Waterproofing of Cut and Cover Tunnels

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1. INTRODUCTION

1.1. General

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

Depending on the appearance of the water (humidity, temporary water pressure, permanent water pressure) the lining system has to be adapted accordingly. This is done through 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 has to be taken into account.
This technical description explains the use of RENOLIT geomembranes for the waterproofing.

1.2. Products of RENOLIT

RENOLIT presents a large offer of suitable plastic sheeting to carry out the waterproofing of 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
- work methodology (underground, drainage, waterproofing system, protection).

1.3.1. Water tightness

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

1.3.2. Flexibility

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

1.3.3. Chemical resistance

Pollution of the ground and of the ground water.

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2. GEOMEMBRANES OF RENOLIT

2.1. Geomembranes RENOLIT ALKORPLAN

The type RENOLIT ALKORPLAN represents all geomembranes made out 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.

The above mentioned geomembranes can also be produced with the following:

- With reinforcement (polyester grid or 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, enrolled in a hard box, width of 2,05m.

- No point of yield will be reached before breakage: after elongation under stress, PVC-P is able to relax and to adapt to the underground.
- High performance concerning bi-directional deformation due to their elasticity (>170%).
- Very high resistance against hydrostatic puncture (>950 kPa/mm).
- High puncture resistance.
- Good resistance against chemicals like acid bases and salts, aging and environmental influences.
- PVC-P Geomembranes resist 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 hot air hand welder (type Triac) and automatic machine (hot wedge and/or hot air), even after many years of use, with a large window of 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.
The following accessories are part of such a system:

- o Protection layer (geotextile, plastic sheeting, ...)
- o Fixation elements (laminated metal sheet, water stop, stainless metal plates, anchor and more)
- o 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 materials has to conform to the demands of ISO 9001.
The control of production starts with the supply of raw material, before proceeding to the laboratory which is responsible for the mixing of the compound, from there it goes to the production, then the logistic department as well as the management. After passing through the mixing and melting unit the compound is transported to the calendaring or extrusion unit. After numerous calendaring drums the final membrane, controlled by many electronic devices for thickness, heat and speed, is extracted and rolled up.
The signal layer geomembrane (35041) is produced on extrusion/laminating machinery where the thin signal layer is laminated on a dark grey geomembrane. Exact heat and pressure are important to receive a perfect lamination between the 2 layers of geomembrane.

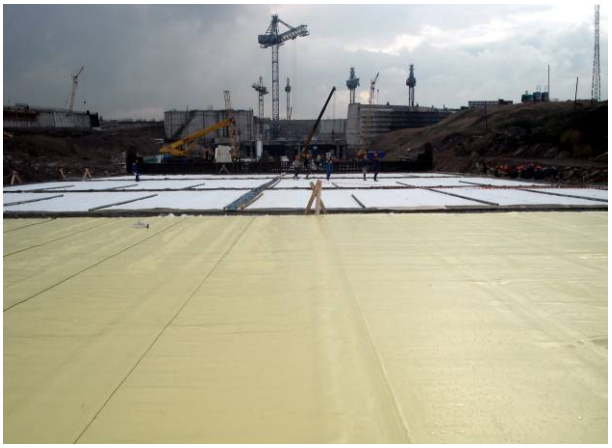
2.5. Geomembrane recommended

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 cut and cover building due to its excellent mechanical properties, handling and durability.
Its high resistance to puncture is valuable to withstand the mechanical aggression caused by the implementation of backfill and to resist high pressure carried out on the geomembrane by the weight of the building : RENOLIT ALKORPLAN 35034 – 35036 – 35041.

3. CONCEPTION OF THE WATERPROOFING SYSTEM

3.1. Foundation Slab

- lean concrete
- geotextile of 500 g/m²
- PVC-P geomembrane of 2,0 mm (1,5 mm)
- Geotextile of 500 g/m²
- PE sheet of 0,25 mm as gliding layer
- Protective concrete



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In order to control and use as repair systems, water stops and injection pipes are installed.
The surface of control areas should not overpass 100 m² of the foundation slab
The foundation slab has to be separated through water stops from the wall section.

3.2. Vertical Faces

3.2.1. Vertical faces with working space

- geotextile 500 g/m²
- PVC-P geomembrane 2,0 mm (1,5 mm)
- geotextile 500 g/m²
- protection layer (card board, concrete blocks)
- backfill

3.2.2. Vertical faces without working space

- retaining wall
- separation layer (e.g. Styrofoam 4 cm or similar)
- geotextile 500 g/m²
- PVC-P geomembrane 2,0 mm (1,5 mm)
- Geotextile
- concrete wall

The same control and repair system is used as for the slab. The water stops are placed in the joint or just near the joint between the slab and the wall.
The surface of control areas has to be determined following the situation on site.

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4. INSTALLATION OF THE WATERPROOFING SYSTEM

4.1. Waterproofing with working space

4.1.1. Lining of the bottom slab

Once the lean concrete is poured, the lining system has to be installed, consisting of:

- Geotextile PP minimum 500 g/m²,
- Geomembrane of PVC-P in a thickness, of at least 2, 0mm
- Protection layer which can be a PVC-P sheet of 1,5 mm to 2,0 mm (RENOLIT ALKORPLAN 35020) or a geotextile of minimum 500 g/m². It is absolutely recommended to put a PE-sheet on top of the geotextile in case this material is chosen as a protection layer, to achieve a gliding between the lean concrete and the concrete slab. Besides the PE sheet avoids the penetration of liquid cement into the geotextile.

This protection layer is installed outside the water stops (if any), which must remain free.

- At the end a last layer of protective concrete has to be poured. In case of using water stops the concrete should not be poured over them, otherwise the compartment system will not work

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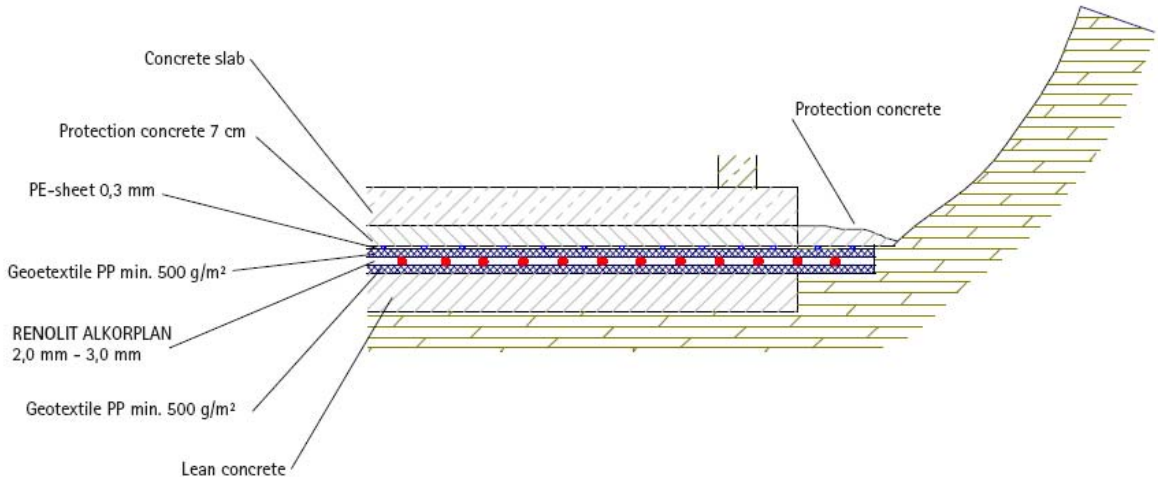


