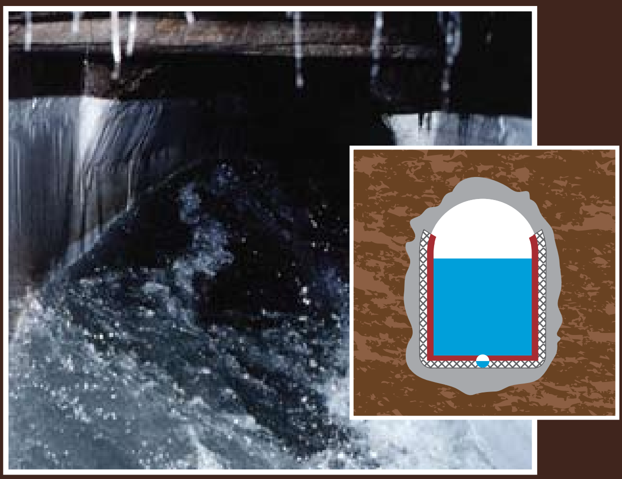
Since 1963

WATERPROOFING SPECIALISTS AND CONTRACTORS WITH GEOMEMBRANES

HYDRAULIC TUNNELS

WATERPROOFING AND IMPROVED HYDRAULIC EFFICIENCY

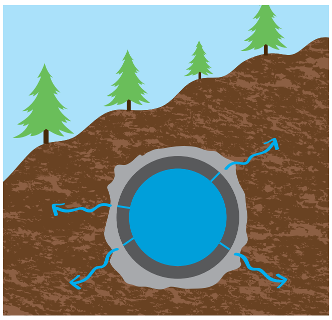


Providing Dry
and Underwater Installations

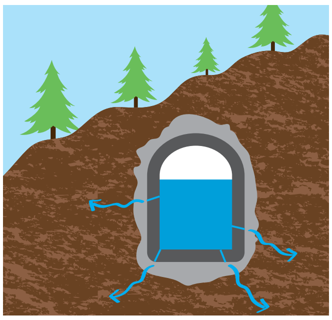
P R O B L E M S

The main purpose of hydraulic tunnels is to convey water for power and water supply under pressure or in free-flow (figure 1 and 2). With the exception of old tunnels excavated in rock, hydraulic tunnels are usually lined. The lining must have a:

- **Structural function**, by supporting the excavation;
- **Waterproofing function**, to avoid that water seeps into the ground jeopardising the stability and the slopes, hence the integrity of the tunnel structure, particularly in areas of low horizontal or vertical overburden; and
- **Hydro/economic function**, to minimise the head loss across the length of the tunnel, and ensure efficient transportation of water.



1 - Conventional pressure tunnel (no synthetic liner).



2 - Conventional free-flow tunnel (no synthetic liner).

The unexpected deterioration of concrete lining systems, even if stability is not at stake, entails high maintenance costs of dewatering. It is therefore advisable to line new built concrete tunnels with an impervious geomembrane during construction.

The consequences of leaks in tunnels

Highly pressurized concrete (reinforced and unreinforced) tunnels crack, due to shrinkage stresses, internal pressure and ground settlement, are water permeable, and are therefore often sources of leakages. Leaks from high-pressurized concrete tunnels are usually very small, however even small leakages 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 cause weakening of the ground (gypsum, salt) resulting in movements affecting the tunnel.

3/4 - Fissures due to movement in the ground at a pressure tunnel.

The applied water head and water velocity may activate existing fissures, create new ones, and increase permeability and roughness of the concrete lining.

5 - Cracks in the concrete structure result in water loss and undesired water flow into the natural slopes.

6 - Existing fissures open due to settlement.

7 – Outward water seepage in a concrete lined tunnel.

8 – Outward water seepage in a concrete lined tunnel.

In concrete lined tunnels, degradation causes an increase in the roughness leading to increased friction losses, resulting in reduced power generation and water supply.

9 – Concrete surface roughness due to inaccurate formwork and poor concreting.

10 - Typical sprayed concrete surface roughness.

In the case of leaking waste water tunnels, a further threat is posed by potentially deleterious substances coming into contact with the groundwater.

