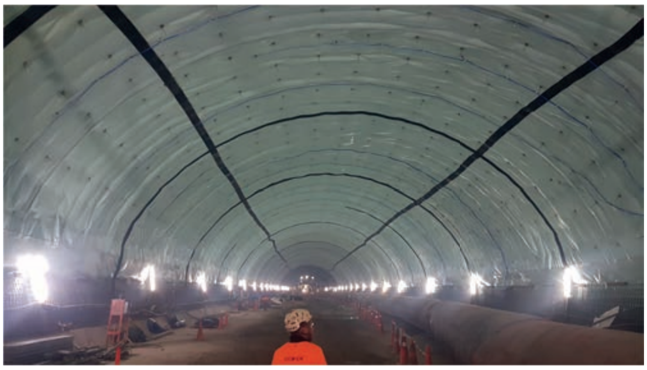
Figure 18.29 Post-grouting: (a) waterstops (in black) dividing the grouting compartments and (b) the box where the grouting hoses terminate before concreting



(a)

(b)

possibility of carrying out future maintenance and remedial works if needed. PVC suction/injection pipes crossing the upper geomembrane (Figure 18.31) allow the vacuum to be established and the airtightness of the system to be verified through variations in the negative pressure. After the airtightness has been verified, or restored with ad hoc procedures, the pipes are taken to terminal boxes accessible for testing after concreting. After concreting of the inner ring, the vacuum test can be repeated to verify that the concreting operations have not damaged the geomembrane system. If a vacuum cannot be achieved, the damage is repaired by post-grouting the gap between the two geomembranes with appropriate resins that react with water, forming a gel that in a very short time fills the compartment and re-establishes the watertightness.

18.6. Geomembrane systems in shafts

The applications of geomembrane systems in surge and pressure shafts are the same as described for hydraulic tunnels. The covered solution is adopted in new construction, and is generally identical to that adopted in hydraulic tunnels, while the exposed solution is used for rehabilitation, or as an additional water barrier for a new concrete lining when there is the possibility of water loss.

In the exposed solution, based on the same considerations discussed for hydraulic tunnels, the preferred waterproofing liner is a PVC composite geomembrane, placed directly over the concrete or over a support layer (Figure 18.32), and selected depending on the condition of the concrete or the opening of cracks and joints.

In shafts, drainage discharge by gravity outside the structure is rarely possible; therefore, inside discharge via one-way valves must be used, placed at the bottom of compartments (Figure 18.33).

The waterproofing liner is fastened vertically by stainless steel profiles anchored by mechanical anchors selected depending on the strength of the concrete. To keep it taut to the concrete, an installation sequence based on progressive closure (Scuero and

Figure 18.30 Reinforcement for the inner concrete lining: (a) support anchor bars for the reinforcement crossing the geomembrane and equipped with watertight fittings and (b) reinforcement supported by the bars before casting of the concrete

(a)

(b)

