The use of PVC geomembranes in tunnels and underground structures-special testable and reparable waterproofing systems

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ABSTRACT: the use of PVC geomembranes for waterproofing applications in tunnels and underground structures has been widely used for many years all over the world.
Nevertheless, the application of a PVC waterproofing geomembrane can be subject to different risks of mistakes and damages that may compromise the proper functioning of the system.
Special waterproofing systems have been developed for tunneling and underground structures in general in last years that can be checked and repaired after the application and also after the completion of the structures.
The purpose of this presentation is to describe the main quality controls to adopt during the production of a PVC geomembrane, the design and the construction phases of a waterproofing system and to analyze the different systems that can be adopted by the designers and the main procedures to repair the different waterproofing systems in case of accidental damages.

Keywords: waterproofing, PVC geomembranes, waterproofing system, synthetic membranes

1 INTRODUCTION

The use of geomembranes in waterproofing applications in tunnels and underground structures is very common all over the world since long time. In Italy there are applications documented since the early 1970's, where the system used was basic and consisting of only one layer of non-reinforced geomembrane sometimes with protection. This type of application has evolved in recent years, now consisting of a variety of repairable systems rather than a single membrane system application.

2 PVC GEOMEMBRANES USED IN CIVIL ENGINEERING APPLICATIONS

Geomembranes made by flexible PVC are widely used within the big family of geomembranes. This is to do with their flexibility, high mechanical resistance and easiness of application. These type of membranes have to be specially formulated, designed, certified and CE marked according to the main European standards for the specific intended use. During the design phase it's also important to consider mechanical, physical and chemical factors that can affect the life of the geomembrane in relation to the service life required for the project in question.

2.1 *Construction products regulation*

The Construction Products Regulation (CPR) n. 305/2011 is the main regulation providing harmonized rules for construction products in Europe. It's a regulation valid in the European Union that gives indications about the CE marking and the Declaration of Performance of construction products when introduced in the European market.

2.2 The European harmonized standard

The European harmonized Standard for geo-membranes used for applications in tunnels is the EN 13491 *"Geo-synthetic barriers - Characteristics required for use as fluid barrier in the construction of tunnels and underground structures"* (1). This harmonized Standard has the scope to specify the relevant characteristics of geo-synthetic barriers (geomembranes) when used as waterproofing barriers for fluids in the specific application fields as defined in the scope of the Standard and the test methods to determine these characteristics. This harmonized standard also has the scope to give indications about how to assess and verify the constancy of performances of the product to the European Standard and factory production control procedures. The annex ZA, that's the relevant part in every harmonized Standards, specifies all the requirements provided by the CPR according to which is possible to put the CE mark on the product and in particular the essential characteristics to declare in the Declaration of Performance (DoP).

2.3 Laboratory tests on PVC geomembranes

Geomembranes used in tunnels are subject to an evaluation of conformity task under system 2+ as reported in the annex ZA of the European Standard EN 13491(1). The manufacturer shall do all tests related to the assessment of the performance of the geomembranes produced, the Factory Production Control and the test on samples produced according to the plan reported in the European Standard. All this is done under the initial inspection and the continuous surveillance of a notified factory production control certification body. The essential characteristics have to be declared in the DoP (Declaration of Performance) that has to be provided by the manufacturers once they introduce the product in the EU market.
The essential characteristics to be declared, according to the European Standard EN 13491(1) for PVC geo-membranes to be used in tunnels, are the following:

a) EN 14150 - Water Permeability: it's a test to measure the steady-state flow of a liquid through a geomembrane in the long term application.
b) EN ISO 527 - Tensile Strength: it's a group of test methods to measure the tensile properties of plastics. It's important to define the mechanical characteristics of a geomembranes in terms of tensile strength and elongation.
c) EN ISO 12236 - Static Puncture: it's a test method to measure the puncture resistance of a geomembrane by measuring the force required to push a flat-ended plunger through it.
d) EN 14575 - Oxidation: this is a screening test to determine the resistance to the oxidation of a geomembrane. This is a test to assess the durability.

