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European Practice on the Use of PVC-P Geomembranes in Tunnels and Underground Structures - Special Testable and Reparable Waterproofing Systems

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Abstract. The use of PVC-P 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-P waterproofing geomembrane can be subject to different risks of mistakes and damages that may compromise the proper functioning of the system. Many 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 give an overview about the different systems that can be adopted by the designers with specific focus on the Double layer system with double Compartments, vacuum Testable and Repairable (DCTR) - Vacuum System

Keywords. Waterproofing, PVC-P geomembranes, waterproofing system, synthetic membrane, waterproofing membranes.

1. Introduction

The use of waterproofing systems consisting of only one layer of non-reinforced geomembrane, sometimes with protection made by another geomembrane, were documented in Italy since the early 1970's. 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. Synthetic PVC-P Geomembranes used in Civil Engineering Applications

Geomembranes made by PVC-P (PVC-Plasticized) are widely used within the 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 specific applications. During the design phase it's important to consider mechanical, physical and chemical factors that can affect the life of the geo-membrane in relation to

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the service life required for the project in question. The Harmonized European Standard for geomembranes used for applications in tunnels and underground structures is the EN 13491 "*Geosynthetic barriers - Characteristics required for use as fluid barrier in the construction of tunnels and underground structures*". This Harmonized Standard has the scope to specify the relevant characteristics of geosynthetic 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 (AVCP) of the product 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 (Construction Product Regulation n. 305/2011) according to which is possible to put the mark CE on the product and in particular the essential characteristics to declare in the Declaration Of Performance (DOP). In general, PVC-P geomembranes used in Civil Engineering application have a nominal thickness of 2,0 mm or higher, depending on the specific conditions of the project (deepness of the structure, pressure of the water, risk of mechanical damages etc…). In particular, National Standards could propose minimum acceptance values for the essential characteristics mentioned in the Harmonized Standards: this is the case of the Italian standard UNI 11489 valid for PVC-P geomembranes.

3. Waterproofing Systems

Geomembrane is the main functional layer of a waterproofing system. All the components of this need to be regarded as an overall waterproofing system. This system is 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.

3.1. Why it's necessary to waterproof?

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

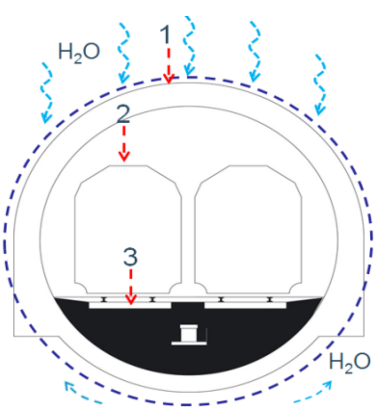

Figure 1. Schematic section of a tunnel.

1. **To protect the infrastructure:** from chemical, physical and mechanical damages caused by water ingress from outside the structure, preserving its service life.
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.

4. The Design Phase

During the design phase it's important to do an accurate risk assessment based on the presence of water and the forecasted intended use of the infrastructure. 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 decide the most appropriate type of waterproofing system. Water coming only from gravity could indicates selection of a top arch waterproofing protection system with longitudinal drainages along the bottom of the waterproofing layer and drains to collect the water. In the presence of aquifers and water table level penetrating or threatening the structure, the implementation of reparable and testable systems is highly recommended.

4.1. The choice of the waterproofing system with PVC-P geomembranes

There are different waterproofing systems in the market, but at least three of them have been commonly used in Europe.

1. **Basic system**: Single layer system with Compartments and waterstop joints (SC). This system consists of one layer of PVC-P geomembrane and waterstop joints welded on it, to create compartment areas to limit the trajectory of the water in case of eventual leakages. The presence of re-injectable 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 (Figure 2).

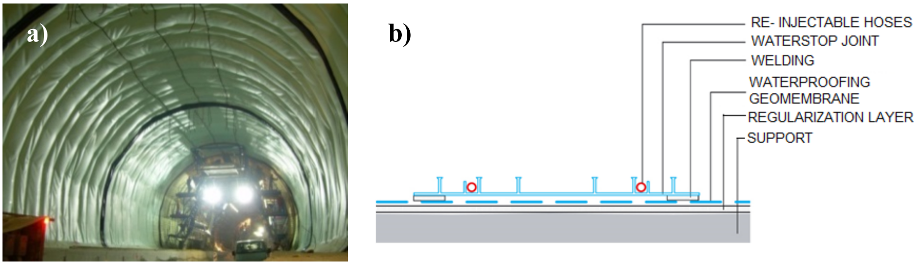

Figure 2. a) SC system installed, b) Schematic section of a waterstop joint with injectable hoses.

