Waterproofing of Tunnels under infiltrating Water

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1. INTRODUCTION

1.1. General

The use of synthetic geomembranes as a waterproofing for tunnels is a sophisticated and safe technology used to protect the construction against the destructive influences of water.

Depending on the appearance of water (humidity, temporary water pressure, permanent water pressure) the lining system has to be adapted accordingly. This is expressed in the thickness of the geomembrane and a system of control and repair. Under the influence of permanent water pressure a minimum thickness of 2,0 mm of the geomembrane is required.
This technical description explains the use of RENOLIT geomembranes for the waterproofing.

1.2. Products of RENOLIT

RENOLIT offers a large range of suitable plastic sheeting to fulfil the waterproofing needs of the foundations :

- RENOLIT ALKORPLAN PVC-P geomembranes
- RENOLIT ALKORTOP PP geomembranes

1.3. Requirements on the waterproofing materials

The quality of the waterproofing depends on:

- choice of geomembrane
- waterproofing system including the preparation of the underground
- way of executing the works (underground, drainage, waterproofing system, protection).

1.3.1. Water tightness

Water tightness depends on the definition of geomembrane (product group, thickness) in order to be able to withstand all influences (e.g. pressure, condition of underground).

1.3.2. Flexibility

This issue has to be taken into consideration during projecting. Depending on the form, angles and settlements of the construction the correct type of membrane has to be chosen.

1.3.3. Chemical resistance

Pollution of the ground and ground water.

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2. GEOMEMBRANES OF RENOLIT

2.1. Geomembranes RENOLIT ALKORPLAN

RENOLIT ALKORPLAN represents all geomembrane of soft, homogeneous and reinforced PVC-P.

2.1.1. References of Geomembranes RENOLIT ALKORPLAN

- 35041, non-reinforced geomembrane, opaque, dark grey with thin yellow signal layer (bi-colour) to prevent any mechanical damage.
  Conform to specification as SIA V280, RVS 8T, DS 853, HEFT 365.
- 35034, non-reinforced geomembrane, opaque, light green (single colour).
  Conform to specification as RVS 8T, HEFT 365;
- 35036, non-reinforced geomembrane, translucent (>70%).
  Conform to specification as fascicule 67 titre III CETE Lyon, NEAT ;
- 35020, non-reinforced PVC-P protection layer.
  Conform to specification as fascicule 67 titre III CETE Lyon.
- 35038, non-reinforced geomembrane, opaque, dark grey, resistant against temporary influences of hydro carbonates and can be applied directly in contact with bitumen.

These geomembranes can also be produced:

- With reinforcement (polyester grid or reinforcement with glass fibres).
- Fleece backed with a PES (polyester) or PP (polypropylene) geotextile.

The mechanical characteristics can change due to the reinforcement and/or the fleece backing.

2.1.2. Properties

RENOLIT ALKORPLAN geomembranes are PVC-P soft membranes, calendared or extruded, rolled into a hard box measuring 2,05m width.

- No point of yield will be reached before break: after elongation under stress, PVC-P is able to relax and to adapt to the underground.
- High performance concerning bi-directional deformation due to its elasticity (>170%).
- Very high resistance against hydrostatic puncture (>950 kPa/mm).
- High puncture resistance.
- Good resistance against chemicals like acids and salts, aging and environmental influences.
- PVC-P Geomembranes are resistant to permanent contact of pH levels between 2 and 10.
- Geomembrane without UV protection can resist 1 month in direct exposition to UV radiation without loosing its mechanical characteristics.
- Very good weld ability with a hot air hand welder (type Triac) and automatic machine (hot wedge and/or hot air), even after many years of use, with large window margin regarding temperature and speed.

- Limited thermal dilatation : 1.5 10-4 cm/cm/°C

2.1.3. Characteristics

See technical data sheets.

2.2. Geomembranes RENOLIT ALKORTOP

This type of geomembrane is made of flexible Polypropylene.

2.2.1. References of RENOLIT ALKORTOP geomembranes

- 35080, homogeneous geomembrane, grey, 2.05 m large

2.2.2. Properties

Geomembranes made of flexible Polypropylene (FPP), homogeneous or reinforced.

- FPP is less flexible than PVC-P.
- A pseudo yield point can be observed after a certain elongation of the material (+-40%).
- Homogeneous geomembranes show good performance concerning bi-directional deformation due to their relative flexibility, especially in cold temperatures.
- Good chemical resistance.
- Medium hydraulic puncture resistance (600 kPa/mm).
- FPP can be welded with hot air and hot wedge automatic machines and with hot air hand welder, with a narrow window of temperature.