Further tests can be performed according to the European Standard for characteristics relevant to specific conditions of use.

3 WATERPROOFING SYSTEMS

The geomembrane is the main functional layer of a waterproofing system. All the components of this need to be regarded as an overall system, not looked at independently. It's always intertwined to the infrastructure of which it is a part. The practical applications and the performance of geomembranes are designed to provide waterproof security of the infrastructure for a period compatible to its service life (2)(3).

3.1 Why it's necessary to waterproof?

It's important to design a correct waterproofing system for three main reasons (figure 1):

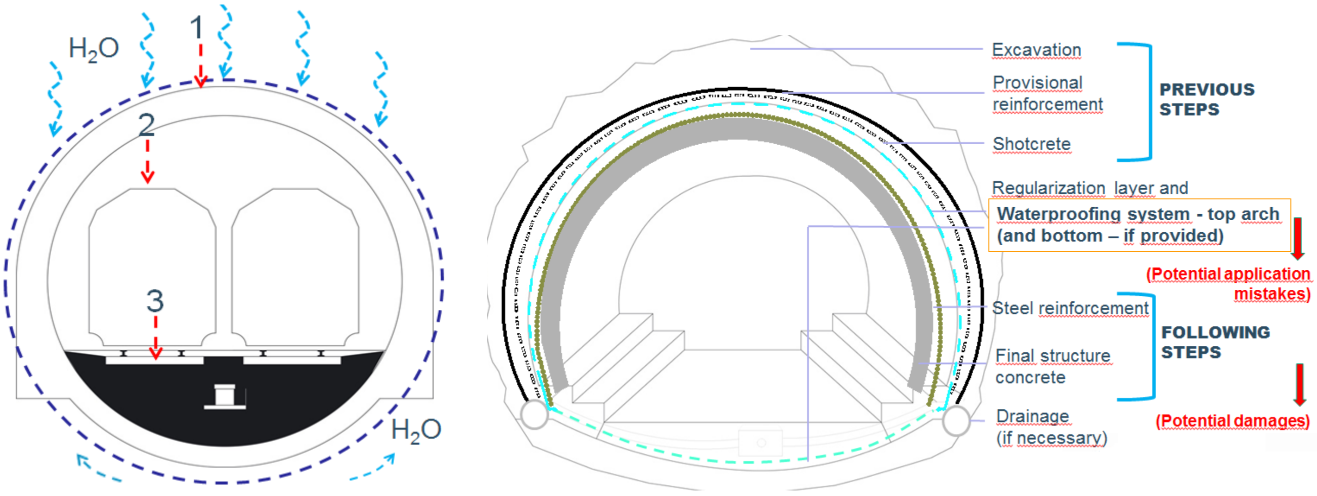


Figure 1. schematic section of a tunnel (a) - main steps of construction (b)

1) To protect the infrastructure: from chemical, physical and mechanical damages caused by water ingress from outside the structure.
2) To protect the system that is present inside of the structure: within the tunnel there are electrical power supplies providing output for various purposes - for the lights and aeration plant but also for the trains and subways.
3) To prevent safety issues: the presence of water leakage can create serious safety issues.

