NEXT GENERATION TUNNEL WATERPROOFING

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ABSTRACT: Sika has been developing a new generation of tunnel waterproofing utilizing sheet membranes, watertight concrete technology, and fully bonded basement waterproofing membranes. This waterproofing concept combines systems well established over the last 50 years with an optimized application. The technology using fully bonded membranes in tunnels was first developed in South Korea and successfully applied in many projects. The fully bonded system, which can also be seen as an improved watertight concrete in accordance with the most advanced tunnel waterproofing standards, offers a reduction of the CO_2 footprint compared to the regular waterproofing membrane by a factor of 2, and an increased reliability compared to the current system. The application is simplified, reducing the work steps but still using the same well-established technique and know-how. The new generation tunnel waterproofing fits the drained tunnels as well as the pressurized systems. It also replaces the waterbars and control sockets needed in the conventional compartment system.

1. INTRODUCTION

Tunnel waterproofing has been a crucial aspect of tunnel construction for many centuries. Ensuring the protection of underground structures from water ingress is vital for their long-term stability and operational safety. The first traces of waterproofing in tunnels go back more than 4'000 years to the Euphrates Tunnel in the city of Babylon where a cut & cover tunnel was then plastered with asphalt. Bitumen only found its way in some cut & cover constructions but is not used anymore in modern tunnelling. Over the years, various materials and techniques have been employed to waterproof tunnels and basements. For instance, in South Korea, where the development has led to the adaptation of the fully bonded membrane systems commonly used in basements, and the optimization of the installation process. In this article, we will delve into the worldwide history of tunnel waterproofing using sheet PVC, TPO (FPO) membranes and watertight concrete, explore South Korea's journey towards fully bonded systems, and explain the technique's advantages. Additionally, we will describe the installation process of this waterproofing membrane in a tunnel.

2. HISTORICAL PERSPECTIVES OF PVC, TPO (FPO) MEMBRANES, AND WATERTIGHT CONCRETE

Modern tunnel waterproofing has come a long way since its inception, with the earliest approaches primarily relying on watertight mortars. Sika was one of the first supplier to develop watertight mortars in 1910. This watertight mortar technology was used 1918 in the old Gotthard railway tunnel opened in 1882, when dripping water had to be controlled to allow the first electrification of the tunnel. Then in the mid-20th century, watertight concrete was a major innovation in tunnel construction, effectively reducing water penetration. However, this method had limitations and was not entirely reliable in providing long-lasting protection against water infiltration. In fact, the constrains of the concrete in contact with the rock did not allow a concentration of the shrinkage movement in the watertight joints. This leads to cracks within the concrete blocks in-between the dilatation-joints and therefor to water infiltrations.

In the 1970s, the introduction of sheet polyvinyl chloride (PVC) membranes revolutionized tunnel waterproofing practices. The Sika (Sarnafil) membranes were the first to be installed in a tunnel in 1967 to waterproof the Gei Tunnel in Switzerland. PVC membranes offered enhanced impermeability, flexibility, and ease of installation compared to watertight concrete. The flexibility of PVC allowed its adaptation to irregular surfaces and accommodate movements in the tunnel structure, eliminating the risk of cracks leading to leaks.

In the following decades, thermoplastic polyolefin (TPO) membranes emerged as an alternative to PVC. Both PVC and TPO (FPO) membranes contributed significantly to improving waterproofing performance, becoming widely used in tunnel projects around the globe.

Figure 1: Gei Tunnel Switzerland opened in 1967

These membranes are commonly used in different systems. Firstly, classic drained umbrella waterproofing protecting structure and operation against percolating water and the compartment system widely used in pressurized tunnels. In this system compartments between the membrane and the concrete lining are created by welding waterbars on the membrane to reduce eventual water migration and allow targeted repair injections. Finally, an active control system composed of two membrane layers welded together in compartments and offering the possibility to control the watertightness of the systems by applying a vacuum in the compartment during the construction phase. These compartments can be injected with raisins in case of later water ingress.

3. REASONS FOR TUNNEL WATERPROOFING

There are mainly three reasons to waterproof a tunnel. The most common one is to protect the service from humidity and water. The impact of water on operation can be very diverse like water harming the installations, ice endangering the service, humidity inducing electrical wastage by creeping current and many more. In case of aggressive groundwater, a waterproofing is needed to protect the concrete structure and reinforcement from corrosion. Finally, in some tunnels a waterproofing is needed to prevent any influence of the excavation on the surrounding hydrogeology. Where per example the drainage of the surrounding groundwater leads to settlement at the surface or to protect the phreatic water of tunnel wastewater seeping in the ground.