2. **Advanced system**: Double layer system with Compartments and Repairable (DCR). This system consists in one waterproofing layer of PVC-P geomembrane 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-P geo-membrane is applied over the PVC-P 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 (Figure 3).

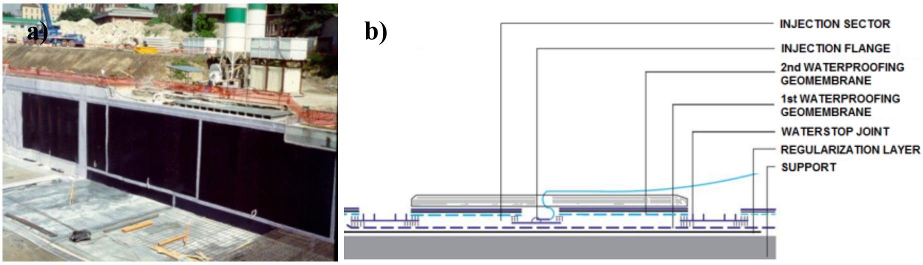

Figure 3. a) DCR system installed, b) Indicative section of a DCR system with injection flange.

3. **Optimal System:** Double layer system protected with double Compartment system, vacuum Testable and Repairable (DCTR) – Vacuum System. This system consists of one waterproofing layer of PVC-P geo-membranes and a second functional layer of structured geomembranes, welded to the first layer along the perimeter to create sectors of maximum 100 m^2. 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 (Figure 4).

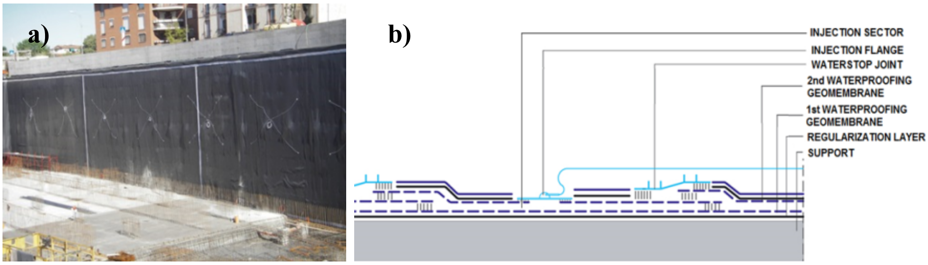

Figure 4. a) DCTR system installed, b) Indicative section of DCTR system with injection flanges and compartments.

5. Design details of the Vacuum System (DCTR)

Any Vacuum System (DCTR) has to be properly designed. First of all it's important to define all the steps of the waterproofing system application. Then it's important to divide the waterproofing system in sectors of maximum 100 m^2, and reducing also this dimension in case of complicated structures or specific project requirements. The application has to be evaluated with creating of sectors on the bottom and from the vertical to the bottom around the perimeter of the structure to be waterproofed. It's also important to create overlaps in correspondence of each corner. This can help in case of injection of resin for repairs.

For each sector minimum 5 injection flanges are to be positioned allowing a proper injection of the resin in all the sector in case of repair.

Each sector and each injection flange has to be properly numbered with a number and correspondent numbers have to be reported in a detailed plan of the waterproofing system. The waterproofing system design will be completed by the positioning in the structure of the boxes where injections pipes, coming from one or more sectors, will be collected. This will allow to easily find the sector with leakages (in case of damages of one or more sectors) because of the water coming from one or more pipes and do injections for repairs of the specific sector. The boxes are to be positioned in locations where they will be accessible at the end of the construction of the structure. All the boxes are to be identified with a specific number in the plan of the waterproofing system (Figure 5).

At the end of the definition of the vacuum sectors, the secondary compartments made by waterstop joints welded on the second layer are to be defined. Usually the sectors made by waterstop joints are created including more vacuum primary compartments following the construction steps, the construction joints and dividing the horizontal from the vertical part of the structure. In any cases, the sequence of application of the vacuum compartments and the waterstop joints provided in the design phase has to take into consideration all the construction phases of the structure.