3.2 Application of a PVC geomembrane: main critical aspects

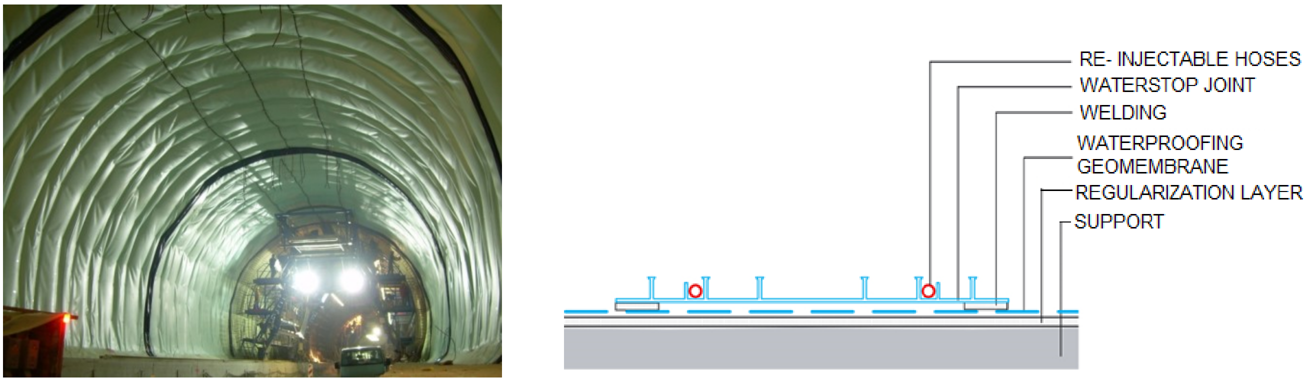
The application of a PVC geomembrane is carried out after important activities, such as excavation, positioning of the provisional reinforcement if necessary and application of the regularization layer made by shotcrete. All these steps are required to prepare an adequate support for the application of the waterproofing system and can be defined as in “previous steps”. The main possible risks are related to application errors. Following the conclusion of the waterproofing procedure there are further activities that can damage the membrane, such as the application of steel reinforcement or the pouring of the concrete (figure 1b).
The best approach to design waterproofing systems is by introducing procedures of ‘checking and testing’ and also to ensure easy repair once the system is covered by the concrete.

3.3 The design phase: the choice of the waterproofing system with PVC geomembranes

During the design phase it is very important to do an accurate risk assessment based on the presence of water and the intended use. In general the presence of water can be related to the presence of confined or unconfined aquifers or to water coming from gravity. In any case it’s important to verify the level of water pressure in order to decide the most appropriate type of waterproofing system. Water coming only from gravity could indicate selection of a top arch waterproofing protection system with longitudinal drainages along the bottom of the waterproofing layer and drains to collect the water. This is the system adopted in various tunnels in Italy, for example Variante di Valico tunnels in the Appennini mountains. In the presence of aquifers and water table level penetrating or threatening the structure, the implementation of reparable and testable systems is highly recommended.
There are different waterproofing systems in the market made with PVC geomembranes, but almost three of them were commonly used. The most appropriate systems should be selected by the designer according to the specific geological conditions, taking into consideration water pressure and type of application.

1) Basic system: Single layer system with Compartments and active waterstop joints (SC)

This system consists of one layer of PVC geomembrane and waterstop joints, welded on, to create compartment areas to limit the trajectory of the water in case of eventual leakages. The presence of reinjectable hoses allows the waterstop joints to be “active” within the structure and create the continuity between the waterstop joint and the concrete structure if it’s not fully realized (figures 2a and 2b).



a) b)

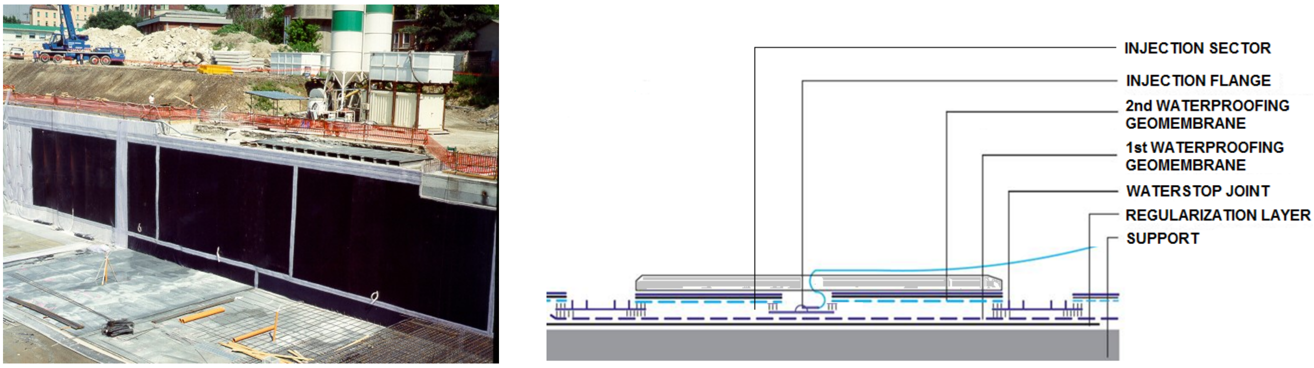
Figure 2. a) Waterproofing system applied - b) Schematic section of a waterstop with injectable hoses