The waterproofing strategy must meet the needs by installing a pressurized, drained, full round or umbrella waterproofing system. The pressurized system prevents any waterflow in or out of the tunnel and the full water pressure acts on the tunnel lining. A pressurized tunnel waterproofing is common in urban soft ground. This is the trickiest waterproofing concept as water will find and penetrate any defect. Measures must be foreseen to seal or contain any leaks. Drained systems allow the protection of the structure and operation without the full water pressure acting on the tunnel lining. The water inflow can also be reduced by injecting the ground around the excavation changing its permeability.

4. RISK CONSIDERATION ON THE CHOICE OF WATERPROOFING STRATEGY

The waterproofing strategy should be based on a risk management approach. Water inflow and water damages have a huge impact on a tunnel lifecycle cost, and the risk can be reduced by installing an adequate waterproofing system. But no waterproofing layer will be 100% failure free. There can be problems with the materials, the handling, the installation, or the design details. Due to the large size of the surface to be waterproofed in a tunnel, even low remaining risks still have a huge impact on the project. If this remaining risk cannot be accepted and controlled, then mitigation measures and/or limitations of the impact of these leakages on the structure need to be planned.

By installing several lines of defense, the risk can be reduced to an acceptable level. For example, compartmentalization into multiple waterproofing sectors can be treated separately by injections to limit water migration and repair any failure. This is a widely used method to reduce the risk. When a punctured membrane is detected, the compartment is injected with resins and the waterproofing layer restored. As these injection systems can be harmed during concreting or due to challenging application, further measures like double membrane layers are recommended, when a fully dry tunnel is mandatory.

Another approach is to reduce the impact of a risk to the minimum. By using fully bonded systems preventing any water migration between membrane and concrete inner lining, the impact of a failure in the waterproofing layer can be reduced to a very localized spot. In case the lining concrete is not watertight at the same and unique spot as the punctured membrane, then a targeted repair by water-tightening the lining with common concrete injection will lead to an elimination of the risk with a high chance of success.

Figure 2: Fully bonded membrane ready for concrete application

The same risk approach is needed in TBM tunnels with single shell segmental lining. The huge length of installed gaskets will inevitably lead to localized failures and measures need to be planed. Furthermore, the concrete of the segments is directly exposed to any aggressive groundwater reducing the durability of the lining. Some major owners therefore do not accept single shell segmental linings in critical tunnels due to this remaining risk and the challenging mitigation measures.

5. DURABILITY

Nowadays owners require a low impact on the operation by maintenance work. A common request is limited maintenance guaranty on the tunnel lining in the first 100 years. Therefore, the waterproofing needs to withstand these minimum 100 years, offering a full protection of the tunnel structure and operation.

The client on the New Swiss Alp Transversals (NEAT) decided in the late 20th century to set up an expert group to clearly define objective requirements and tests to replicate the 100 years durability of waterproofing membranes in a tunnel. Since the aging process in the PVC or TPO (FPO) membrane is a chemical reaction and the higher the temperature, the faster a given chemical reaction happens, accelerated aging tests were defined. Membranes are put in a hot aggressive water bath for long periods up to one year and the change on membrane properties, like elongation at break, are measured. The reduction on characteristics can then be extrapolated to determine when the end-of-life level will be reached. The goal is for the membrane to fulfil its waterproofing duties throughout the full life cycle coping with any stresses and movements that can occur on the system. These standardized tests were compiled in major tunnel waterproofing standards like the Austrian ÖBV. So far, only the high-quality PVC and TPO (FPO) membranes fulfil the 100+ years durability tests. Other systems may withstand the aging degradation and prevent any water inflow on the long term, but as long as the aging behaviour cannot be proven based on objective standardized tests, a risk remains.

Fact is, that the most widespread reasons for refurbishment and repair of tunnels under operation are water induced damages.

6. FULLY BONDED WATERPROOFING MEMBRANES

The turn of the century witnessed the introduction of a revolutionary technique for waterproofing - the fully bonded waterproofing membrane. This membrane is a multi-layered composite sheet with a carrier layer, and a bonding layer.