2.2.3. Characteristics

See technical data sheet.

2.3. Accessories

Geomembranes are the most important part of a waterproofing system. To make it function in a correct way different accessories complete the whole system. All accessories have to be compatible with the used geomembrane.
Following accessories are part of such a system:

- Protection layer (geotextile, plastic sheeting, …)
- Fixation elements (laminated metal sheet, water stop, stainless metal plates, anchorage amongst others)
- compartment and injection devices to be able to control and repair the waterproofing after pouring concrete (water stops, injection pipes, …)

2.4. RENOLIT Production

The whole procedure of production including the management and the purchase of

raw material has to conform to the demands of ISO 9001.
The control of production starts with the supply of the raw material, from there it goes to the laboratory which is responsible for the mixing of the compound, then it continuous through to production, from there to the logistic department and ends at the management department.
From the mixing and melting unit the compound is transported to the calendaring or extrusion unit. From the numerous calendaring drums the final membrane, controlled by many electronic devices for thickness, heat and speed, is then extracted and rolled up.
The signal layer geomembrane (35041) is produced on an extrusion/laminating machinery where the thin signal layer is laminated on dark grey geomembrane. Exact heat and pressure are important to receive a perfect lamination between the 2 layers of geomembrane.

2.5. Geomembrane recommended

RENOLIT group manufactures and markets a complete range of PVC-P, PE or PP geomembranes in response to a wide variety of applications. Experience has shown that the PVC-P geomembrane is the most suitable for waterproofing of tunnels due to its excellent mechanical properties and its durability in accordance with the expected lifetime of the building: RENOLIT ALKORPLAN 35034 – 35036 – 35041.
In addition, this geomembrane can be laminated with a geotextile in polypropylene (up to 700 g/m²) for bonded applications, and receive a reinforcement grid made of polyester or glass.

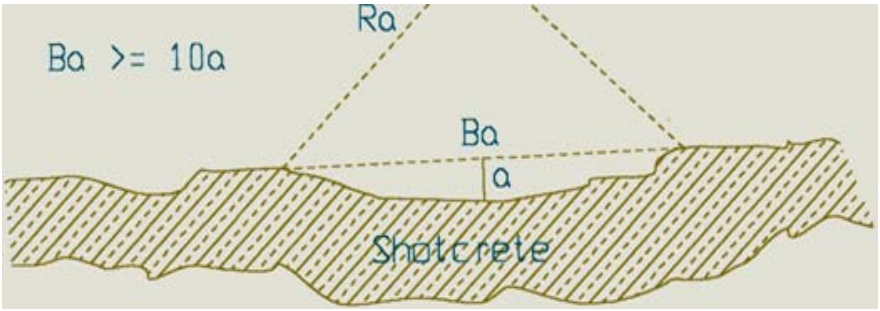
3. CONCEPTION OF THE WATERPROOFING

3.1. Components

- Geotextile minimum 500 g/m² Polypropylene (no Polyester), depending on the surface.
- Geomembrane of homogenous thermoplastic material like PVC-P, TPO, min 2,0 mm thick, transparent (French prescription) or with signal layer.
- Fixing elements.
- Reinforcement strips to protect the geomembrane in the area where shuttering for concrete shell finishes.
- Protection geomembrane (French prescription)
- Anchors if necessary to hold the reinforcement of the inside concrete shell.
- Water stops (mainly for tunnels under water pressure)
- Injection device (mainly for tunnels under water pressure)

3.2. Support

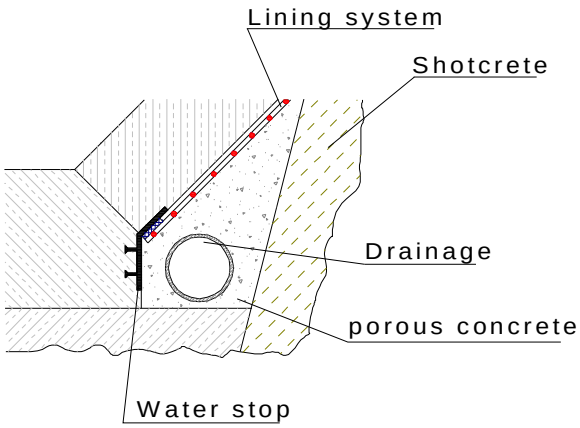
The surface of the support has to be as flat as possible, the used granulate should not be greater than 16 mm. The geometry of the surface (Ba ≥ 10 a) should be followed to avoid possible folding of the geomembrane after the concrete is poured (see drawing of geometry recommended by Austrian standard HEFT 365).
When the concrete of the inside shell is poured, it puts pressure on the geomembrane which is deformed and is pressed against the support. Where the surface is very irregular, folds in the geomembrane will occur. In tunnels with water pressure these folds can lead to failures of the lining membrane.