2) <u>Advanced: Double layer system with Compartments and Repairable (DCR)</u>

This system consists in one waterproofing layer of PVC geomembranes and waterstop joints welded on it to create areas to limit the trajectory of the water in case of eventual leakages .

In the DCR a second protection layer made by PVC geomembrane is applied over the PVC waterproofing layer and welded along the perimeter of the waterstop joints creating injection sectors.

On the protection layer are welded injection flanges connected to injection pipes allowing the injection of resin in case of leakage and even when the structure is completed (figures 3a and 3b).



a) b)

Figure 3. a) DCR system Installed - b) Indicative section of a DCR System with Injection Flange

3) <u>Optimal: Double layer system with double Compartments, vacuum Testable and Repairable (DCTR)</u>

This system consists of one waterproofing layer of PVC geomembranes and a second functional layer of geomembranes with one structured surface, welded to the first layer along the perimeter to create sectors of maximum 100 m2. On the second layer are welded injection flanges (minimum 5 per sector) connected to injection pipes that allow the user to do a vacuum test immediately after the application and also the injection of resin in case of leakage even when the structure is completed. The system is covered by a protective layer and completed by the application of waterstop joints welded on the structured membrane according to the project requirements (figures 4a and 4b).

a) b)

Figure 4. a) DCTR system installed and b) Indicative section of DCTR system with flanges and compartments

3.4 Application of a waterproofing system made by PVC geomembranes: critical steps

Once the most appropriate waterproofing system is selected and implemented by the designer, the subsequent sensitive phase is the installation of the system. Many critical aspects can arise during the application steps and it's important to define and execute a strict plan of control based on checks during the execution phase.

a) Preparation of the support: in this step it's important that the support is adequately regularized by a shotcrete layer or other compacting materials with the requisite thickness to create a level and planar surface without holes and disparities that can cause damage to the geomembrane. In particular, it's important that nails or bolts are completely covered by cement that has to be made level with the surrounding substrate. Temporary anchoring has to be completely covered and eventual flows of water have to be collected and drained away by means of pipe or drainage systems of suitable capacity. The ratio between height and width of irregular areas, should be lower than 1:10. The minimum curving ray of irregularities (swellings or recesses) should be 20 cm.

b) Choice and utilization of the most appropriate regularization layer: the type and performance are to be selected according to the condition of the substrate, taking into account the presence of irregularities and also of the type of fibers used in the shotcrete (HDPE or metallic). The regularization layer (normally it's a polypropylene protective geotextile) has to be applied correctly, with appropriate overlaps and by means of PVC discs of fixation (about 3-4 for sqm) fixed by shot nails and also by shot nails alone and it has to carefully follow the shape of the support.

c) Application of the waterproofing PVC geomembrane/system: this application has to be carried out in proper way by skilled applicators by laying the geomembrane following the shape of the support, welding the membrane on the PVC discs of fixation of provisional support and then by welding together the PVC geomembranes by an appropriate automatic welding machine (with hot air or hot metal wedge) with double seams or single seam of welding (depending on the system used and type of tests required). The membrane has to be applied by reducing as much as possible the use of the manual welding machine that has to be limited to local details.

d) Application of the waterstop joints: they have to be applied in the correct position according to the project to create an adequate separation between different sectors of concrete structure (3). Following this they have to be welded correctly to the membrane below along the two sides by hot air automatic or manual welding machine.