Geomembrane waterproofing systems are a cost effective and efficient solution to prevent design and construction delays, minimize outage loss, repair and maintenance costs, and other consequences of a failure that could be caused by a minor leak.

The geomembrane waterproofing system

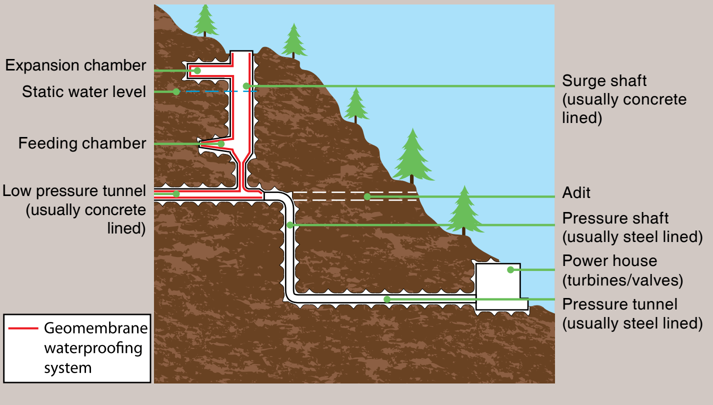
The purpose of the waterproofing geomembrane in a hydraulic tunnel is to prevent water and other deleterious chemicals from entering cracks and joints in the inner concrete lining where it would act like a hydraulic jack and affect the durability of the reinforcement, and to prevent water inside the tunnel from escaping into the surrounding ground and compromising the stability of the ground and of the structure.

The CARPI tunnel waterproofing system consists of an impermeable preferably PolyVinylChloride (PVC) flexible geomembrane in most cases laminated during fabrication to a protective geotextile into a geocomposite.
The flexible geomembrane provides the watertight seal whilst also spanning joints and existing cracks and accommodating any movement that could cause the formation of new cracks. The free geotextile layer protects the waterproofing geomembrane against damage from contact with the substrate and prevents interlocking between outer and inner linings in case of differential movement.

Fields of application

Geomembrane systems can be installed as waterproofing liners in new pressure and free-flow new tunnels, in surge shafts and expansion chambers, or as a repair measure in existing tunnels. When installed inside existing tunnels, geomembranes are placed directly over the deteriorated lining. They are thin enough (in the order of a few millimeters) not to encroach on the internal tunnel envelope. In new construction, the geomembrane is installed directly onto a smoothing layer of sprayed concrete lining or on the outer lining.

The waterproofing geomembrane can be applied to the entire tunnel cross-section (pressure tunnels) or specifically to the problematic areas (free-flow tunnels), and can be located between the outer sprayed concrete and the inner concrete lining (new construction) or applied to the existing lining and left exposed (rehabilitation).



11 – Fields of application. Waterproofing of tunnels, surge shafts and expansion and feeding chambers. Geomembranes can be used as a seamless solution in all of these structures.

Benefits of the geocomposite waterproofing system

Structural

- Protects the concrete tunnel lining from deterioration.
- Improves the stability of the tunnel and of the natural slopes.

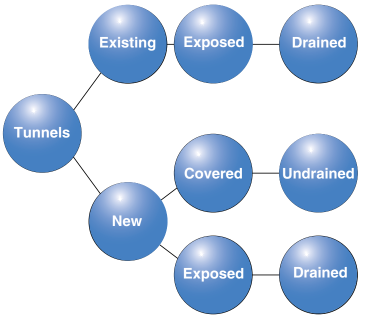
Waterproofing

- Stops inward leakages.
- Stops outward leakages.

Hydraulic/Economic Efficiency

- Increases the water flow, by minimizing leakages, decreases water level (figure 15).
- When left exposed, does not reduce the tunnel envelope.
- Minimizes future maintenance.
- When left exposed, improves hydraulic efficiency through smoothness of the geomembrane.
- Quick and easy installation even with restricted access (figure 14).
- Minimum mobilisation of equipment and minimum time (figure 16).