3.3. Installation of the bottom drainage

The so called umbrella tunnels (Waterproofing system only in the vault – no water pressure) needs drainage at the bottom of the tunnel in order to evacuate infiltrating or temporary water.
A good technical solution has to guarantee that the water will not infiltrate between the waterproofing system and the inside concrete shell.

Drainage and Waterproofing



4. INSTALLATION OF THE WATERPROOFING SYSTEM

Before starting the installation, the installer has to confirm that the surface of the support follows the specification.

The scaffolding for the installation of the lining system can be built on the slab of the tunnel. Depending on the type of scaffolding used, the geotextile and the geomembrane will be installed from one side of the tunnel to the other (use of hydraulic scaffolding) or from the highest point of the tunnel to both sides (manual scaffolding).

The hydraulic scaffolding is costly but makes for more comfortable working conditions for the installer. It has to be adjusted following the geometry of the tunnel.
The geotextile will be positioned on the steel bar of the moving basket, where it will be unrolled automatically when lifting the basket. The geotextile will be fixed with the fastening roundels to which the geomembrane will be welded in the second turn of the basket. After having fixed both items the scaffolding can be moved and put into position for the next placement of waterproofing system.

The use of conventional scaffolding means hard work. First the rolls of geotextile are brought to the highest level of the scaffolding, and fixed to the shotcrete surface with the roundels. Then the geomembrane is unrolled on top of the scaffolding, and spot welded to the fixation roundels starting from the highest point of the vault.

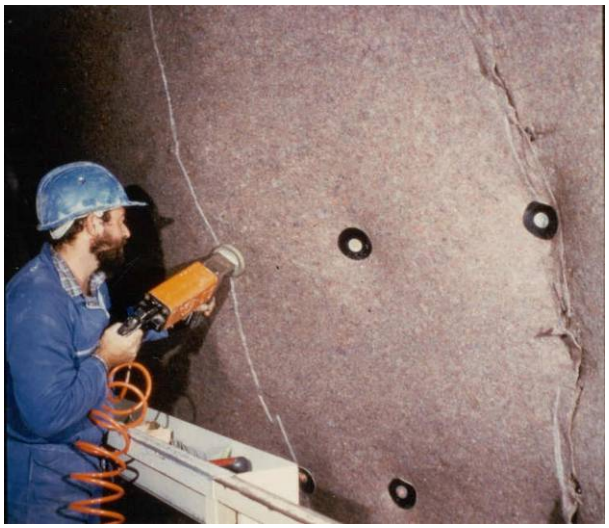
The geomembranes are welded together with automatic welding machines producing a seam with testing canal.

Hydraulic scaffolding on wheels

Scaffolding for manual installation

4.1. Installation of the Geotextile

The geotextile will be fixed with fixation roundels: in the wall area about 2 pieces per m², on the vault 3 pieces per m². The fixation elements have to be fixed on the deep spots of the shotcrete surface to avoid elongations of the geomembrane during pouring of the concrete shell (the geomembrane will be welded to these fixing roundels).
The geotextile is lifted to the scaffolding, unrolled and fixed with the fixation roundels to the shotcrete surface. The geotextile has to have an overlap of minimum 10 cm. The geotextile will be fixed completely over the surface of the daily planned work.
In areas of important irregularities it is recommended to double the geotextile.

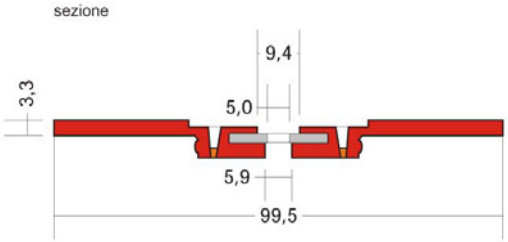


Fixation of the geotextile

Fixation of the geomembrane by spot welding

4.2. Fixation roundels

The task of the fixation roundel is on the one hand to fix the geotextile to the shotcrete surface by shot nails, and on the other hand to serve as a welding surface in order to fix the geomembrane to the tunnel. The roundel is composed of the same material as the geomembrane to ensure compatibility between the materials.
It is recommended to use "knock-out" roundels, in the rare case of pressure due to infiltrating water.
Example of flat PVC-P roundel with knock-out system, with a steel washer:



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4.3. Installation of the Geomembrane