e) Positioning of the steel reinforcement and concrete pouring: steel reinforcement has to be applied using adequate spacers to avoid any mechanical damages to the waterproofing system. Concrete pouring has to be carried out avoiding any mechanical damage to the waterproofing system

3.5 Application of a waterproofing system made by PVC geomembranes: testing procedures

There are tests available for single points of welding or linear welding of the geomembranes and tests for surfaces of applied geomembranes. In some cases tests can only be carried out if they have previously been foreseen. Below are the main tests used globally:

1) Non-destructive mechanical test of the joints: test is performed by passing the tip of the welding tester along the welding line exerting enough pressure to detect any weak point (figure 5). This operation is absolutely necessary to check the integrity of the welding and has to be performed when the welding has cooled. In case there are discontinuity points or points with poor adherence, spot patches of the same type of material shall be welded to ensure the continuity of the joint.

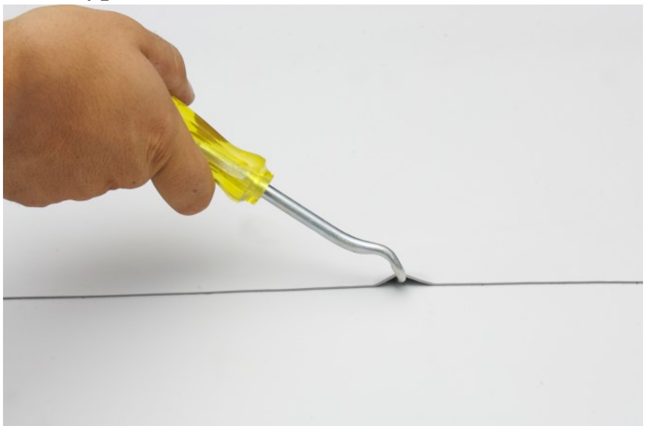


Figure 5. manual control by welding tester

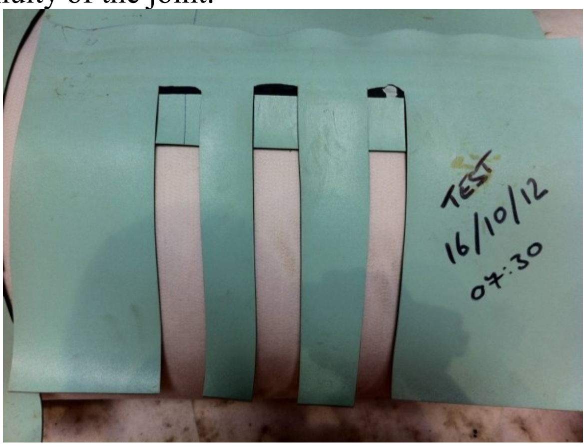


Figure 6. peeling test of the joints

2) Destructive mechanical peeling test of the joints: this test must be carried out at the start of the work to determine if the setting of the automatic welding machine is correct. Specimens of 10 mm have to be cut on the welding line and tested manually or with appropriate equipment to verify the good resistance of the welding (figure 6).
3) Pneumatic welding test (only for weldings performed with double track automatic welding machine): this method allows the user to test welding lines performed with double track automatic welding machine and is based on the assessment of the air pressure drop in the welding test channel. Fit pincers have to be used to tighten the ends of the relevant welding lines. Then a needle connected to a pressure gauge has to be introduced in the channel between the two welding lines (figure 7), air pressure has to be manually pumped up to 2 bars, stabilized and kept for test for a minimum of 10 minutes. During this period the loss of pressure shall not be more than a certain defined percent. Local regulations prescribe different testing parameters, also considering different thicknesses of the tested membrane. When using transparent geomembranes the pneumatic test can be also performed with contrast liquid with the same times and pressure values. Any point where the welding is inaccurate is, in this case, immediately highlighted by the appearance of colored spots. Obviously a successful pneumatic test grants the perfect performance of the welding lines.