The use of flexible PVC geomembranes allows the combination of continuous watertightness and improved friction properties, such as that of steel liners, with the strength of the (reinforced) concrete of the inner lining at a much lower cost.



12 – Design options.

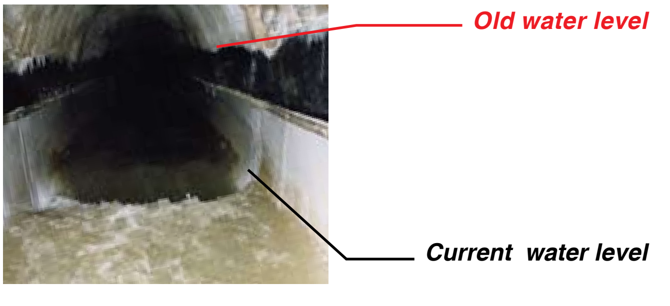
In the case of hydraulic tunnels, the reliability of the seal is of particular significance since once in operation they are not easily accessible for subsequent repairs.

Patents

Through the use of its patents, CARPI has achieved improved hydraulic efficiency of the geomembrane liner, innovative drainage systems, and increased safety of the lining system.

13 – CARPI patented system: discharge inside the tunnel is made with PVC valves operated by pressure differentials.

14 – Quick and easy installation even with restricted access on the Frailino free-flow tunnel (Italy).



15 – Increased water flow, thanks to minimization of the leaks, decreases water level (Frailino free-flow tunnel, Italy).

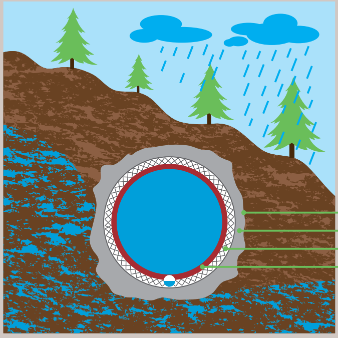
16 – Minimum mobilisation of equipment (Belden pressure tunnel, USA).

Pressure tunnels may be waterproofed with an exposed drained geocomposite liner or covered geomembrane system, depending on the project requirements. In both cases the waterproofing geomembrane layer is applied across the entire inside face (figures 17 and 21).

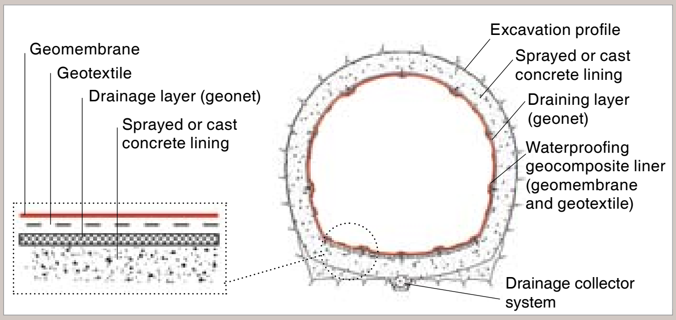
Free-flow tunnels are usually waterproofed with an exposed drained geocomposite liner installed to the wet area only (figure 19).

Pressure tunnels - exposed drained geocomposite

In pressure tunnels lined with an exposed geocomposite, underground water is usually collected in the invert or haunches by means of a drainage system (figure 17). Drainage is necessary to avoid uplift on the geocomposite by water in the natural slopes, when the tunnel is emptied.



17 – Diagram showing a pressure tunnel with exposed geocomposite.

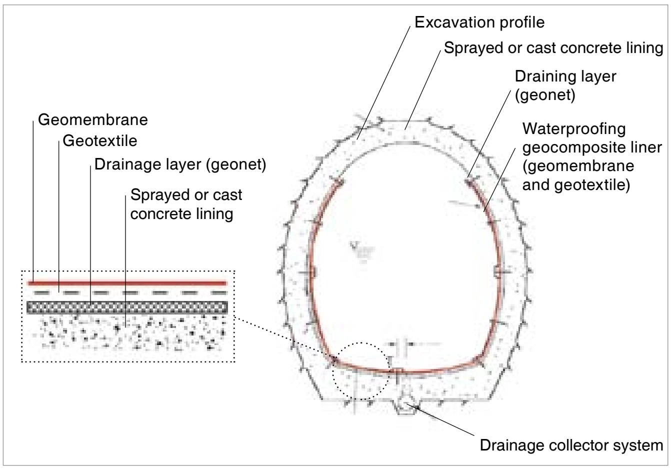


18 – A typical pressure tunnel cross-section. The geomembrane is exposed and fastened with the CARPI patented tensioning profiles and flat profiles.