The manufacturer of geomembranes has to produce the correct length of geomembrane following the indications of the installer, which corresponds to the perimeter of the tunnel to be waterproofed. Besides the indicated length a middle mark will be applied as well as a line on one side of the membrane at a distance of 5 to 8 cm. The middle mark shows the installer where he has to fix the membrane to the highest point of the vault (manual scaffolding), the side line indicates the necessary overlap for the welding.
The installer unrolls the geomembrane on top of the scaffolding, welds it to the fixation roundels on the highest point of the vault and proceeds with this work downwards till the whole geomembrane is attached to the fixation roundels.
In this way the daily quantity of geomembrane will be attached to the tunnel surface. Returning the scaffolding to the beginning of the newly fixed membranes, the geomembranes are welded together, with the help of welding automats, producing a double seam with testing canal.
The installer has to take care that the machine is well adjusted concerning temperature, speed and pressure. Therefore it is crucial to adjust the machine through trial welding every day before starting the initial welding works.

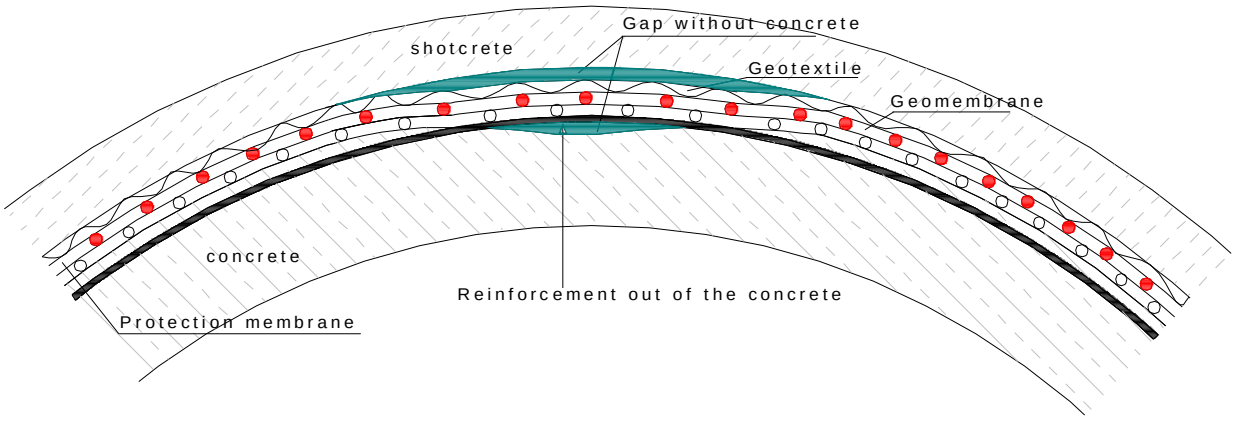
4.4. Reinforcement strip

Shuttering units for the inside concrete are, in general, between 8 to 12 m. At the end of the shuttering unit a head shuttering has to be placed. The placement of this shuttering, consisting of small boards, is a great danger for the waterproofing system. During the fixing of the boards the geomembrane could get damaged. Therefore a protection strip of about 50 cm is placed onto the geomembrane at the end parts of the shuttering unit in order to strengthen the lining system.

4.5. Concrete for the vault

Throughout the concrete procedure a strain will be applied to the geomembrane, provoking a slight elongation due to the weight of the concrete. Experiences in the past have shown that, depending on the surface of the shotcrete and the way of installation of the lining system, folds can appear due to the pouring the concrete. A smooth surface of the shotcrete guarantees less folds in the geomembrane.
The peak of the vault has to be done with great care. After having poured the concrete, it starts to settle and leaves a gap on top of the vault. Precautions have to be taken to close this gap by injecting cement after the concrete has settled.
The steel bars have to be embedded completely in the concrete as well as the anchors of the water stop (if present).

Top of the Vault
French Waterproofing System



4.6. Anchors for reinforcement bars

The installation of the reinforcement steel is one of the most important dangers to the lining system. In the vault the geomembrane is usually not protected and therefore exposed to the danger of being perforated during the reinforcement works. The steel bars have to be placed at a certain distance to the lining system. In case of a not self carrying reinforcement it is highly recommended to use anchors on which the reinforcement bars are fixed at a correct static distance. Such anchors are able to hold loads of over 30 kN depending on the quality of the shotcrete.
This type of anchor is a complete closed system, water is unable to enter between the lining system and the inside concrete shell.
The anchor consists of a hard PVC-P tube with a flange, on which the PVC-P geomembrane is welded on.
After having installed the geomembrane, a hole is drilled into the shotcrete through the geomembrane. The PVC-P tube is bonded into the borehole. The soft PVC-P flange is welded to the geomembrane.
Into the PVC-P tube a steel pin is introduced in order to fix the reinforcement steel of the inside concrete shell.