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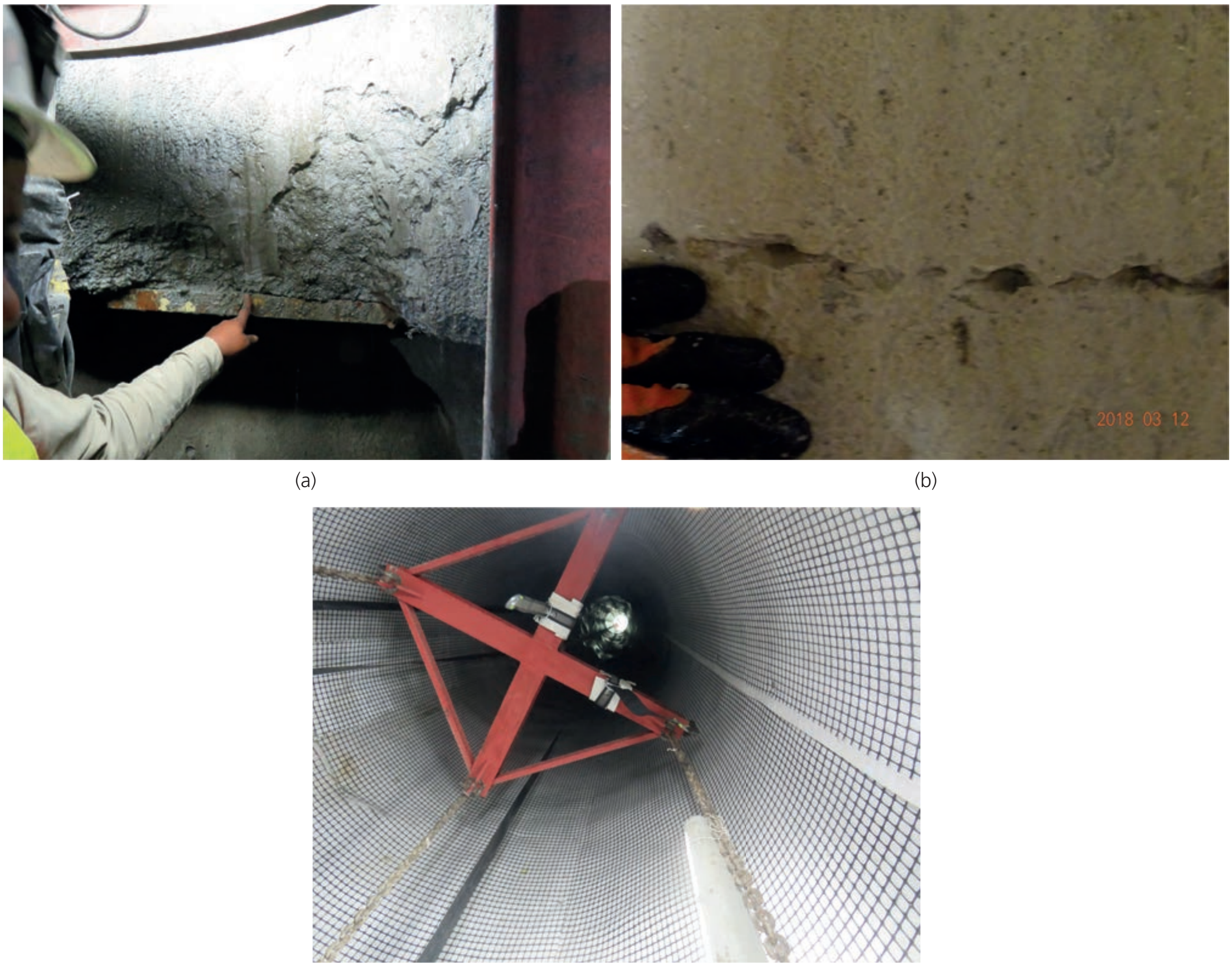
Figure 18.31 Vacuum system: the suction/injection pipes (a) before and (b) after establishing the vacuum

(a) (b)

Figure 18.32 Conditions of (a, b) the substrate dictate the selection of (c) the support layer. In this case, possible further opening of cracks required a geocomposite formed by a geogrid with a high bearing resistance and a high modulus, laminated at manufacturing to an anti-puncture geotextile



(a) (b)

(c)

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Figure 18.33 One-way mechanical discharge valve at the bottom of compartments

Vaschetti, 2020) can be used: after the ‘first phase’ anchorage lines have been placed and fastened, the ‘second phase’ anchorage lines, positioned in between the first lines, are installed and fastened, forcing the liner closer to the concrete and producing a tensioning effect in between two adjacent first-phase anchorage lines. This method avoids the formation of slack areas and wrinkles in the geocomposite (Figure 18.34).

Watertight perimeter seals are placed at the boundaries of compartments (Figure 18.35). For additional safety, they are sometimes doubled or tripled.

18.7. Summary of the main points

- Geosynthetics can be successfully employed in underground construction. In particular, PVC geomembranes have been successfully used in hydraulic tunnels, transport tunnels and shafts as barriers against water and gas infiltration from the

Figure 18.34 PVC composite geomembrane taut to the inner concrete lining

Figure 18.35 Watertight perimeter seals at (a) the connection surge shaft/pressure shaft and (b) the bottom of a compartment

(a) (b)