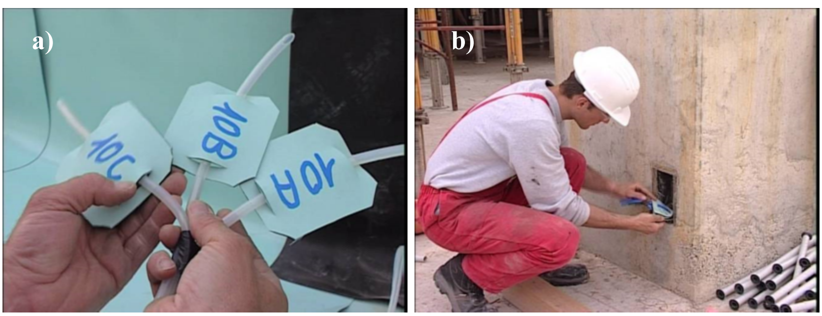

Figure 5. a) injection pipes numbered for each sector, b) positioning of the box in the structure.

6. The Application Phase – the Vacuum System

Before to start the application phase it's important to analyze well the plan of the sectors prepared in the design phase and do a preliminary verification if there is any modification in the realization of the structure or in the construction phases to be reported in the plan that has to be updated accordingly.

Main welding tools required for the application are:

- Manual hot air welding machine: this can be purely manual or in the version "Leister Triac-Drive" with manual welding supported by a motor. In this case the pressure roll of the welding machine is to get 1 line of welding (Figure 6).
- Automatic welding machine Leister Twinny: this machine has to be equipped by a special pressure roll to get one line of welding. This can reduce the

possibility of passage of air from a sector to another one (Figure 8). In case of presence of a specific prescription about the use of a double line of welding to allow the pressure test of each welding, for the weldings of geomembranes of the first waterproofing layer it's possible also to use a double line of welding (Figure 7). Nevertheless, in this case it's important to take care about the ends of the welding lines that have to be properly sealed by patches welded to each end of welding line.

All the sectors are to be realized to reduce as more as possible the quantity of manual welding and then try to use the maximum of automatic weldings. Then, only part of the weldings around the perimeter of the second layer, mostly on the verticals, could be done by manual welding machine.

Figure 6. Leister Triac Drive.

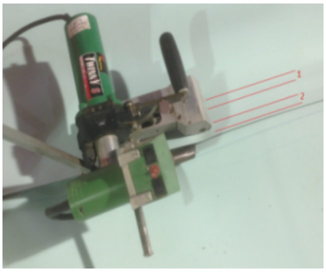

Figure 7. double line welding.

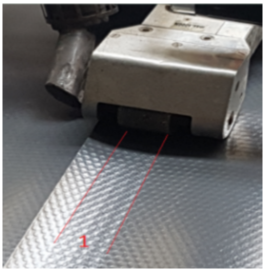

Figure 8. single line welding.

First of all the first layer (the PVC-P waterproofing layer with smooth surface) is applied and all the membranes are welded each other by automatic welding machine. Then, the second layer (the vacuum layer composed by different PVC-P membranes with structured surface welded together) is applied with the structured surface in direct contact to the first waterproofing membrane surface.

All the structured membranes of one sector are welded each other by automatic welding machine and then the full sector obtained (vacuum layer) of maximum 100 m^2 is welded around the perimeter to the waterproofing layer below already prepared before. In this way a closed sector of maximum 100 m^2 is obtained.

The other vacuum layers made subsequently are to be welded in the same way to the waterproofing layer. Nevertheless, in correspondence of a vacuum sector previously made, it's important to keep an overlap of minimum 10 cm between the vacuum layers.

In case of presence of complicated elements, the application of the waterproofing system has to be organized by preparing pre-fabricated parts and then welding them together to create full sectors. This has to be provided during the design phase also as general indication. At the end of the application of each vacuum sector, the position of the injection valves has to be identified according to the design plan then a circular hole has to be done in the vacuum layer in correspondence of each injection valve. Subsequently, a layer of soft geodrain of about 50x50cm has to be positioned between two layers in correspondence of each flange to avoid any adherence between two layers during the vacuum test. Finally, the PVC-P injection flanges have to be welded on the second layer and they have to be connected through special clips to the injection pipes, with maximum length of about 10 mt, that are to be collected in a box positioned in the structure in an accessible point.