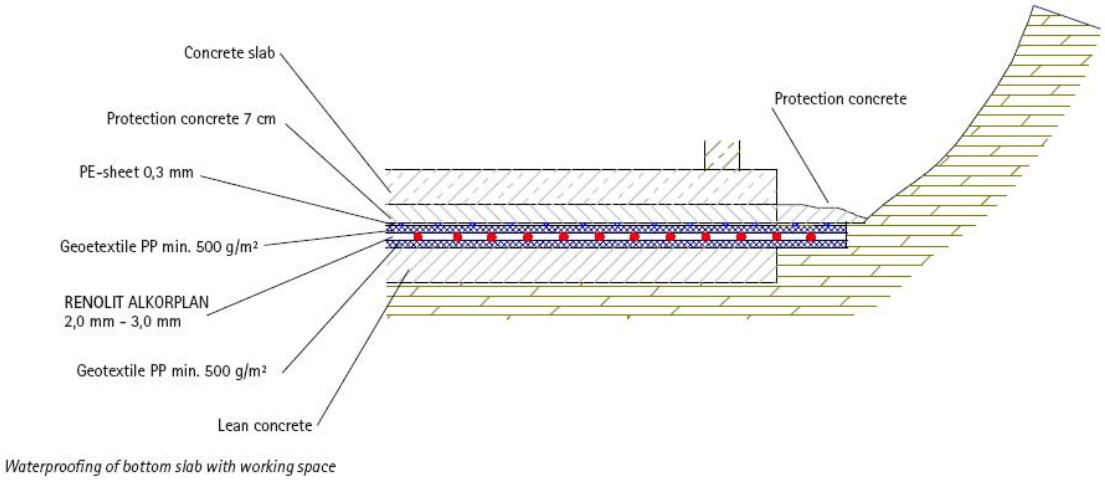
Waterproofing of bottom slab with working space

4.1.2. Lining between Slab and Wall

The lining system is over passing the concrete slab on each side, in order to connect the waterproofing system of the wall. The waterproofing system - over passing the bottom slab - has to be protected (e.g. porous concrete) until the walls are constructed.

Depending on the height of the wall, it will be constructed in successive steps. After finishing the concrete works of the wall (first section), the protective concrete (shown in the drawing above) will be removed, the connection between waterproofing system slab and wall can be executed.

A very sensitive point for the lining is the change from horizontal slab to vertical wall. Local pressures at the corners mean serious stress; therefore it is very important to work on these areas with great care.



Waterproofing of bottom slab with working space

Corner in 2 layers

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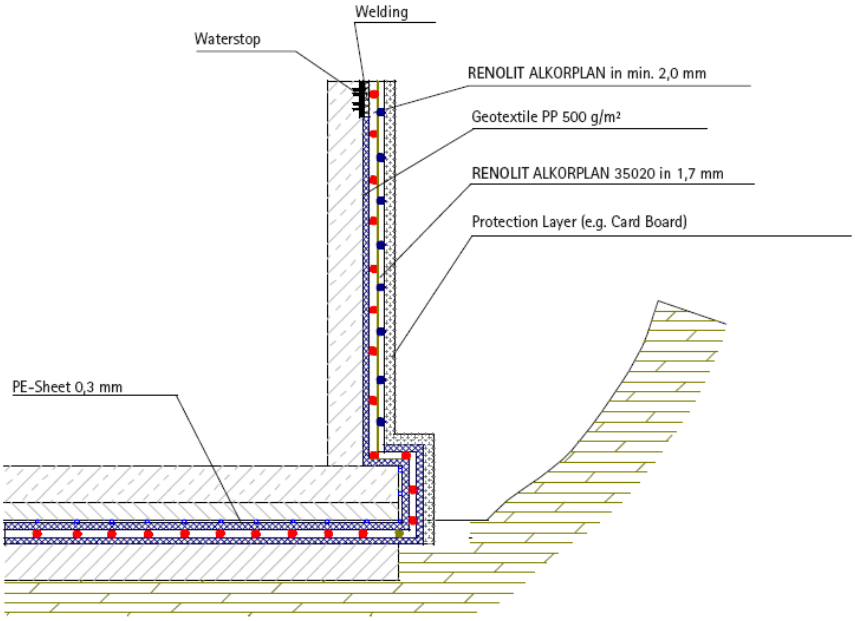
4.1.3. Lining of Vertical Faces

The fixation on top of the wall can be done in different ways. There is the possibility of placing a water stop into the upper side of the shuttering. After the concreting the shuttering is removed, the water stop cleaned and the membrane welded to the water stop. This is for sure a good technical solution and creates in addition a compartment system. In case the backfill follows the concrete works of each wall section the waterproofing will be fixed temporarily. To continue the waterproofing work, the backfill is brought to the desired height and the concrete of the next section of wall is executed. After the shuttering of this section is removed the waterproofing follows. The temporary fixation underneath will be removed and the geomembrane welded to the fixation to guarantee water tightness.
This procedure will continue until the projected work has been finished. The final fixation on the highest level can then be done with the help of a water stop or a mechanical fixation.



Waterproofing of the wall

This procedure of work will continue till reaching the projected ending.

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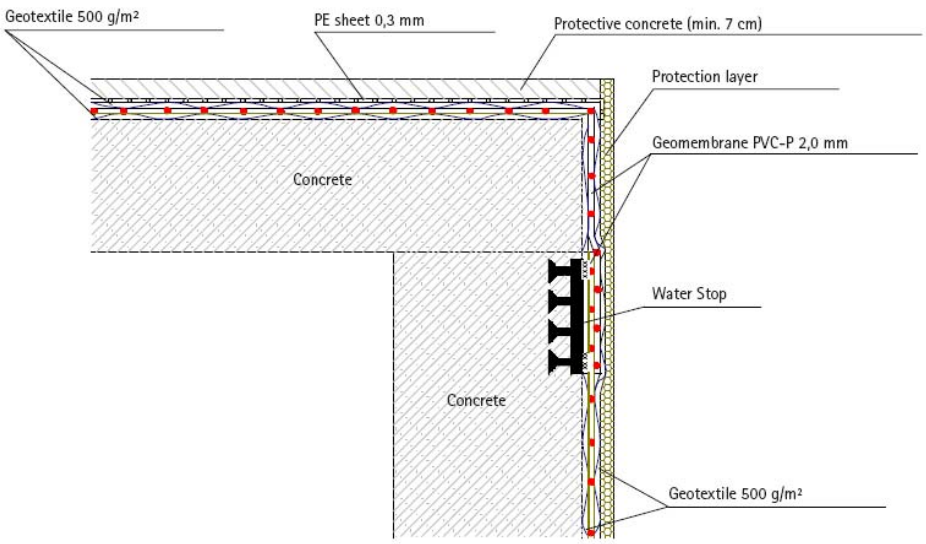
4.1.4. Waterproofing of the ceiling