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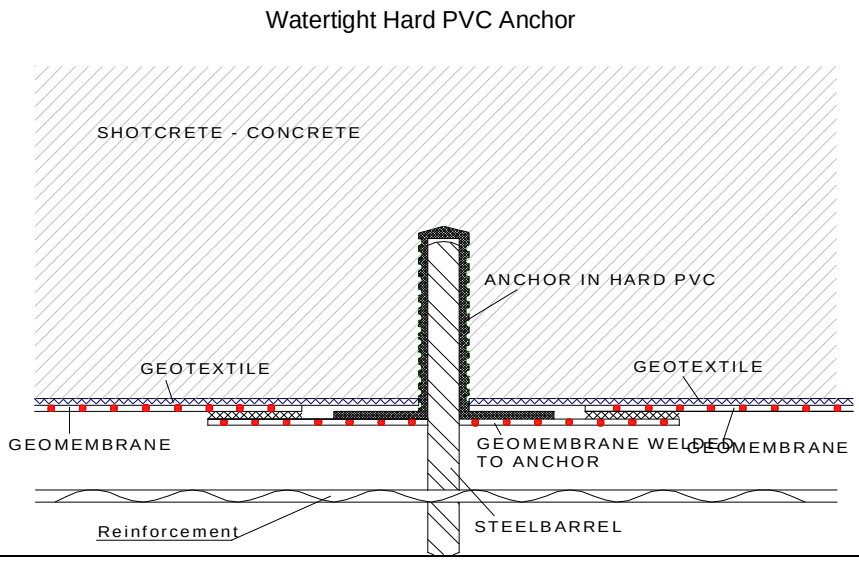


4.7. Compartment system

Water stops are mainly used in tunnels with water pressure.
The water stop divides the lining system into compartments which limits the spreading of the infiltrating water, in case of leakage.
In combination with an injection system a repair of a leaking compartment can be done without damaging the geomembrane, and at a reasonable cost.

4.8. Bonded system

The latest development in tunnel waterproofing is the employment of bonded waterproofing systems. Overall tunnels are becoming longer with the development of high speed trains. These tunnels are constructed with TBM machines (Tunnel Boring Machine) where the geology permits it and where the profile of the excavated zone is regular.

Tübbing are placed to the shotcrete and make a perfect surface to bond the geomembrane onto.
For such an application a geomembrane with a laminated Polypropylene fleece is the correct material to achieve a water tightness of the construction.
Special machines were developed for the installation of the geomembrane. They have a cleaning, brushing and a bonding unit and can be managed with only three people. The performance with such an installing automat is much higher than with a conventional installation method.
RENOLIT is able to offer the right geomembrane for this application.

Installation Automat for bonded system

5. MATERIAL

5.1. Geomembrane

The choice of the geomembrane should be done following the task the geomembrane needs to fulfil (PVC-P, PP or PE).
PVC-P Geomembranes are the most suitable material for the waterproofing of tunnels and foundations due to their excellent mechanical performance and their good chemical resistance.
During the past 40 years all kind of PVC-P geomembranes were formulated and due to the existing standards in Europe two types finally conquered this difficult market.
In the German spoken countries the "signal layer" geomembrane (bicolour) became the chosen one.
In France and other Mediterranean countries the translucent geomembrane was chosen as the suitable material for this important sector as waterproofing material.

5.1.1. System with signal layer

The target of the "signal layer" geomembrane is to detect failures and leakages through a very thin signal layer. The signal layer should be a bright coloured thin upper-layer (less than 0,2 mm in DS 853) so that the dark colour of the geomembrane underneath can be seen in case of any mechanical impact to the material. The two layers have to be made with the same raw material, to prevent any delaminating.

The signal layer geomembrane can be produced in two ways :

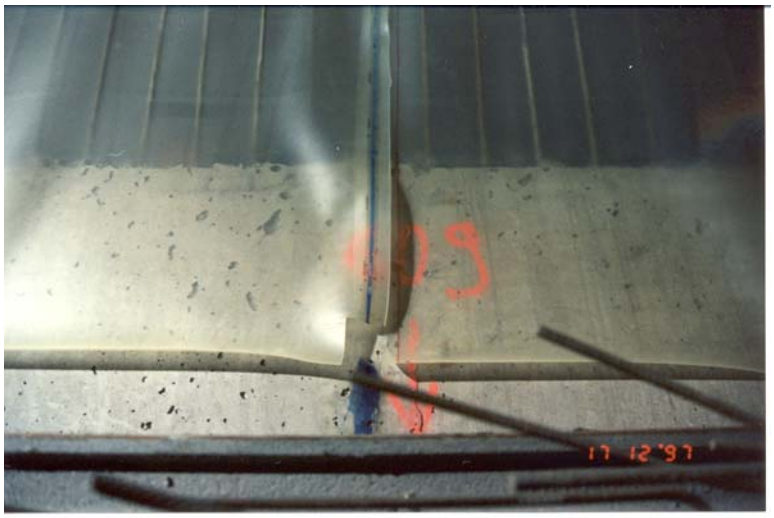
- by calendaring a 0.2mm thin signal layer to be laminated with the geomembrane;
- by printing.