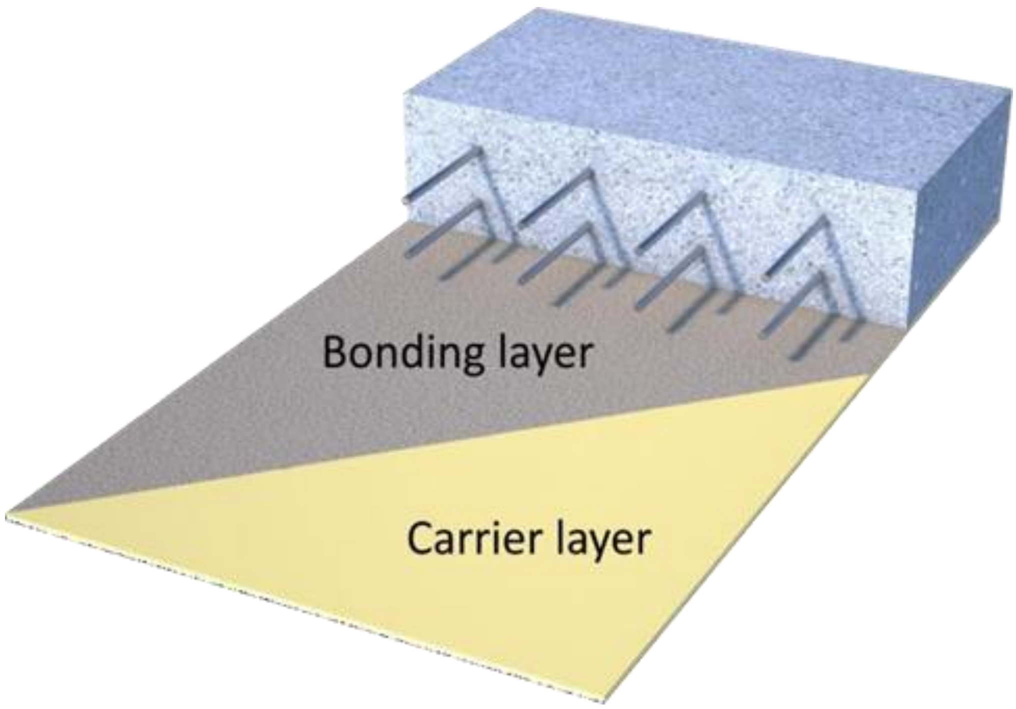

Figure 3: Fully Bonded Waterproofing Membrane

The (mechanical and chemical) bonding layer provides excellent adhesion to the concrete, creating a continuous waterproof seal. The bond occurs when the fresh concrete is poured against the bonding layer creating a strong connection when hardened. Additionally, the carrier layer provides mechanical protection to the bonding layer, enhancing the system's durability and robustness. The carrier layer consists of a fully watertight TPO (FPO) membrane with a proven durability.

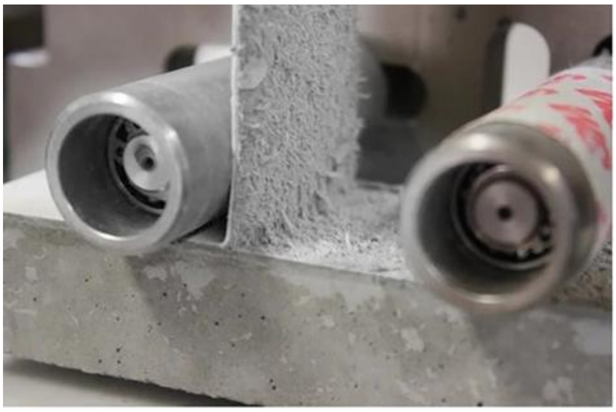

Figure 4: Strong bond between membrane and concrete

This fully bonded system overcomes the limitations of the earlier sheet membrane technique. It prevents water from migrating between the membrane and the tunnel concrete lining. The EN standards require a bond resisting to 7 bars water pressure to call it a fully bonded membrane. In practice, the effective bond is higher than the required 7 bars.

The system preventing water migration allows a precise location of any damage in the membrane leading to water leaks through the concrete lining. The bond also offers superior resistance of the membrane to ground movement and mechanical impacts, thereby ensuring the longevity of the tunnel structure.