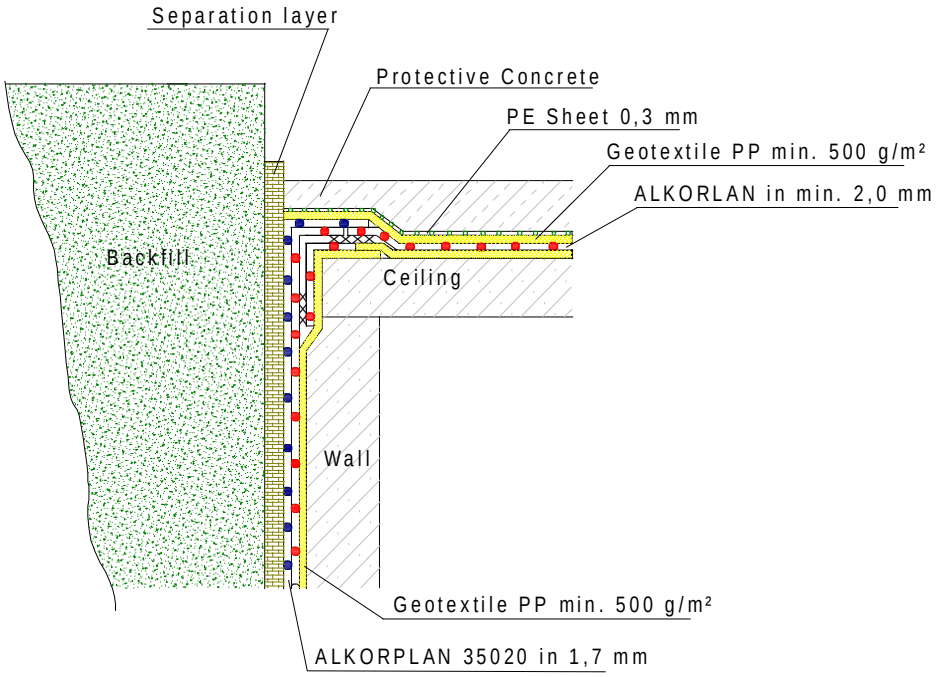
The joint between wall and ceiling can be executed in different ways. A technical good solution is to use a water stop to fix the geomembrane to the wall and make there the joint for the horizontal lining of the ceiling slab.



The surface of the ceiling has to be clean and free of debris and stones, without holes. The system of waterproofing is identical to the raft.

Waterproofing of Cut and Cover Tunnels

Connection Wall Ceiling Slab



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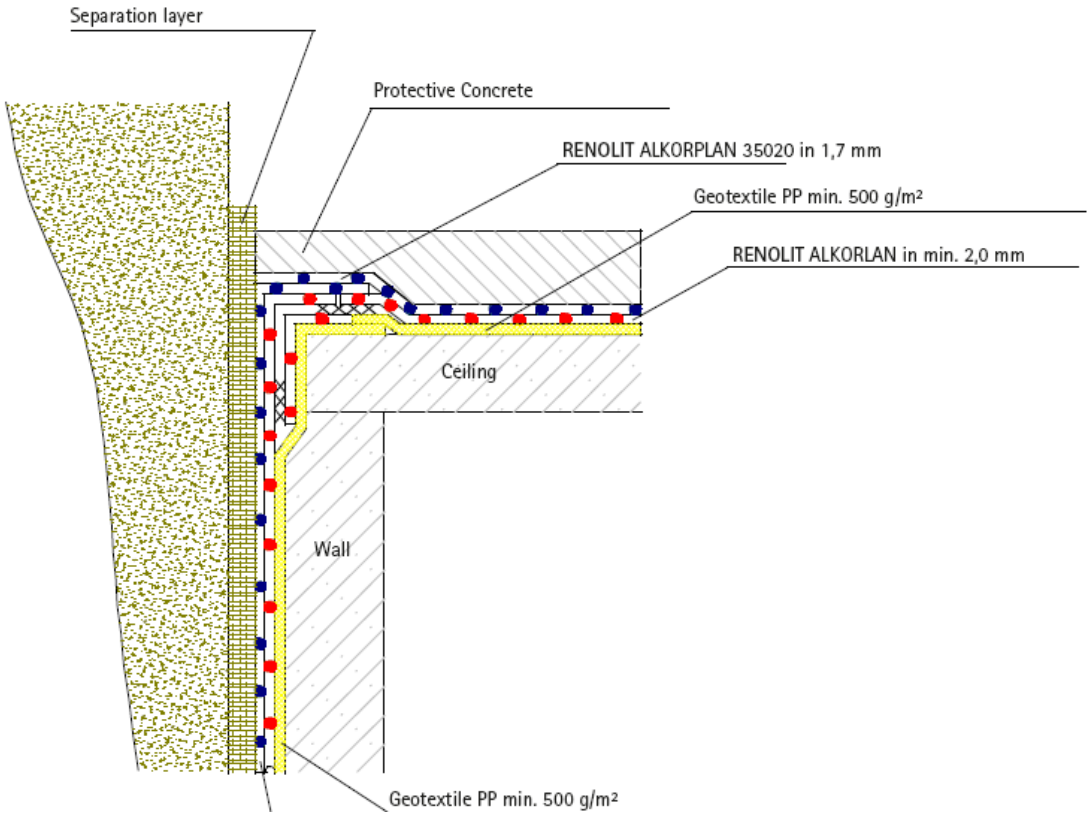

4.2. Waterproofing without working space

4.2.1. Waterproofing of the raft

The execution of the waterproofing of the bottom slab without working space is similar to the one with working space, besides the connection point for the wall lining. The waterproofing has to be fixed temporary to the retaining wall at a specific height to guarantee a safe connection with the waterproofing of the wall. The temporary fixation has to be removed before continuing with the concreting of the vertical faces. A geotextile has to be placed between the retaining wall and the geomembrane.

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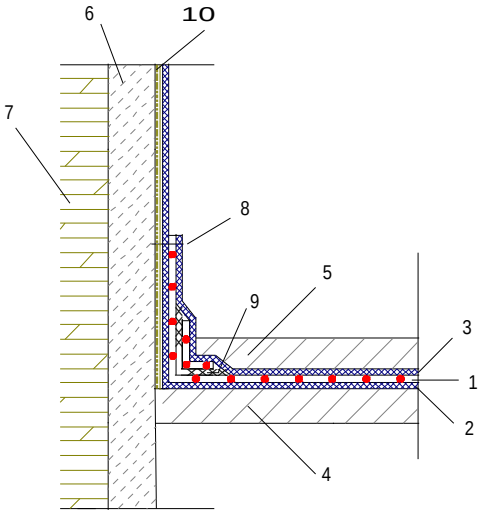
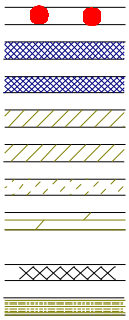
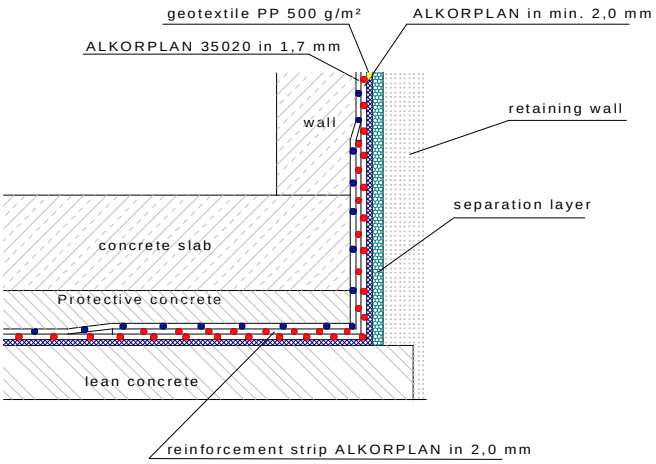
STANDARD - DESIGN FOUNDATIONSLAB - WALL