5.1.2. Translucent system

The use of a translucent geomembrane allows for a very good visual control of the welding (continuity + burning).

This picture shows visually that the welding is of good quality as the welding is more translucent than the area of the testing canal, but the black traces in the beginning of the welding tell that the temperature was very high, or the hot wedge not properly cleaned. In such a case a special investigation of the quality of welding in this area can be done immediately. With an opaque geomembrane such defaults never show.

The double welding can be controlled with air pressure as well as with coloured liquids. The advantage of this method is to detect immediately the place where the welding has failed.



control with colour liquid

5.1.3. Resistance of RENOLIT ALKORPLAN PVC-P geomembrane under pressure:

- Intense tests for the St. Gotthard tunnel in Switzerland (Project of NEAT) showed the high shear/compression resistance of translucent PVC-P membrane RENOLIT ALKORPLAN (type 35036 2mm thick), even under high pressure:
  - Load of 2Mpa
  - Horizontal movement of 3mm

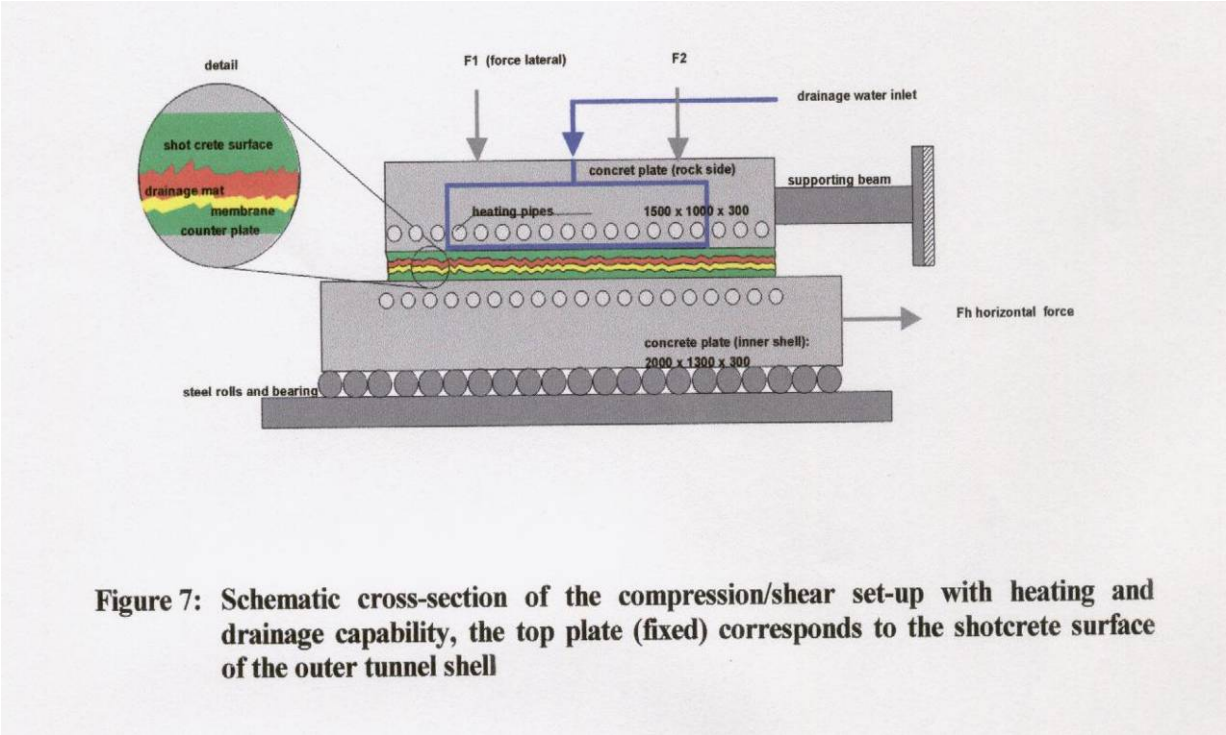


Figure 7: Schematic cross-section of the compression/shear set-up with heating and drainage capability, the top plate (fixed) corresponds to the shotcrete surface of the outer tunnel shell

source : The Sealing of Deep-seated Swiss Alpine Railway Tunnels – New Evaluation Procedure for Waterproofing Systems – NEAT AlpTransit