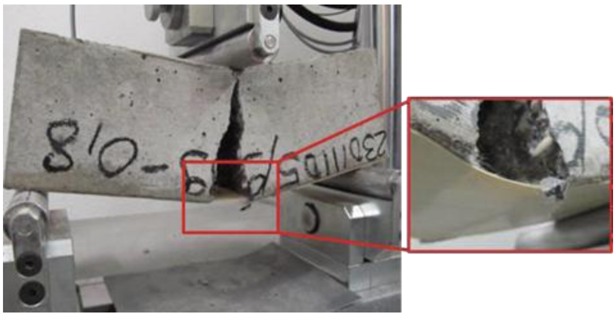

Figure 5: Crack bridging test

The fully bonded membranes show high flexibility (bi-axial) and excellent crack-bridging capabilities due to the unique combination of high quality membrane with high elasticity and strong bonding resistance.

Typically, fully bonded membranes are used in basement waterproofing. The thickness of the carrier layer varies between 0.8 mm and 1.2 mm. Sika developed fully bonded membrane with up to 2.0 mm carrier layer designed for underground constructions with higher water pressure. The membrane can be welded like the loose laid membrane without a bonding layer. The fully bonded technology saves the need of compartment systems, the waterbars and the control sockets. The first tunnels using this technology are in South Korea. In South Korea typically a 1.0 mm thick carrier layer is used. A first project using the 2.0 mm carrier layer is the Riedberg Tunnel located in Switzerland.

7. EVOLUTION IN SOUTH KOREA

The evolution of tunnel waterproofing in South Korea coincides with its rapid industrialization and infrastructure development. By the 1980s, as South Korea began constructing numerous underground facilities and tunnels, waterproofing became a critical issue.

Early efforts involved conventional waterproofing methods such as the use of watertight concrete and a sheet membrane. However, these techniques had limitations. For instance, the watertight concrete approach did not entirely prevent water leakage in tunnels, and the sheet membrane method required extensive maintenance due to membrane damage from various construction activities.

By 2015, to overcome these challenges, South Korea started to explore innovative waterproofing solutions and worked towards developing more effective waterproofing systems. This pursuit of excellence led to the introduction of fully bonded systems in tunnel waterproofing. Till today about 4 million m² fully bonded tunnel waterproofing membranes were successfully installed in South Korea.

Figure 6: SikaProof®-110

The fixation of the membrane to the primary rock support was optimized to reduce the work steps and increase ease of application. The membrane including the functional layer can still be hot air welded as in the conventional loose laid membrane system. The quality weld prevents concrete from flowing through poor connections between the different membrane strips when the fresh concrete pushes the membrane into uneven bumps. The fully bonded system addresses issues that plagued older methods, such as the formation of water pathways between sheet membrane and inner lining concrete surface. The blockage of water migration facilitates the localization and repair of leaks as wet spots or dripping cracks coincide with punctured membranes and can easily be fixed with localized concrete injections. Therefore, the system is less sensitive to application quality issues.

The membrane thickness can be reduced to 1.0 mm in comparison to the classic loose laid membrane system, as the membrane works in combination with the inner lining concrete and is not exposed to the same stresses as conventional loose laid membranes. The use of high quality long lasting TPO (FPO) membrane layer allows very long life expectancy of more than 100 years proven by the standardized durability tests.

The system was successfully applied in several South Korean projects among others the Milyang - Ulsan expressway (172’000 m² in 2020), the Kangjin – Kwangju expressway (155’000 m² in 2022) or the Ansung – Sungnam expressway (165’000 m² in 2022).

Figure 7: Tunnel in South Korea with SikaProof®-110

8. POSITIONING IN RELATION TO TUNNEL WATERPROOFING STANDARDS

Most countries, with extensive tunnel projects, have national standards guiding designers regarding tunnel waterproofing. Clients with large tunnel inventory often have their own additional guidance. As an example, in Switzerland the SIA-272 standard regulates the waterproofing and drainage of underground constructions. In addition, the Swiss Federal Railway as well as the national road authorities specify in addition that no single shell segmental lining is acceptable. Only double shell lining including a waterproofing layer and an inner lining are allowed based on their bad experiences on segmental lining water tightness.

Unfortunately, most standards are outdated and reviewing national standards is slow and time consuming. It is therefore important to clearly position new systems in relation to the existing standards.