1 ALKORPLAN 35041 2,0 mm
2 Geotextile 800 g/m²-500 g/m²
3 Geotextil 500 g/m²
4 Lean concrete
5 Protective concrete
6 Shotcrete
7 Retaining wall
8 Temporary fixation
9 Welding seam
10 Separation Layer



Waterproofing of foundation without working space



Execution of the lining system between slab and wall

4.2.2. Lining of Vertical Faces

The waterproofing works are carried out before the concrete works of the walls. The waterproofing has to be brought to the height over the next concrete section of the walls and fixed temporary over this level on the retaining wall. When the lining works continue, the temporary fixation is removed, the next part of the lining system welded to the installed membrane and placed over the vertical surface of the next section. If the construction continues in this way, the described method will be repeated. (Sketch without water stops).

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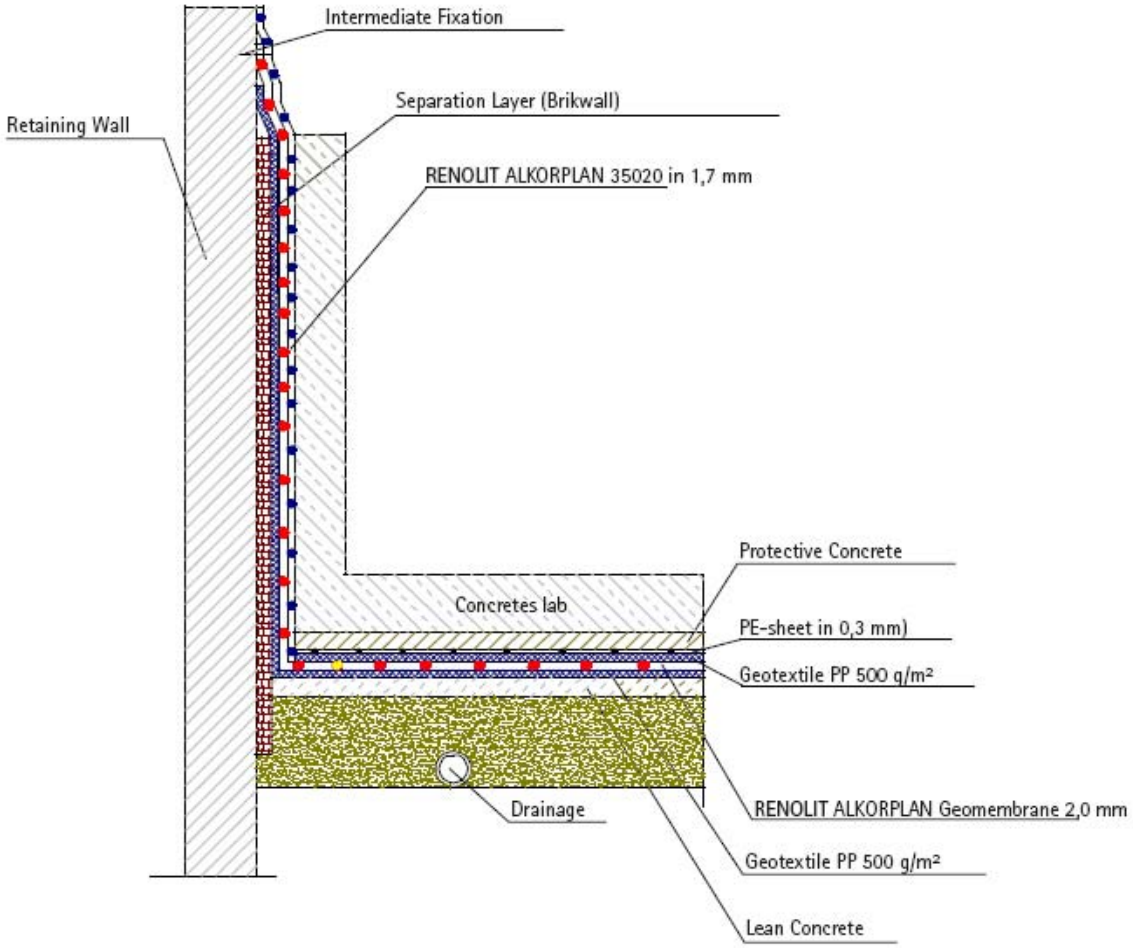

4.2.3. Waterproofing of the ceiling slab

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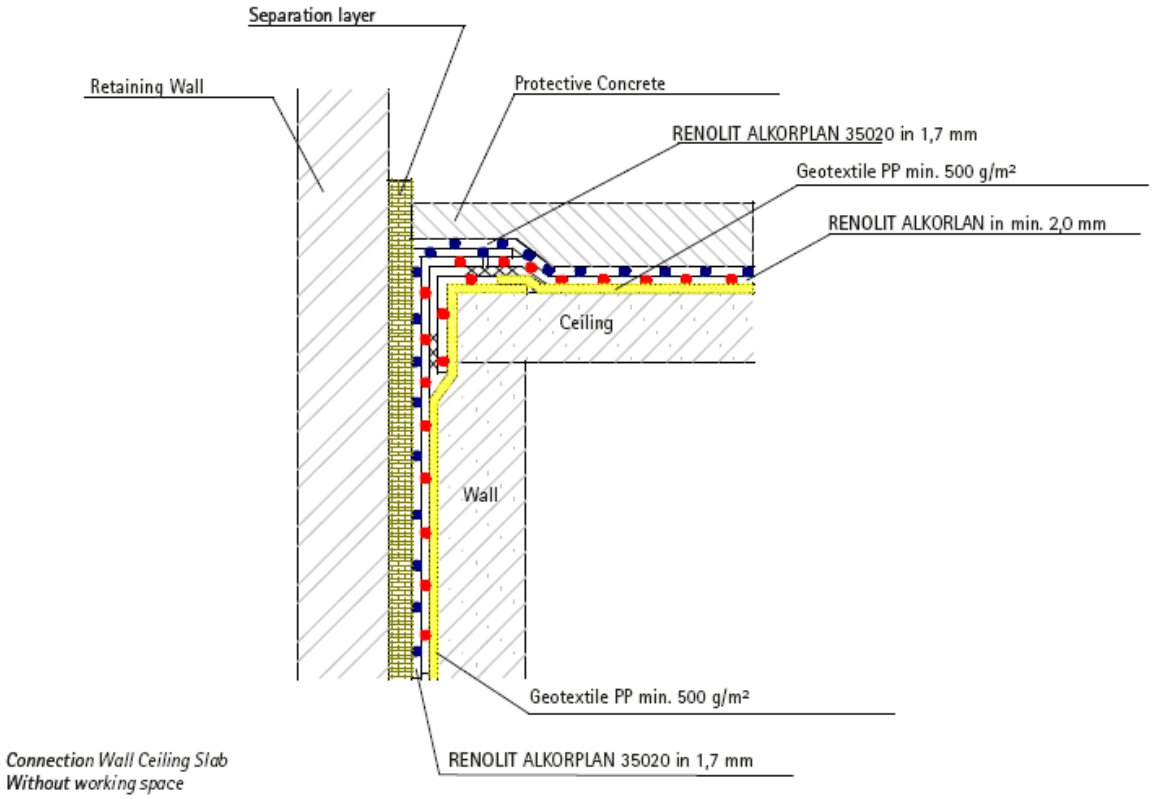
The surface of the ceiling has to be clean and free of debris and stones, without holes. The system of the waterproofing is identical to the raft.