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surrounding ground, and to prevent water seeping in the ground from the tunnel/shaft. They are a key element in hydraulic tunnel/shaft design.
- Geomembrane systems have reached a high degree of refinement and reliability. Many years of successful performance of PVC geomembranes in hydraulic tunnels, transport tunnels and shafts have shown that an adequately designed and installed geomembrane system is durable and reliable under high water heads, and in demanding environments.
- In the rehabilitation of hydraulic tunnels and shafts, when compared with steel linings, a geomembrane system provides several advantages, including financial and time savings.
- In the construction of new hydraulic tunnels and shafts, a geomembrane/composite geomembrane should be integrated in the lining system to prevent water infiltration that can cause failure of the surrounding ground and structure, and to avoid/minimise financial losses due to maintenance/repair costs and loss of service.
- In the rehabilitation of hydraulic tunnels and shafts, geomembranes are commonly selected because their flexibility allows potential crack growth to be accommodated.
- Geomembranes in traffic tunnels protect the inner concrete lining from deterioration by creating a barrier to water that could infiltrate from the natural ground.
- Geomembranes in traffic tunnels protect the traffic and equipment inside the tunnels.

18.8. Common questions and their answers

Questions

1. Are geomembranes used in new tunnels and shafts construction? If yes, can they be used under high water heads?

2. How do geomembrane liners compare with more traditional steel liners?

3. Does the installation of a geomembrane allow consolidation grouting operations?

4. In the rehabilitation of hydraulic tunnels and shafts, does an exposed geomembrane provide benefits in terms of hydraulic efficiency?

5. Can a covered geomembrane be repaired?

6. What are the repair measures for leakage in traffic tunnels?

Answers

1. Geomembranes have seen extensive use in new construction of hydraulic tunnels with high water heads, particularly in Austria. Examples are

- The Kölnbreinstollen Tunnel in the Malta scheme (Austria), subjected to maximum static and dynamic pressures of 24 and 30 bar, respectively. The geomembrane lining consisted of two single geomembranes, one being a 2 mm geomembrane made of regenerated PVC, and the other a 1.5 mm fibre-glass-reinforced PVC geomembrane.
- The Sellrain-Silz hydropower scheme pressure shaft (Austria), under a maximum static pressure of 48 bar and a maximum dynamic pressure of 74 bar. A 3 mm PVC geomembrane with a 400 g/m^2 PP geotextile was installed as a waterproofing layer.
- The Rotenberg Tunnel in the Langenegg power scheme (Austria), subjected to 350 m water head, employed a 5 mm-thick geomembrane for waterproofing.
- The Wallgaustollen Tunnel (Austria), with a hydrostatic head of 120 m, employed a 5 mm-thick PE geomembrane.
- The San Fiorano Tunnel (Italy), with a hydrostatic head of 103.11 m, employed a 4 mm-thick PVC geomembrane.

A recent outstanding project is the 10.4 km third Niagara Tunnel, completed in 2013 and one of the largest tunnels in North America. It is waterproofed using a double waterproofing geomembrane applied to the tunnel wall in advance of the final concrete pouring. The tunnel runs under the city of Niagara Falls, parallel to the two existing 100 m-deep water tunnels but at a lower depth of 140 m.

2. The ability to eliminate leakage and the durability of steel and PVC geomembrane liners are equivalent; however, other characteristics of PVC geomembranes make them, in some cases, more attractive than their traditional counterparts.

Steel liners are generally transported inside the tunnel in sections and then assembled in place. When access to the tunnel is difficult, installation of the steel liner may require splitting of the liner into even smaller sections, which results in time-consuming assembling and welding operations inside the tunnel. In contrast, the components of a PVC lining system have dimensions and weight such that they can all be easily taken, even by hand, through very small accesses, and the installation equipment is a simple scaffolding that can be easily constructed inside the tunnel.

A steel liner is less flexible than a PVC liner: as a consequence, once the steel liner has been assembled, there may be considerable voids between the steel and the existing surface of the tunnel. It is therefore essential to take into account the time and costs required for the extensive grouting that is needed to fill the voids and provide adequate congruence between the steel liner and the supporting concrete. The time and costs associated with adequate plugging of all grouting holes should also be taken into account. A PVC geomembrane, on the other hand, being very flexible, can adapt to the existing surface of the tunnel so that fewer voids will be present and little grouting will be needed.

Steel liners, with a thickness of the order of centimetres, will cause a slight alteration in the hydraulic profile of the tunnel, while PVC geomembrane liners, with a thickness of the order of millimetres, do not alter the tunnel cross-section appreciably.

Steel liners have lower elongation limit compared with PVC geomembrane liners, and may fail in the presence of settlements, deformations or the opening of large cracks. PVC geomembrane liners have superior performance, also adapting to active fissures and cracks, and eliminating any risk of failure from leakage.