Free-flow tunnels - exposed drained geocomposite

In free-flow tunnels the exposed geocomposite waterproofing system is typically applied to the lower section of the tunnel, which in existing tunnels coincides with the wet damaged area.

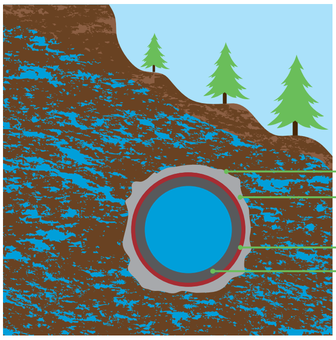
19 – Diagram showing a free-flow tunnel with exposed geocomposite.



20 – A typical free-flow tunnel cross-section. The geomembrane is placed over the walls and invert and left exposed. It is fastened with the CARPI patented tensioning profiles and flat profiles.

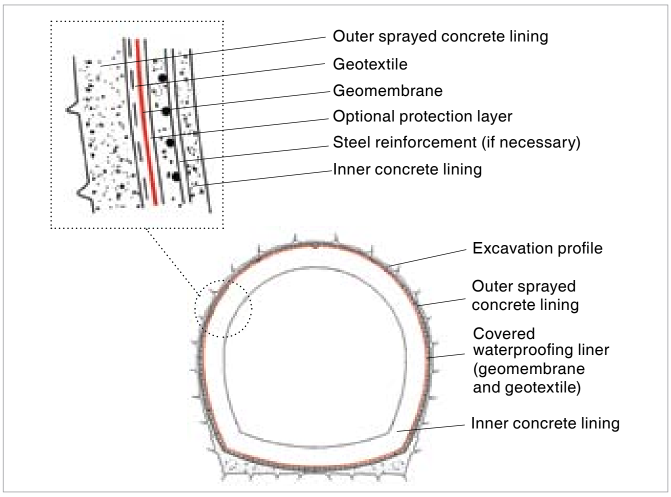
Pressure tunnels - covered geomembrane

In pressure tunnels, where the geomembrane waterproofing system is covered by an inner lining, no drainage is required.



21 – Diagram showing a pressure tunnel with covered geomembrane system.

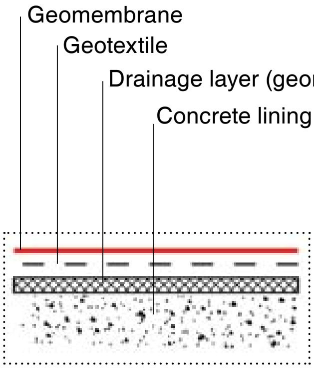
This makes it necessary for the geomembrane system and inner concrete lining to be designed to cope with the groundwater pressure (figure 21).



22 – A typical pressure tunnel cross-section. The geomembrane system is placed all around the tunnel cross-section and covered with a structural inner concrete lining (usually reinforced).

The end of the waterproofed section is sealed by means of a watertight perimeter seal and also drained as for pressure tunnels described above.

The exposed solution can be adopted in rehabilitation as well as in new construction, for water velocities of several meters/second and uplift pressures of several MPa.
The geomembrane is generally bonded to a geotextile to form a geocomposite.



23 – Layering of the drained system.

The waterproofing system must ensure that imperviousness is provided and maintained notwithstanding the 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 (figure 24) and covered with a support (figure 25) geogrid prior to the installation of the waterproofing system. The efficiency of the CARPI system to accommodate displacements, rotations and opening of fissures without rupturing has been proven by +30 years of field performance.

24 – Large cracks are injected with acrylic resins or cementitious grouts prior to the installation of the waterproofing geocomposite system.