Connection Wall Ceiling Slab
Without working space

5. COMPARTMENT SYSTEM

This system helps to limit the repair works in case of damage. The water stop, welded to the geomembrane, divided the lining system into compartments which limit the spreading of the infiltrating water. The surface of one compartment should not overcome 100 m².
The anchors of the water stop have to be well embedded into the concrete in order to stop any spreading from one compartment to the other.
The PVC-P water stops are welded to the geomembrane (with welding automate for horizontal surfaces).
Through these compartments the area of leakage can be determined precisely to a certain limited surface. In combination with an injection system, a repair of a leaking compartment can be carried out without damaging the geomembrane, which also keeps the cost at a reasonable level.

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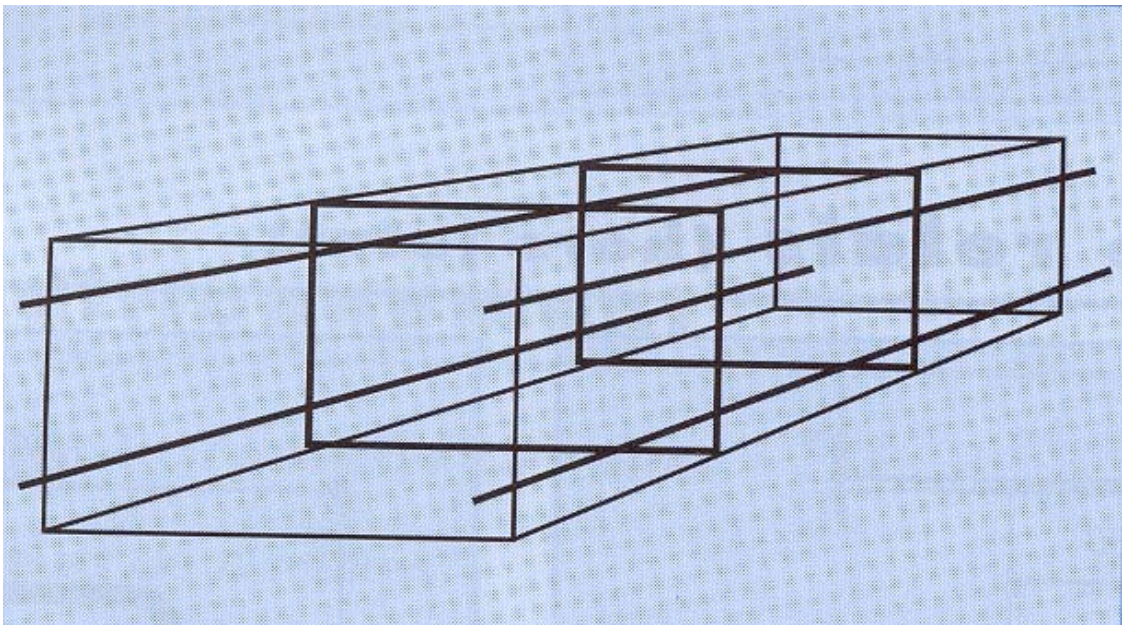
Depending on the joints (working joints or dilatation joints) an external water stop or an expansion water stop has to be used.



scheme of compartments in cut and cover tunnel

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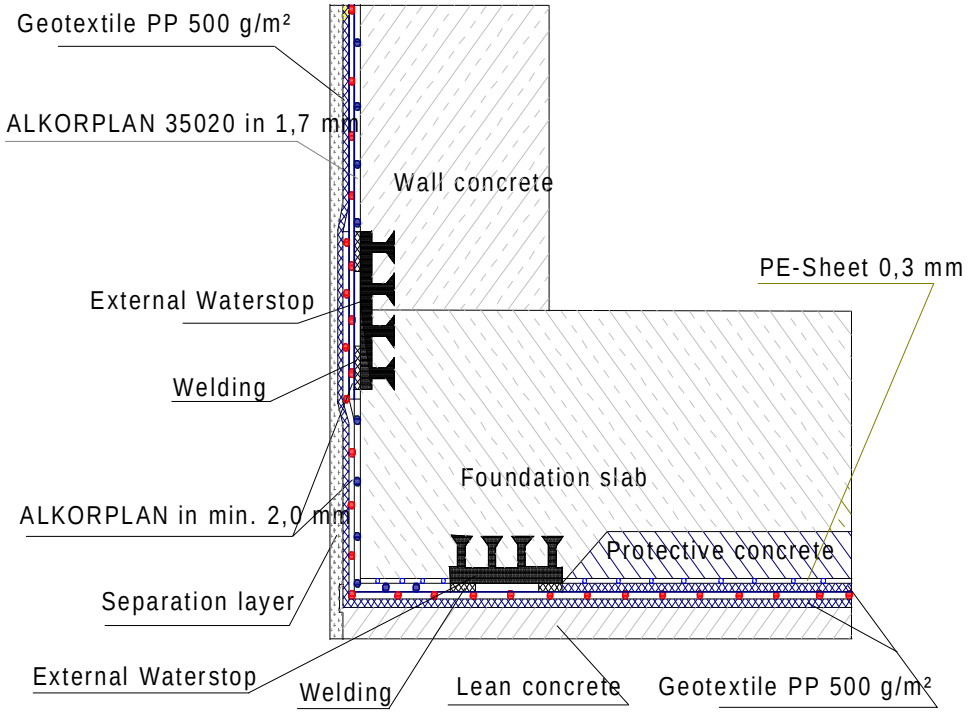
Waterproofing of Cut and Cover Tunnels

Foundation slab - Wall



Execution of lining system with external water stops

water stop installed

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6. MATERIALS

6.1. Geomembrane

The choice of the geomembrane should be done following the task the geomembrane should 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 have been made, and in view of the existing standards in Europe two types have finally conquered this difficult market.
In the German spoken countries the “signal layer” geomembrane (bicolour) entered all important standards.
In France and other Mediterranean countries the translucent geomembrane was the convincing one as the suitable material for this important sector as a waterproofing material.