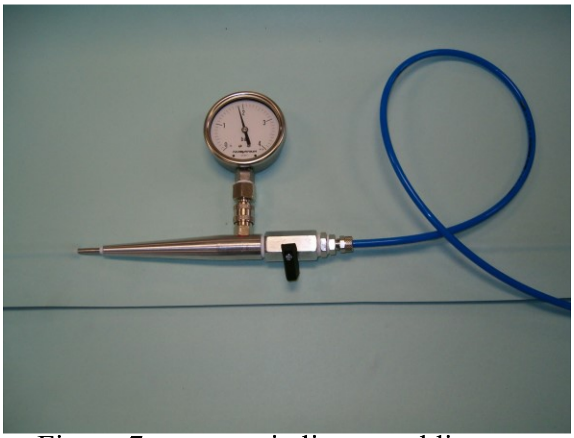


Figure 7. pneumatic linear welding test

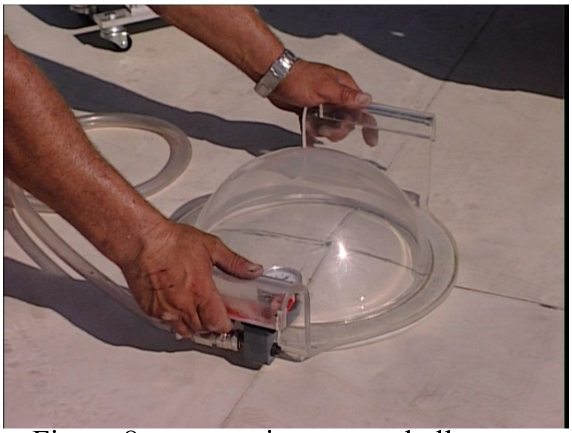
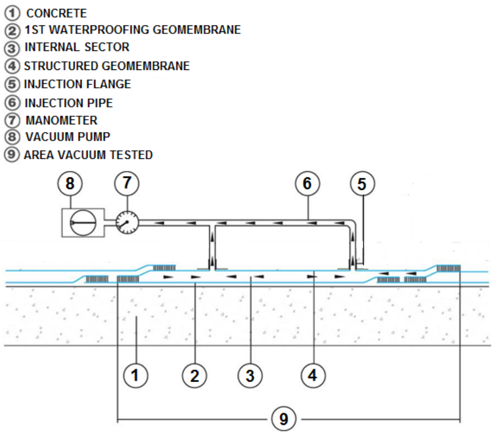


Figure 8. pneumatic vacuum bell test

3) Test of triple points and patches with vacuum bell (figure 8): this test is based on the use of a device composed by a rigid, transparent plastic half-sphere, 40 cm diameter, with two ergonomic handles along the border, equipped with a manometer scale ranging from 0 to -1 bar and a knob to control the depression level inside the cap. The lower border has a gasket for a perfect sealing on flat surfaces, to create a depression inside the cap. The cap is connected by a flexible tube, that’s length is about 150 cm, to a small vacuum pump, equipped with a switch that, as soon as it is on, allows a continuous air extraction from the internal area of the cap. The test will be performed as follows: detect the test point and spray a solution of soap and water on the welding, turn the compressor on and set the cap above the test point. From this moment on the manometer will show the progressive rising of the internal depression level, it can be adjusted to about -0.2 bars using the depression control knob. At this point the underlying welding can be observed through the transparent half-sphere and the following two situations could occur:
    a) absence of bubbles along the welding. The test has a positive result.
    b) bubbles on the observed area. This fault can be highlighted with the welding tester. In this case the point does not pass the test, and a patch of the same type of geo-membrane shall be welded on the point.

4) Vacuum test on surfaces prepared for "vacuum systems" (DCTR).