25 - In addition or alternatively to injection of large cracks a geogrid is installed over an active crack.

The drainage layer, consisting of one or multiple layers of geonet, is layed out and secured to the existing substrate via impact anchors (figure 26).

26 – A highly transmissive geonet is installed when high drainage capacity is required (Belden pressure tunnel, USA).

The continuous drainage system provided by the geonet behind the geocomposite can dissipate excessive external water pressure through free-flow discharge outside the tunnel or by one-way PVC valves (figure 28), patented by CARPI, inside the tunnel itself.

27 - Intensive research was made at TUM, Technical University of Munich, to investigate the behaviour of water convergence structures lined with geomembranes (TUM Technische Universität München, Wasserbau und Wasserwirtschaft, Nr. 106, 2006, Patrick Schäfer, Basic Research and Rehabilitation of Aged Free Flow Canals with Geomembranes).

28 – Discharge inside the tunnel can be made with valves operated by pressure differentials (testing at Belden pressure tunnel, USA).

The geocomposite is secured to the subgrade via patented tensioning profiles (figures 31 and 32) that anchor the waterproofing liner to the existing tunnel liner and pretension it to eliminate wrinkles and slack areas, improving hydraulic efficiency. The number, type and position of the profiles is designed as a function of negative pressure caused by backwater in case of dewatering, or suction occurring during operation of the tunnel, or the dynamic action of the maximum water velocity infiltrating behind the geocomposite. The design is undertaken to worst case scenario.

29 – Scaffolding for the installation of the geocomposite (Thissavros pressure tunnel, Greece).

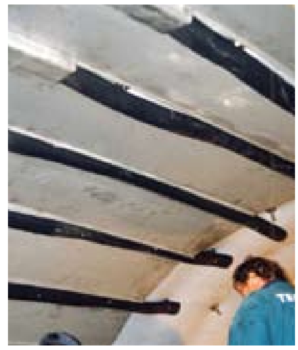
30 - Laying of the geocomposite inside a pressure tunnel (Belden pressure tunnel, USA).

Excessive deformation of the geomembrane system, due to backpressure of water present behind the geocomposite which may lead to bursting, is prevented by the specially designed patented tensioning profiles and by drainage.

31 – Upper tensioning profiles installed over the geocomposite to remove any slack (Thissavros pressure tunnel, Greece).

32 – Stretching of the geocomposite through tightening of the upper tensioning profile (Belden pressure tunnel, USA).

33 – Laying of the geocomposite inside a pressure tunnel (Spalov pressure tunnel, Czech Republic).



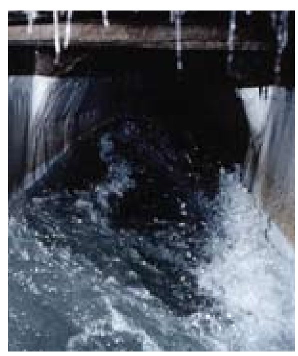
34/35 – Steel support plates in the crown fastened to the concrete with a system designed to accommodate movement in a section of high suction during transient (Spalov pressure tunnel, Czech Republic).

Stainless steel submersible watertight perimeter seals are used at the boundaries of the lined stretch (figures 37 and 38).

36 – Binn free-flow tunnel, Switzerland.

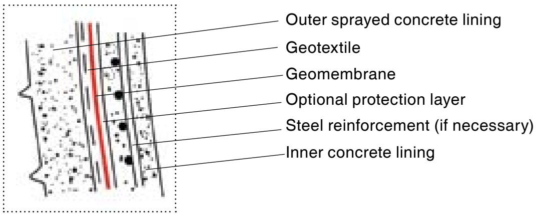
37 – View from the pressure tunnel towards the steel lined section (Thissavros pressure tunnel, Greece).

38 – Watertight perimeter seal at Belden pressure tunnel, USA.



39/40 - Exposed geomembrane systems anchored to resist high water velocity (pictured 4 m/s) and turbulence (Chavonne free-flow tunnel, Italy).

The fully tanked solution is typically adopted for new pressure tunnels, but can also be used in rehabilitation in case of particularly severe service conditions.
The geomembrane is not bonded to the geotextile.