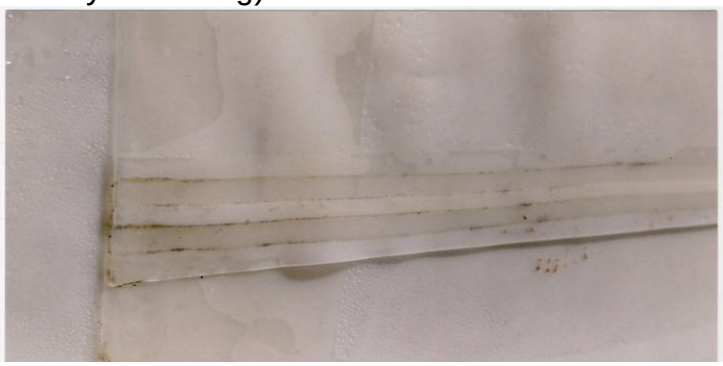
6.1.1. System with signal layer

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 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.

6.1.2. Translucent system

The use of a translucent geomembrane allows 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 at the

beginning of the welding show that the temperature was either 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 would appear.
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 of failure of the welding.

6.1.3. 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

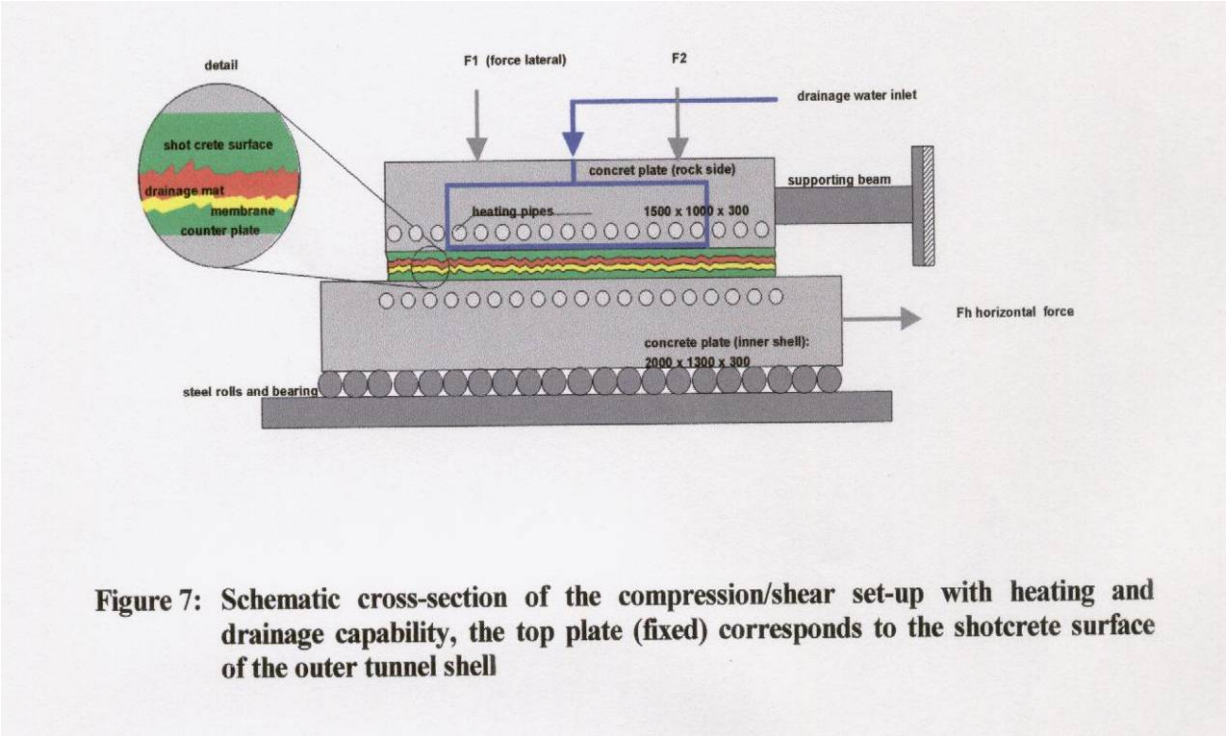


Figure 7: Schematic cross-section of the compression/shear set-up with heating and drainage capability, the top plate (fixed) corresponds to the shotcrete surface of the outer tunnel shell

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 by a geotextile 700g/m² + geomembrane RENOLIT ALKORPLAN 35036 2mm + protection layer RENOLIT ALKORPLAN 35020 1.9mm offers a dynamic puncture resistance higher than 8.5J (fascicule 67 titre III of C.C.T.G.)

6.2. Geotextile

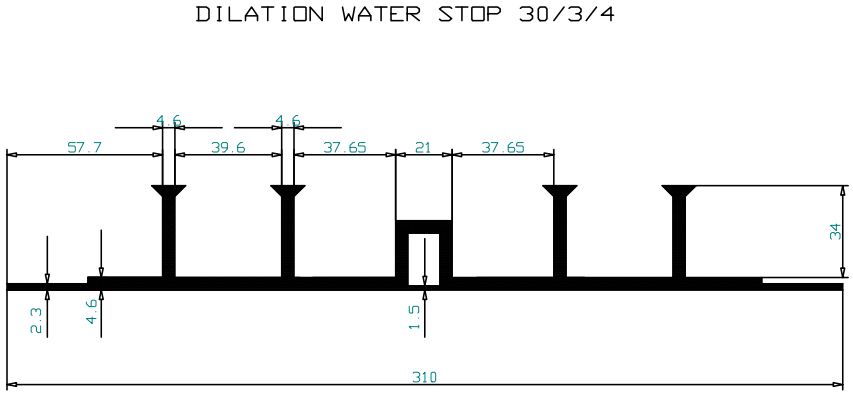
The geotextile has to be made of Polypropylene fibers, short fibers mechanically fixed or long fibers. Polyester geotextile has to be avoided because of hydrolysis of polyester due to the alkalinity of concrete. The freshly applied concrete attacks the Polyester geotextile and after a certain time the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

6.3. Water stops

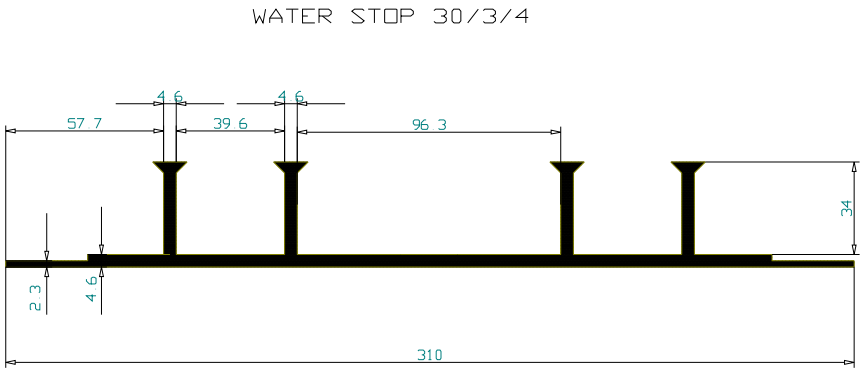
It is recommendable to use water stops with integrated injection tube as it is important to assure the water tightness in the joints.
They are used between concrete sections.