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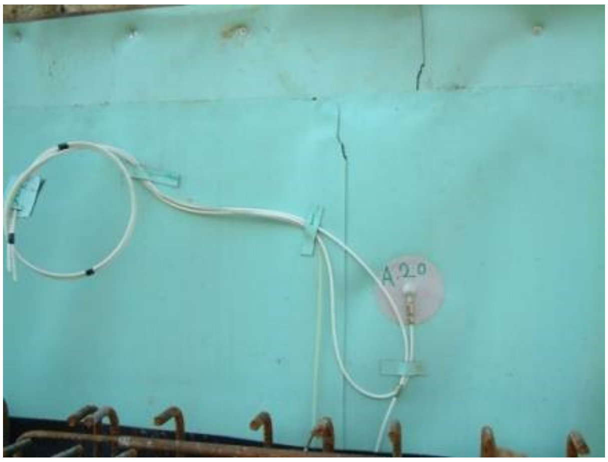


b)

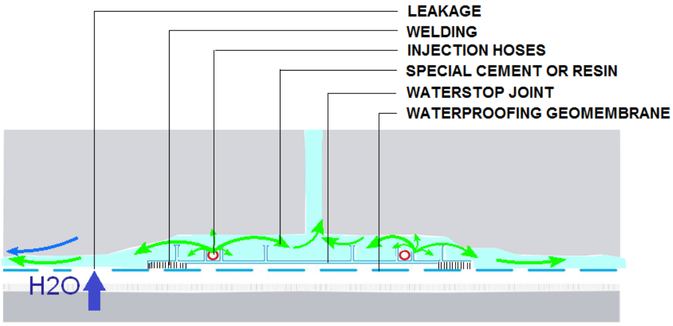
Figure 9. a) schematic detail of vacuum test - b) Vacuum system applied ready to be tested

This test requires the use of a special vacuum pump fitted to create a negative pressure equipped with vacuum-meter with connected closing valve. This pump will be connected by fit valves and tubes to the injection flange in PVC, thermo welded on the second structured membrane (figure 9). Between the injection flange and the waterproofing geomembrane the positioning of a minimum 30 cm x 30 cm of soft geo-drain it's necessary to avoid local adherences between the injection flange and the geomembrane. After it has been connected to all the tubes referred to a single sector, it is possible to proceed with the beginning of the vacuum test. Once all the gauges are opened and the pump turned on, it carries the depression of the sector up to the maximum value of - 1bar . Once the maximum level of depression of -1bar is reached, it's necessary to proceed slowly and gradually, lowering the vacuum level up to the value of -0.5 bar acting on the closure of each valve of the pump. Once this value is reached, test starts measuring time for 10 minutes. After this period, the residual pressure to be recorded should not show a loss higher than 20% of the initial value. The result of the test will be reported with a cross-examination on fit forms containing the number of the sector, the values and the person in charge of the test. It is advisable to test the waterproofing system at least at the end of the realization of each waterproofing single compartment. Nevertheless, further tests after following steps of construction can be required by the quality control on site.

4 POST EXECUTION: REPARATION METHODS

In some cases the use of special waterproofing systems opens up the possibility to do local injections that can eliminate the leakages or need to do full repairs of damaged areas after the waterproofing system is completed.

a) Active waterstop joints system: in this case the presence of re-injectable hoses gives the possibility to inject in different steps special cement for injections and, finally, resin (figure 10).



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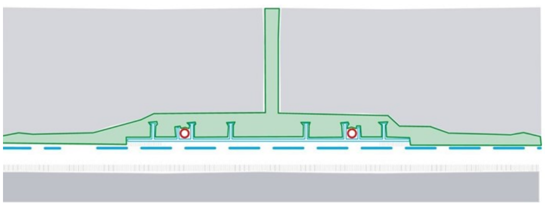
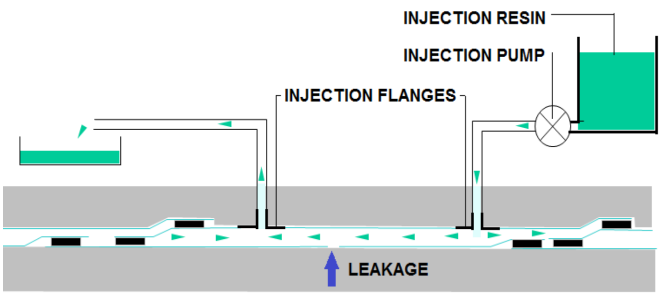


b)