This can allow the possibility to carry out the vacuum test and do injection of resin, if required, when the structure will be completed.

6.1. Testing procedure of the Vacuum System (DCTR)

This test describes the use of a special vacuum pump fitted to create a negative pressure equipped with different (minimum n. 5) vacuum-meters with connected closing valve. This pump will be connected by fit valves and tubes to the different injection flanges in PVC-P, thermo welded to the second structured membrane. After it has been connected to all the injection pipes referred to a single sector, it is possible to begin the vacuum test. Once all the gauges are opened and the pump is 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 (Figure 9). Once this value is reached and the vacuum pressure in the sector is stabilized, 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.

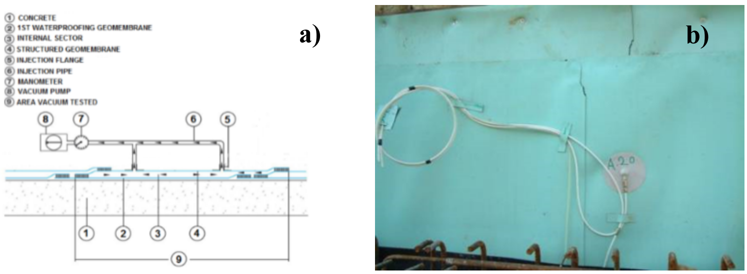

Figure 9. a) schematic detail of vacuum test, b) real vacuum system applied.

7. Post Execution: Vacuum System - Reparation Method

The use of a special waterproofing systems as the Vacuum System 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.

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. All the sectors have to be well identified in a plan with the number of each sector and number of each pipe in the sector (Figure 10).

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 (Figure 11). Nevertheless, other types of resins can be used depending on the specific site conditions.

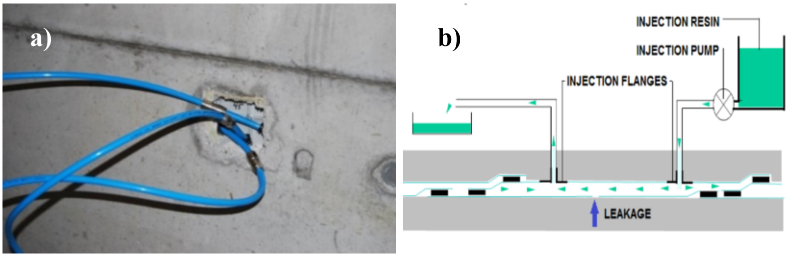

Figure 10. a) Vacuum test/injection hoses, b) schematic detail of the injection process.

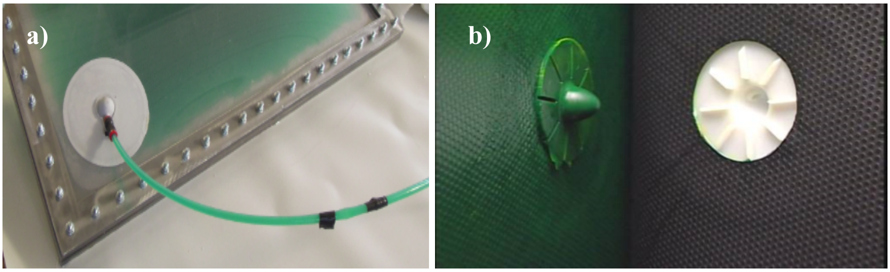

Figure 11. a) Injection flange and hose in a sector, b) acrylic resin after curing into the sector laboratory simulation of injection in the.

8. 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.

Among different possible systems, the Vacuum System represents the optimal one because it's possible:

a) To check with vacuum test the whole surface of the waterproofing system when necessary
b) To quickly and precisely identify in which sector there is the leakage
c) To easily repair each sector separately with reduction of time and costs

The adoption of the vacuum system represents the best warranty for a well-functioning, sustainable and reparable waterproofing system for tunnels and underground structures.

References

[1] EN 13491:2004/A1:2006: *"Geosynthetic barriers - Characteristics required for use as fluid barrier in the construction of tunnels and underground structures".*

[2] UNI 11489:2013 *"Geosintetici con funzione barriera- Geosintetici a base di polivinilcloruro plastificato – Caratteristiche e limiti di accettazione" in Italian ("Geosynthetic barriers – PVC Geomembranes - Characteristics and acceptance limits").*