6.4. Water stop for Expansion joint

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



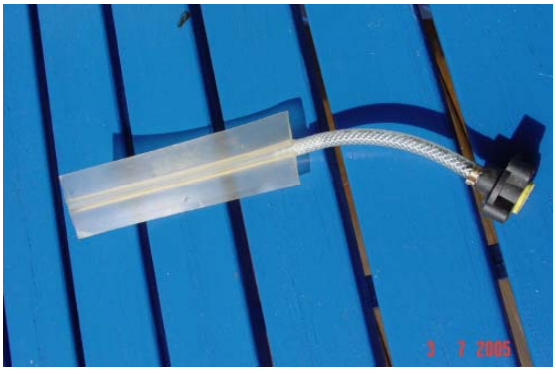
Example of normal water stop following DS 853

6.5. Injection devices

In addition to the water stops, injection devices are welded at specific points to the geomembrane. The task of the injection devices is to provide the possibility to inject liquid waterproofing materials in order to close an eventual leakage of the geomembrane. These liquids or resins are based mostly on two components acrylic or polyurethane. The injection devices go through the concrete shell and are always reachable in case the waterproofing system fails.
The injection work is a difficult task and has to be carried out by experts. The injection resin has to be pressed through the injection pipes between geomembrane and inside concrete. The mixture of the two resin components is very important as on the one hand it has to stay liquid long enough to be able to spread over the whole surface of the compartment and on the other hand it has to harden quickly so it does not leak out by the infiltrating water.

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

Injection pipe



Injection tube

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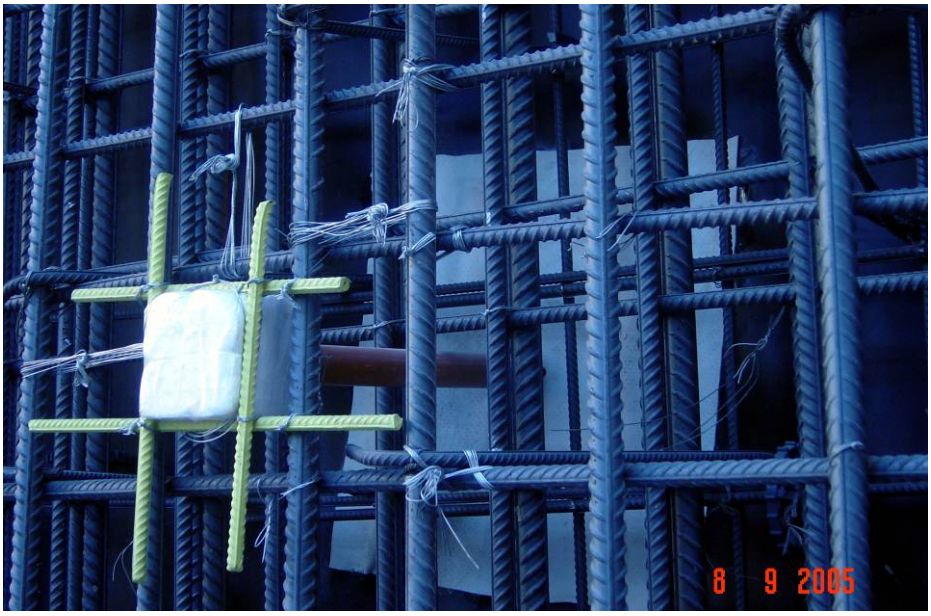
6.4.1. Injection pipe

The injection pipe is a hose on which a PVC-P tube will be welded through THF. One has to ensure that the tube can resist a pressure of at least 6 to 8 bars. No metallic device will be used to avoid the danger of perforating the geomembranes.

The exit piece of the injection pipe has to be integrated into a safe device of the surface of the concrete



Protected inlet of Injection Pipe

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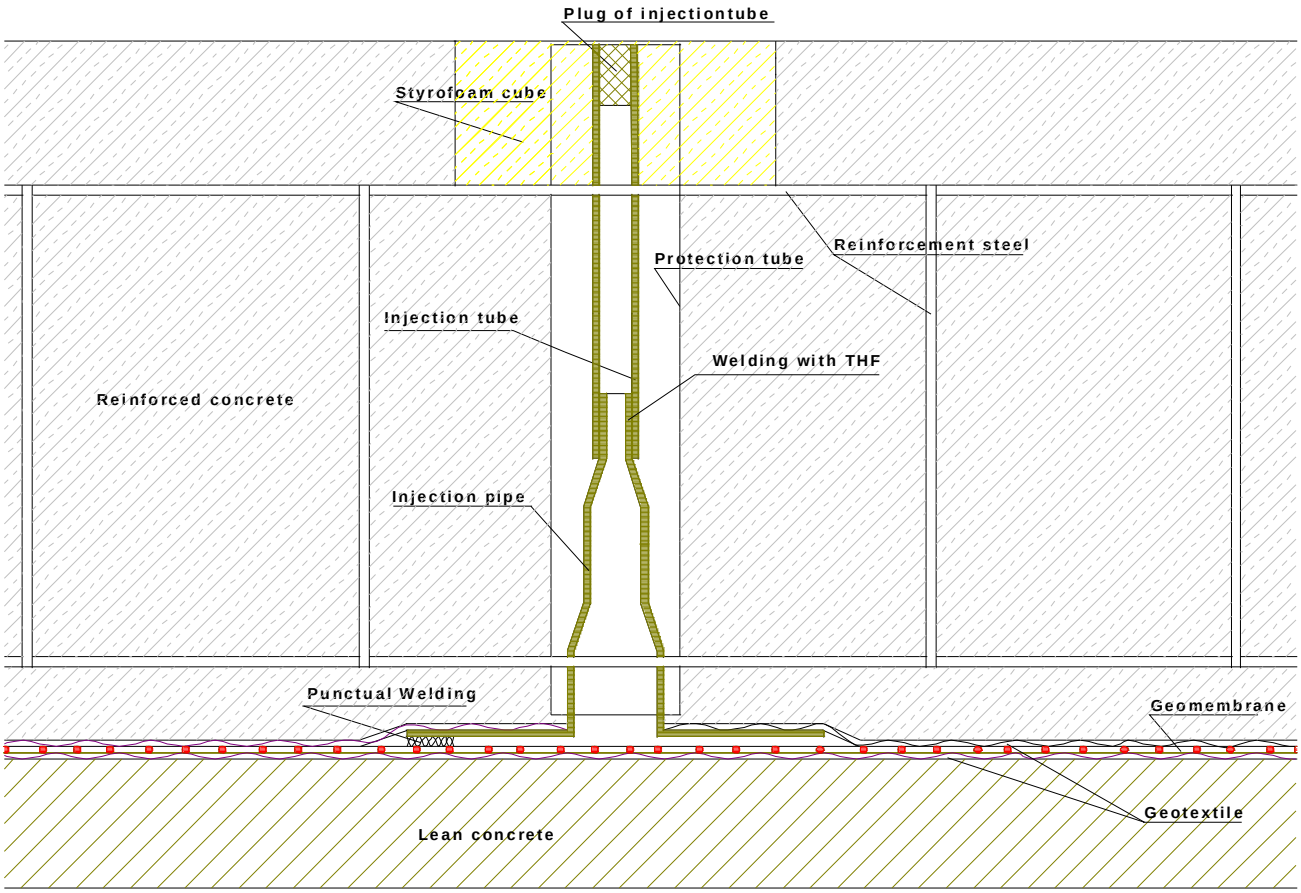
Injection System



Installed Injection Pipe spot welded to the Geomembrane

6.4.2. Injection tube

Alternative injection device: injection tubes spot welded to the geomembrane that open when the resin is injected under pressure.