- The German laboratory SKZ showed that the translucent PVC-P geomembrane RENOLIT ALKORPLAN 35041 2mm thick had an excellent behavior under pressure (EN ISO 604):
  - Compressive stress, at 20% compression, is 13.3 MPa, when a minimum of 2.5 MPa is required;
  - Compression, at 2.5 MPa compressive stress, is 7.5%, when a maximum of 20% is required.

- The French Institute CETE showed that the waterproofing system composed of geotextile 700g/m² + geomembrane RENOLIT ALKORPLAN 35036 2mm + protection layer RENOLIT ALKORPLAN 35020 2.0 mm offers a dynamic puncture resistance higher than 8.5J (fascicule 67 titre III of C.C.T.G.)

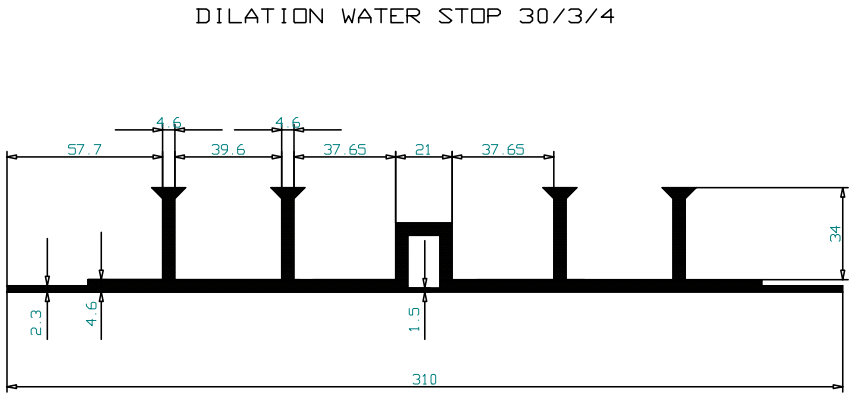
5.2. Geotextile

The geotextile has to be made of Polypropylene fibers, short fibers that are mechanically fixed or long fibers. Polyester geotextile has to be avoided because of hydrolysis of polyester due to the alkalinity of concrete. The freshly applied concrete attacks the Polyester geotextile and after a certain time the geotextile dissolves completely.

5.3. Water stops

5.3.1. Water stops for expansion joints

This water stop is placed in all dilatations of the construction. In case of important movements of the construction the middle bulb is able to break into the thin part of the bottom to follow the movements without loosing water tightness.



Example of water stop for expansion joint following DS 853

5.3.2. Water stop for Normal joint

They are used to create the compartment system.

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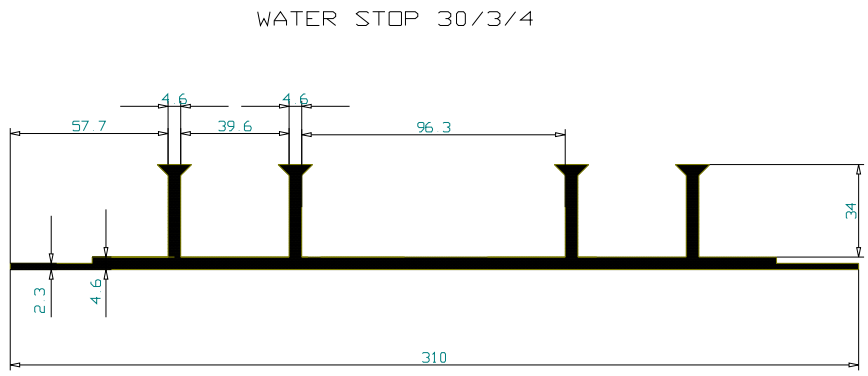
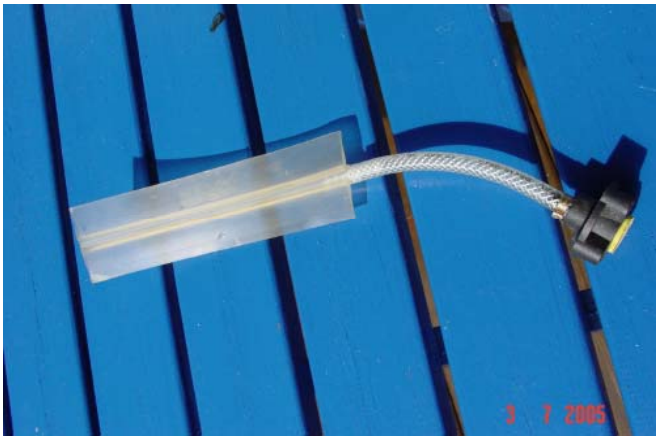