Figure 10. schematic explanation of the injection in injectable hoses on waterstop joints. a) injection and b) full connection/sealing between concrete structure and waterstop joint

It may be possible that waterstop joints are not completely embedded into the concrete structure after the pouring of the concrete. In this situation, in case of leakage, the water can pass over the membrane to different sectors and also exit from the gaps left in the concrete structures related to the pouring steps. The injection of special cement is carried out to fill the space that could be present between the waterstop joints and the concrete structure. The final injection of resin is important to fill all the small capillarities and completely stop the passage of the water (figure 10b).

b) Injections in “vacuum systems” (DCTR): in this case the design of the waterproofing system and the division in sectors with injection flanges allows the possibility to do repairs on the whole surface of each sector (figure 11). All the sectors and flanges have to be well identified and numbered in a plan.



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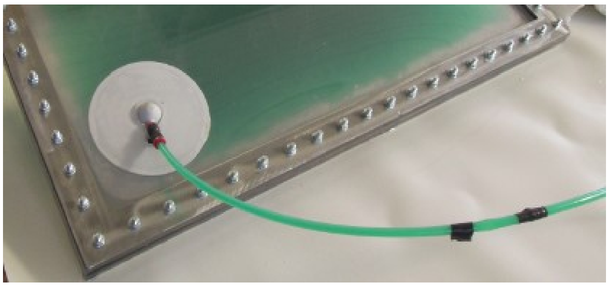

b)

Figure 11. a) schematic detail of the injection process, b) injection flange and hose in a laboratory simulation of injection in the sector

Then it’s possible to identify each compartment and its flanges/hoses by the number of identification put on each hose even once the waterproofing system is completely covered by the concrete. Repairs shall be done normally by injection of special acrylic resin at low pressure up to the complete filling of the sector. It is normally used a two-component acrylic resin with low viscosity suitable for injection in compartments. Nevertheless, the specific type of resin and also the parameters of its reaction have be decided upon according to the situation of the jobsite, the type of leakage, the pressure of the water, etc.

5 CONCLUSIONS

It’s important to properly waterproof a tunnel or an underground structure to preserve its durability but also the safety and the durability of its internal spaces and technological systems. Nevertheless, this objective cannot be reached solely with the use of a single geomembrane alone. It is about a waterproofing system as a whole, where the geomembrane is the main component. The choice and the correct design of an appropriate waterproofing system is the basis of a good and safe project. Nevertheless, this is only the first point because the correct implementation of a waterproofing system includes different phases that can be summarized:

1) The design phase. In the design phase it’s important:
   a) to analyze the specific conditions of water presence and intended use of the work.
   b) To choose the most appropriate waterproofing geomembrane for the specific intended use and adequate performances for the specific application.
   c) To define the most appropriate waterproofing system related to the specific condition of water presence and intended use of the building.
   d) To evaluate the level of testability and reparability expected for the system.
   e) To properly design all details of the waterproofing system
2) The execution phase. Once a waterproofing system has been properly designed, it’s important to take care of the execution phase. It’s very sensitive step in the realization of the waterproofing system. During this phase it’s important:
   a) to correctly apply all the elements of the waterproofing system
   b) To check if all the elements are correctly assembled.
   c) To test partially or totally the system (in case of testable systems).
3) The post execution phase. In the post execution phase it’s important:
   a) to have the possibility to reduce the area of influence of eventual accidental leaks (by separating different sectors)
   b) To have the possibility to repair completely surfaces of different sectors (in case of reparable systems).

The correct and complete evaluation and implementation of all the phases described above represents the best warranty for a well functioning, sustainable and reparable waterproofing system for tunnels and underground structures.

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