The fully bonded membrane can be seen as an “upgraded” watertight concrete. Due to the interaction of the membrane and the concrete, the membrane thickness can be diminished, at the same time the crack requirements for the concrete can be loosen and steel content reduced.

The requirements to prove the durability of the carrier waterproofing layer are defined in most tunnel waterproofing standard with the same tests as for the loose laid membranes. Therefore, the fully bonded membrane complies with the usual requirements in the tunnel waterproofing standards / guidelines, even if the system is not yet described in the latest.

The fully bonded membrane also protects the concrete effectively against aggressive ground water, a constraint that was heavily limiting the use of watertight concrete in underground constructions.

9. SYSTEM DESCRIPTION

Figure 8: Membrane buildup

1. Rock
2. Spray concrete
3. Nail fixation
4. SikaProof®-110 waterproofing membrane
    a. EVA-based waterproofing layer
    b. Functional layer for full bond
    c. Geotextile spot-fixed to the waterproofing-layer
    d. Geotextile strip
5. Inner lining concrete

The waterproofing layer is a fully and permanently bonded, flexible sheet membrane waterproofing system. It consists of an elastic polyolefin (FPO) membrane containing a unique hybrid bonding layer on polyolefin (PO) basis, which bonds permanently with the fresh concrete structure. The membrane is a pre-applied waterproofing system that is designed to be installed before the steel reinforcement (if needed) is fixed and the lining concrete is poured. The concrete is cast directly against the membrane system, where the fresh concrete isembedded completely into the hybrid bonding layer and creates a permanent dual bond both mechanically and adhesively.

The dual bond prevents any lateral water migration between the membrane system and the hardened concrete. The membrane sheets can be hot air welded together to prevent any fresh concrete flowing behind the membrane between the seams. This is possible in conventional tunnel excavation when the membrane is pushed into uneven bumps when pouring the fresh concrete into the vault formwork.

The geotextile on the backside of the membrane is punctually fixed, allowing the full elasticity of the membrane. Conventional waterproofing membranes with a fully laminated geotextile on their back are losing their elasticity due to the geotextile "reinforcement". When the fully laminated membrane is exposed to high stress, the geotextile ruptures locally leading to a local over-elongation of the membrane, as all movements occur at this point.

The punctually fixed geotextile on the back of the SikaProof®-110 fully bonded membrane allows simplified fixing and acts as a cushion layer to protect the membrane from rough substrates. The loose geotextile strips can directly be nailed to the substrate holding the membrane in place.

10. WATERPROOFING CONCEPTS

There are two different waterproofing concepts. One is a drained system preventing any water pressure on the tunnel lining and the other is the pressurized system with the full water pressure acting on the lining.

Figure 9: Drained system

In the drained system the membrane is installed only in the vault like an umbrella. Drainage pipes are placed in the arch-foots and the membrane stretched down to the drainage. A drainage layer needs to be installed outside the membrane to drain the water down to the drainage pipes. The fully bonded membrane will guarantee a water tightness comparable to class "fully dry" and there is no risk of any water migration along the tunnel inside the waterproofing layer.

The other concept is a pressurized watertight construction. The water does not get drained by the tunnel and the full water head acts on the concrete lining. The membrane is installed fully around the circumference of the tunnel.

Figure 10: Pressurized system

Due to the water pressure the system is exposed to far more stresses than the drained system. Depending on the hydrostatic water pressure, thicker membranes than used in the drained system are recommended. Although due to the system being fully bond, the membrane thickness remains much lower than the loose laid system. A punctured membrane will have the full water pressure acting locally on the concrete lining. In case of crack or poor concrete quality the water will cause a damp to wettish surface. But this water ingress can be easily fixed by localized concrete water-tightening injections.

In shallow pressurized tunnels a 1.0 mm thick fully bonded membrane is installed on the full circumference and welded together. Commonly the invert is installed in a first step and the vault completed in a second step.