Example of normal water stop following DS 853

5.4. Injection devices

Two different injection systems are available:
- injection pipe
- injection tube

Injection pipe



Injection tube

5.5. Scaffolding

5.5.1. Simple Scaffolding

In general, simple scaffolding is used, running on rails or on wheels. The scaffolding consists of stable elements which can be transported easily and allows adaptations following the dimensions of the tunnel.

5.5.2. Hydraulic Scaffolding

A more sophisticated scaffolding is one with a hydraulic basket turning from one side to the other.

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5.6. Welding tools

5.6.1. Automatic hot wedge welding machine

This kind of machine works with an electric heated wedge. Above and underneath the wedge there are two pressure rolls which are both independently motorized. The hot wedge is guided between the overlapped geomembranes; the two pressure rolls move the machine at a specific speed. Temperature, pressure and speed are adjusted before executing the final welding.

The machine is completely electronically guided. When the outside temperature changes the electronic guidance adjusts the temperature accordingly.

Automatic hot wedge welding machine

5.6.2. Automatic hot air welding machine

The machine is a combination of hot wedge and of hot air automatic welding machine.

The hot air temperature, the pressure, and the speed welding are adjustable in step less way and are electronically controlled.

Automatic hot air welding machine

5.6.3. Hand welder

The hand welder works with hot air and is indispensable on an underground project. All details have to be executed with this well known device.

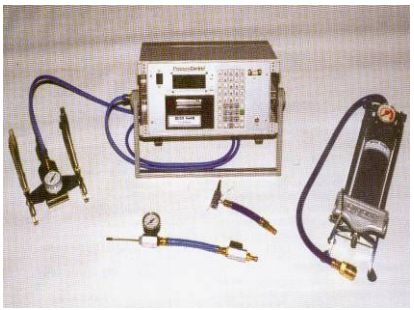
6. CONTROL AND TESTING OF WATERPROOFING

The whole waterproofing work has to be controlled carefully because the smallest leakage can lead to big problems in the future, therefore every seam executed on site or in prefabrication has to be tested.

6.1. Control of double seam through air pressure

The machine welding is produced with a so-called testing canal. After having finished the welding work the seams have to be tested through air pressure or through a coloured liquid which also has to be introduced under pressure into the canal.
The air canal is closed on both sides of the testing distance. A testing needle (e.g. type Leister) is introduced into the testing channel. The needle has a conical form to avoid evacuation of the air under pressure.
The pressure has to be 2 bars and may not be reduced by more than 20 % due to the elongation capacity of the PVC-P material, within 15 minutes, up to an exterior temperature of 30°C.
In case of failure the pressure will go down.
In case of testing with coloured liquid, the leakage of the welding can be detected immediately as it will pour out of the leakage of the welding.
In case of defect welding, it has to be repaired in a careful way by hand welding.
After successful testing, a patch of PVC-P has to be welded over the penetration hole of the testing needle.

Every single welding has to be tested in this way by noting the time, the date, and the pressure at the beginning and at the end of the test.
This information will be written into a daily protocol, which has to be signed by the control engineer, the contractor and the installer.



Control devices

Control by coloured liquid

Double seams control

6.2. Control of hand welding

A steel pipe connected to a compressor with a diameter of 3 to 4 mm is drawn along the seam under an air pressure of 5 bars.
Leakages are immediately detected through the developing air bubble due to the applied air pressure.

7. CONCLUSION

Tunnel waterproofing requires full concentration and precise work. Mistakes can lead to leakages which are difficult to repair and then only by important commercial means. The installer faces the problem that the work carried out can be responsible for the failure of the lining system. Therefore it is crucial that the contractor is fully aware of the sensitivity of the waterproofing work.

The range of geomembranes of RENOLIT for the tunnel lining is complete and offers you the correct material for the right application:

- RENOLIT ALKORPLAN 35034 opaque geomembrane following RVS 8T- Austria
- RENOLIT ALKORPLAN 35036 translucent geomembrane with Avis Technique – France

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- RENOLIT ALKORPLAN 35038 black geomembrane resisting to bitumen
- RENOLIT ALKORPLAN 35041 geomembrane with signal layer following RVS 8T, DS853

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