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Steel liners do not alter the natural groundwater conditions. PVC geomembrane liners with a drainage system behind can improve groundwater conditions by extracting water from the soil. The entire system must, however, be designed to minimise and resist backpressure.

Steel liners are statistically more expensive than PVC geomembrane liners. The cost of a geomembrane system is usually 20–30% of the cost of a steel liner, and the installation time is generally 15–25% of the total time required for the installation of a steel liner. This is estimated taking into account the cost of supply, but also the different design, logistics and installation requirements. Reduced outage time of the tunnel that results in, for example, higher hydropower production, and associated higher financial income, should also be added to the financial advantages offered by the geomembrane solution.

3. Consolidation grouting is typically undertaken to improve rock conditions by grouting cavities in the natural excavation, and is generally performed prior to the installation of the waterproofing system; thus, it clearly does not interfere with the placement of the geomembrane.

Additional grouting can be placed behind the waterproofing geomembranes; that is, between the outer sprayed concrete lining and the geomembrane (grouting of the outer gap), and between the geomembrane and the inner concrete ring (grouting of the inner gap). Grouting is undertaken by installing grouting pipes that cross the geomembrane (grouting of the outer gap) or are installed on the geomembrane (grouting of the inner gap). The grouting pipes are usually placed at regular intervals, and are equipped with watertight fittings if they cross the geomembrane. This grouting system must be installed before casting of the inner concrete lining.

Grouting the outer and inner gaps aims to fill the voids between the waterproofing geomembrane and the adjacent layers. Post-grouting can also be used to repair damage to the geomembrane (see Question 5).

4. The resistance of the tunnel lining to the flow of water in it is represented by Manning's coefficient, n. Manning's coefficient depends only on the surface roughness. Exposed PVC geomembrane systems in tunnels benefit from the intrinsic very low hydraulic roughness of PVC geomembranes, which is maintained over time, while in concrete linings the surface roughness tends to increase over time. If the geomembrane is anchored with a system that at the same time permanently tensions the PVC liner, so as to avoid folds and the formation of slack areas, very low hydraulic roughness can be assured at construction and in the long term.

Additionally, since the PVC geomembrane liner is only a few millimetres thick, when this system is adopted there is effectively no reduction in the cross-section of the tunnel. In contrast, the selection of other lining systems, such as sprayed concrete, concrete or even steel, implies a potentially significant reduction in the cross-section.

5. In hydraulic tunnels and shafts, it is generally assumed that the inner concrete lining will inevitably be fissured. The internal water pressure, applied through the fissures in the concrete lining directly to the geomembrane, pushes it against the external surface of the sprayed concrete lining. Therefore, in the case of damage to the geomembrane, the flow of water through the breach in the geomembrane is partially reduced by the confinement action created by the pressure.

Post-grouting of the inner gap to fill the voids between the waterproofing geomembrane and the inner reinforced concrete lining can also be used to repair any damage to the waterproofing liner and to avoid any water leakage during future operation. The grouting system is installed before casting of the inner lining, with the grouting pipes attached to the waterproofing geomembrane on the side facing the inner concrete lining and connected to a control box placed in front of the reinforcement.

To obtain perfect filling of all the voids, to stop a leak in the geomembrane, it is generally necessary to grout fine cement slurry. The setting time of the grouting material must be carefully planned. The flow, density, setting and pressure of injection must be constant in the injected area. When grouting is carried out, it is important to ensure complete, uniform and fast dispersal of the grouting mix in the entire grouted area. The best control of the quantity of grout and of the efficiency of the grouting operation is achieved by reducing the area in which grouting is done, which means creating compartments in the system. Compartments allow easier and more effective inspection, location of damage, and repair by post-grouting. Compartments are created using PVC waterstops heat welded to the waterproofing geomembrane, and then embedded in the concrete of the inner ring.

The compartmentalisation system will confine the water from accidental leakage to the area of the leak, making it possible to establish the location of the infiltration, reducing the area of investigation for leak detection, and minimising the extent of the repair. By preventing cementitious grout entering adjacent areas, the volumes of grout necessary to inject are lower, and there is a more efficient control of grout distribution. This results in a system for future repair that does not require any demolition of the inner concrete structure.