Injection tube welded to geomembrane

Injection tube

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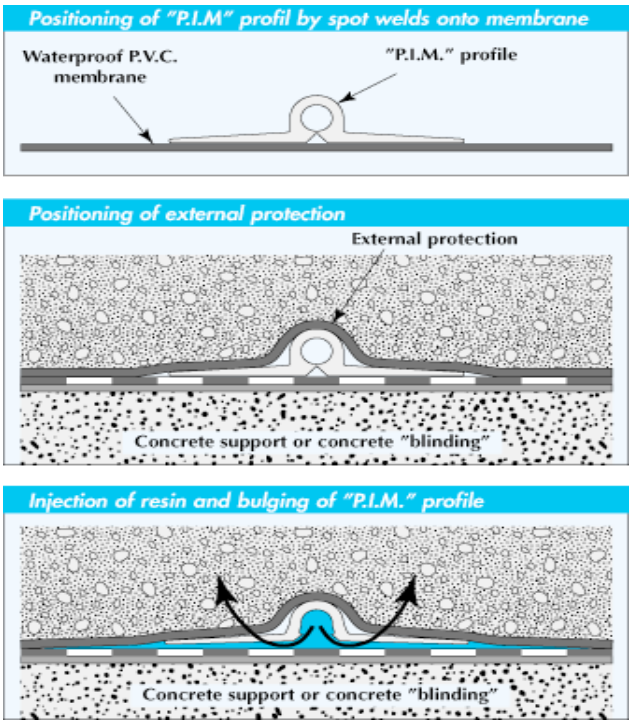

6.6. Welding tools

6.5.1. 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 advance the machine at a determined 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

6.5.2. Automatic hot air welding machine

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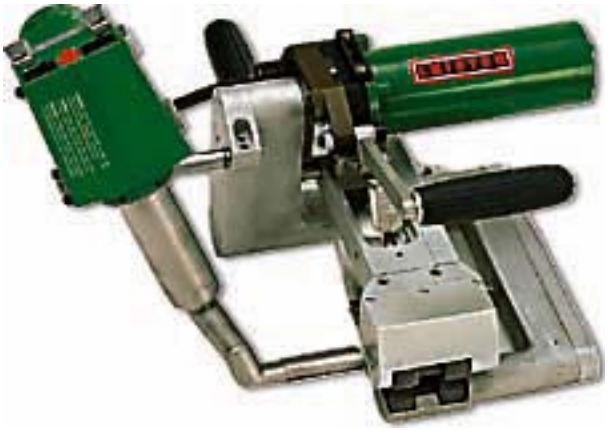
The machine is a combination of hot wedge / hot air automatic welding machine.
The hot air temperature, the pressure, and the speed of welding are adjustable in step less way and are electronically controlled.



Automatic hot air welding machine

6.5.3. Hand welder

The hand welder works with hot air and is indispensable for underground projects. All details have to be done with this well known device.

7. CONTROL AND TESTING OF WATERPROOFING

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

7.1. 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 air leakage 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 a defect welding, it has to be carefully repaired by hand welding.
After successful testing, a patch of PVC-P has to be welded over the penetration hole of the testing needle.

All welding jobs have to be tested and the time, date, and pressure noted at the beginning and at the end of the test.
The information will be noted into a daily protocol form, which has to be signed by the control engineer, the contractor and the installer.

Control devices

Double seam control

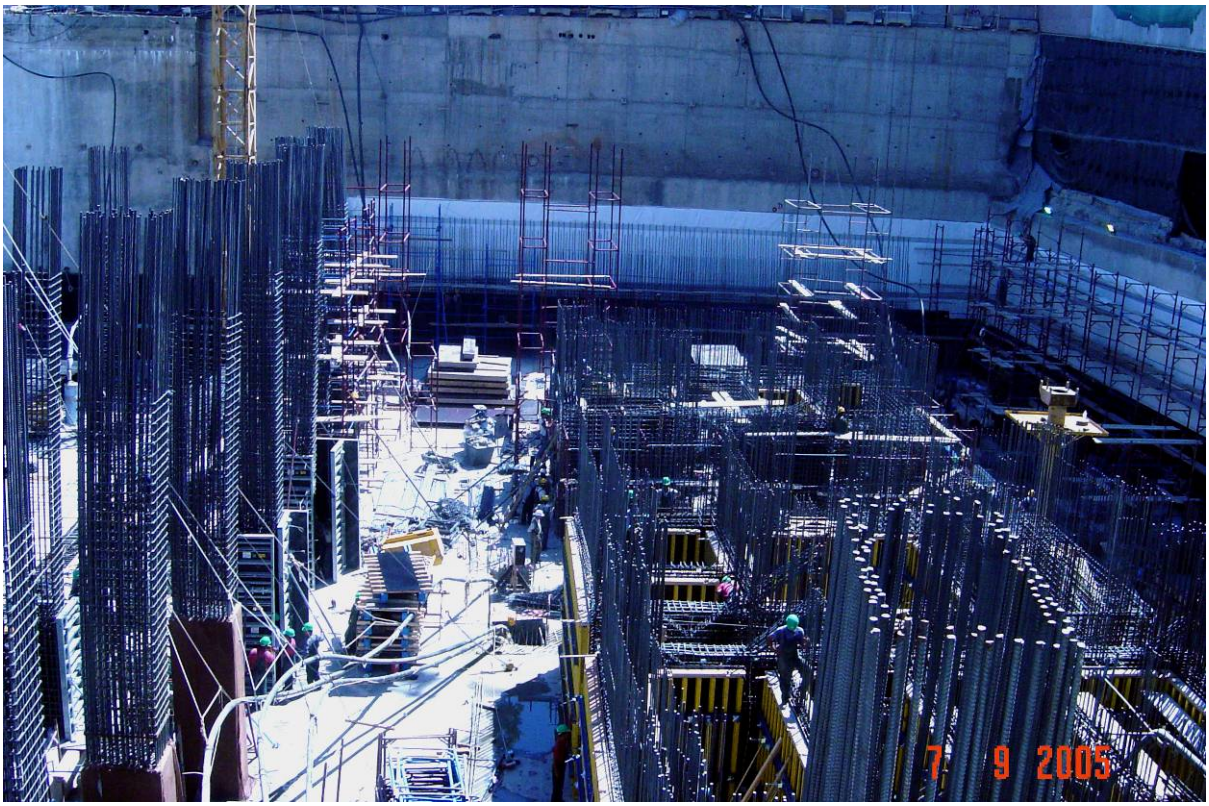
7.2. Control of hand welding

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 though the developing air bubble due to the applied air pressure.

8. CONCLUSION

Waterproofing of Cut and Cover Tunnels

The installation of waterproofing systems in cut and cover tunnels is a sophisticated piece of engineering. Only a precise installation can lead to success. The slightest mistake will allow water to enter between the geomembrane and the inside concrete shell.
The installer cannot be the only responsible for the success of a waterproofing system under such circumstances, too many risks for damage can occur after he has finished his work.
The contractor has the duty to execute his work in the same professional, careful way as the installer to deliver a dry work.
This is a difficult task and failures in the lining system can happen. Therefore a repair system is foreseen from the beginning throughout the integration of the compartment system with injection pipes. It delivers a realistic chance to close any leakages in the waterproofing system.



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