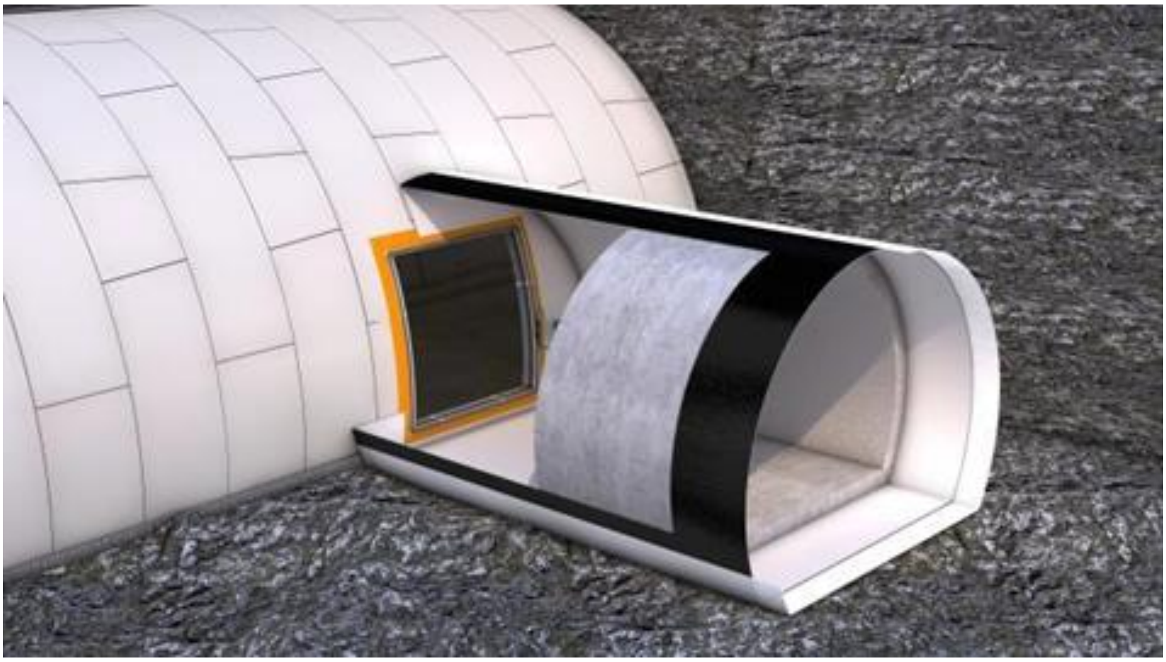

Figure 11: Cross passages in TBM tunnels

Another typical pressurized waterproofing is used in cross passages between two TBM excavated tunnels with a single shell segmental lining. Here a fully bonded membrane can be connected directly to the segments using a tape. The 2.0 mm membrane is recommended when facing higher water pressure and due to a better weldability to the tape. The Sikaplan® WT Tape-200 is fixed to the segments with epoxy glue. The fully bonded membrane is then hot air welded to the tape offering a watertight connection between the segments and the membrane. This offers a high level of watertightness at low cost.

11. THE INSTALLATION PROCESS

The speed of waterproofing installation can easily be adapted to the general speed of the tunnel lining installation and is never the critical path.

With the geotextile punctually-fixed to the waterproofing SikaProof®-110 membrane, the application is simplified. At the same time, thanks to its spot-fixing, the geotextile does not act as a reinforcement for the membrane and limiting its elasticity. The elongation at break of the membrane remains unchanged.

Figure 12: Scaffolding for membrane installation

The installation procedure of the waterproofing system depends on the site conditions. As for all tunnels waterproofing, the installation should be performed by skilled and experienced waterproofing contractors, specifically trained in membrane welding and installation. The membrane is delivered to site in 2.0 to 2.1 meter wide rolls with a length adapted to the construction geometry in order to reduce waist. The 2.0 to 2.1 meters are a common size in waterproofing as this allows an appropriate handling in the tunnel and limits the weight of the rolls.

For the installation, only a nailer, hot air welding equipment and a scaffolding adapted to the size of the tunnel are needed.

The substrate needs to comply with the supplier's requirements for waterproofing membrane installation. The roughness of the primary lining shall be smooth and free of harmful objects like steel fibers and anchor heads. This is to prevent a puncture of the membrane when the membrane is pressed by the fresh concrete against the rock support. A layer of spray concrete without steel fibers and smaller aggregate size is used to reduce the roughness. An evenness of 1:10 (depth D to length L) is needed on the substrate surface. This is to prevent an overextension of the membrane when pushed into bumps by the fresh concrete.