41 – Layering of the fully tanked system.

The geotextile, which protects the geomembrane from puncturing, creates a sliding surface below it avoiding that excessive stresses are applied to the geomembrane, and prevents interlocking between outer and inner concrete linings should differential movement occur. It is secured to the subgrade (figure 43) by nails equipped with special disks (roundels). The disks, which provide temporary anchorage of the geomembrane to prevent it from hanging away from the vault of the tunnel are designed to avoid that excessive stresses are applied on the geomembrane, in correspondence of the roundels, before concreting of the inner lining occurs. The geomembrane is placed over the geotextile and heat welded to the back surface of the roundels. The flexible geomembrane typically has permeability at least three orders of magnitude lower than new concrete and thus provides the watertight seal whilst also spanning joints and cracks, covering any damage to the sprayed concrete lining and accommodating any movement.

42/43 – Left: view of the regularizing sprayed concrete lining prior to the installation of the waterproofing layer. Right: geotextile applied in the foreground and the geomembrane in the background (Edolo pressure tunnel, Italy).

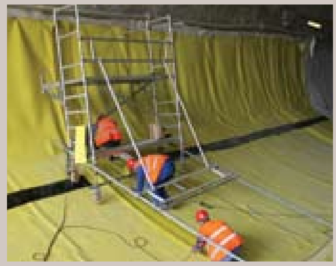
44 – Geomembrane heat welded to roundels (Ponte Giulio pressure tunnel, Italy) .

45 – Geomembrane installed in the crown, walls and invert. Protective sacrificial layer of geomembrane (black) in invert (Edolo pressure tunnel, Italy).

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 47).

The concrete is then cast, embedding the waterstops. The location of circumferential waterstops is strictly related to the length of the formwork. Longitudinal compartmentalization will be located at the joint between the invert and the walls.

46 - Post-grouting arrangement at a waterstop cross joint.



47 – Longitudinal compartment seal made by welding the waterstop to the geomembrane. The waterstop is then embedded into the concrete inner lining.

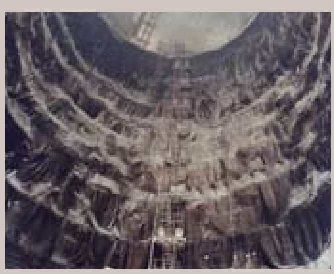
The inner concrete lining is usually constructed in two stages, one stage for invert and another for crown and walls. Since, as recognized by international experience, perfect placement of the concrete and filling of all voids at the vault is practically impossible to be achieved 100% of the time, an 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.
Reinforced inner linings will require anchoring steel bars to support the steel reinforcement cage before concreting.
In order to prevent seepage in correspondence of the anchorage steel bars and all other geomembrane crossings, a special detail is required. If reinforcement is self supported however, no anchoring is required. New design trends seek to avoid or minimize penetration of geomembrane.

48 – Formwork for the inner concrete lining (Edolo pressure tunnel, Italy).

49 – Completed installation of the inner concrete lining (Edolo pressure tunnel, Italy).

The covered geomembrane system is also extremely suitable for application in pressure shafts with unlimited head. Tests have already been performed fully successfully up to 900m.

Geomembranes are also suitable for application to the intrados of precast concrete segment in segmentally lined TBM tunnels (see figure 51).



50 – Edolo surge shaft, Italy.

51 – Geomembrane on the intrados of a precast segment.

Belden - USA

Thissavros - Greece

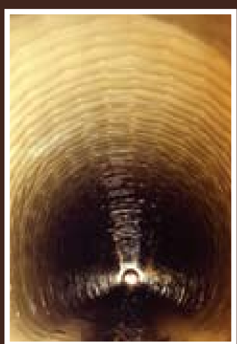
Binn - Switzerland

Signayes - Italy

Spalov - Czech Republic

Gandellino - Italy

Frailino - Italy



Ponte Giulio - Italy

Villoresi syphon - Italy

Senhora do Porto - Portugal

Edolo - Italy

Edolo Shaft - Italy

Chavonne - Italy

Armisa Gaggio - Italy

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