6. Repair measures in traffic tunnels depend on the extent of the leaks. Localised small leaks are sometimes repaired with simple corrugated elements placed in front of the local source of the leak. This low-cost rehabilitation measure should, however, be considered a temporary intervention, because it does not create a barrier to water infiltration into the inner ring, and continuing deterioration will require – sooner or later – adopting one of the following measures.

Leakage can be stopped by post-grouting the compartment or compartments where it is detected, via the injection pipes whose terminations can be seen in the post-grouting box. This method has already been described in the answer to Question 5.

In the case of large, persisting and diffuse leakage, full-face rehabilitation can be considered, which is done by installing a

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new geomembrane liner on the existing leaking inner concrete ring. The new geomembrane system is identical to that used in new construction: an anti-puncture protective geotextile is placed on the inner concrete ring and fastened with PVC roundels, to which a PVC geomembrane is welded to provide temporary anchorage before casting of the new inner concrete ring. Depending on the conditions of the existing inner concrete ring, simple cleaning or hydro-jetting to remove unstable parts, sometimes followed by some concrete repair, is carried out before placing the new geomembrane lining system.

Since casting of an additional inner concrete ring reduces the free space available for traffic inside the tunnel, the need to restore the lost space must be evaluated through consideration of the expected traffic inside the tunnel. A common measure is to partially demolish the invert of the tunnel, to lower the invert to the extent necessary to allow the free space necessary for the largest vehicles using the tunnel.

Acknowledgement

Photographic material relating to the installation of geosynthetics in hydraulic and transport tunnels and shafts was provided by courtesy of Carpi Tech.

REFERENCES

Cazzuffi D (1995) Évaluation du comportement de différent types de géosynthétiques prélevés sur canaux de l'Enel. *Proceedings of Rencontres '95, Beaune, France*, vol. 2, pp. 9–15. (In French.)

Cazzuffi D and Venesia S (1989) The use of thermal analysis for the evaluation of the durability of a 24-year-old PVC geomembrane. In *Geosynthetics: Microstructure and Performance* (Peggs ID (ed.)). *American Society for Testing and Materials, West Conshohocken, PA, USA*, pp. 17–25.

Cazzuffi D, Ferrara G, Venesia S, D'Ischia A and Silvestri T (1986) Transmissivity of geotextiles and related products: laboratory tests and practical applications. *Proceedings of the 3rd International Conference on Geotextiles, Vienna, Austria*, vol. 3, pp. 879–884.

Cunegatti M (2019) European practice on the use of PVC-P geomembranes in tunnels and underground structures – special testable and reparable waterproofing systems. *Proceedings of the Pan American Conference on Soil Mechanics and Geotechnical Engineering, Cancun, Mexico,* pp. 1279–1285.

Heigerth G (1982) Determination of load bearing capacity of the rock mass and lining layout for a high stressed pressure shaft. *Proceedings of the ISRM Symposium, Aachen, Germany*, vol. 3, pp. 1253–1260.

Heigerth G, Finger W and Schlosser K (1979) Triebwasserweg Oberstufe – Anlagenbeschreibung, Bauausführung. *ÖZE* **32**(1/2). (In German.)

Laufer H (1985) Austria's contribution towards the development of water power, hydro power schemes and large dams in Austria. In *Die Talsperren Österreichs, No. 29* (Simmler H (ed.)). *Springer Verlag, Wien, Germany.*

Scuero AM and Vaschetti GL (1997) Waterproofing a pressure tunnel with a drained polyvinylchloride membrane composite. *Proceedings of Geosynthetics Asia 97, Bangalore, India,* pp. III.35–III.42.

Scuero A and Vaschetti G (2020) Geomembranes to line surge shafts. *Proceedings of the 4th GeoMEast International Congress and Exhibition, Cairo, Egypt.*

Scuero AM, Wilkes J, and Vaschetti G (1999) Waterproofing tunnels with geosynthetics in Europe. *Proceedings of iGEM, University of Illinois at Urbana-Champaign IL, USA*, pp. 841–852.

Seeber G (1982) New ways for the construction of pressure tunnels. *Proceedings of the ISRM Symposium, Aachen, Germany*, vol. 2, pp. 705–716.

Seeber G (1985) Planung und Optimierung der Triebwasserwege von Pumpspeicherwerken. *Österreichische Wasserwirtschaft* **37**(1/2). (In German.)

Yoo C (2015) The use of geosynthetics in underground works, Keynote Lecture. *Proceedings of the International Conference on Rock Mechanics, Montréal, Canada.*

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