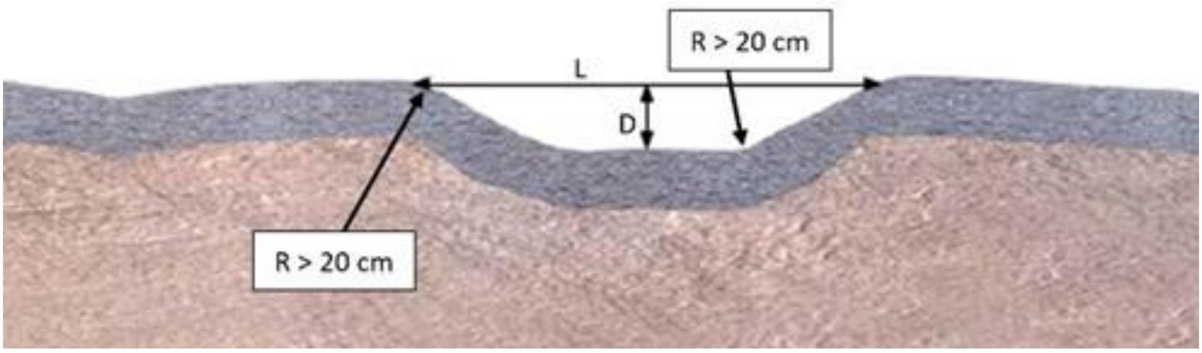

Figure 13: Geometrical substrate requirements

Due to the fully bonded properties of the membrane the watertightness is less at risk than with loose membranes as the water inflow at a leakage will mostly be blocked by the concrete.

Figure 14: Fixation of the membrane using the geotextile

The membrane is unrolled, and the attached geotextile fixed with a nail gun to the substrate. First the middle strip (4b, figure 8) is attached followed by the edges of the geotextile (4c, figure 8). The next membrane strip can then be fixed parallel with a slide overlap of approximately 10 cm.

Figure 15: Hot air welding of the membrane

Then the two membrane sheets are hot air welded together. Best is the use of an automatic double seam welding equipment. These machines produce two parallel weld seams leaving an air channel in the middle.

This air channel can then be pumped with air and the weld seams checked by controlling the air pressure kept in the channel. Fully bonded membranes can tolerate some insufficient welding due to the restrain of water migration. A quality welding offers an additional safety in the system. TPO (FPO) is a thermoplastic, so it can be hot air welded. Combined with the concrete lining the membrane creates a monolithic layer that protects the whole tunnel from water inflow. The welding can also be done manually. The single weld is tested using a screwdriver to control the continuity of the seam.

Figure 16: Test of welding seams

The tunnel lining formwork can be installed once the waterproofing membrane is completed. The formwork is filled with the fresh concrete and the concrete compacted. Immediately with the pouring of the concrete the functional (bonding) layer starts to interact with the concrete and the bonding takes place. After the concrete has cured the full bonding strength is reached. The gap filling in the crown is recommended after 28 days to prevent any debonding due to injection infiltrating. The gap filling needs to be done with shrinkage compensated mortar to prevent any shrinkage cracks between concrete and mortar.

12. REDUCED INSTALLATION STEPS

This next generation waterproofing for tunnels reduces the work steps for installation from 4 steps to only one step. The installation of the conventional systems needs several work steps. For a pressurized compartment system, in a first step, a cushion layer is installed with the fixation disc, then the membrane is spot welded to the discs and the membrane strips welded together. Finally, waterbars and injection hoses/ports are installed and the waterbars in the crown injected to guarantee the full bedding. Later, any compartment showing water inflow due to a leakage, needs to be injected with raisins.

In drained tunnels with an umbrella waterproofing the drainage layer is attached using the fixation discs. In a second step the membrane is spot welded to the discs and terminated towards the drainage system in the side walls. In a last step the membrane strips are welded, and a protection layer installed where needed.

With the new buildup, the membrane can be installed in one step using the geotextile for fixation. This is a massive reduction of work steps and costs compared to the actual widely used concepts.

13. CONCLUSION

Over the past 60 years, tunnel waterproofing has witnessed significant evolution worldwide. The transition from watertight concrete to sheet PVC and TPO (FPO) membranes marked a substantial improvement in tunnel waterproofing practices. In the last decade only, minor evolutions managed to implement themselves. South Korea's commitment to innovation led to the development and adoption of fully bonded systems, which provide a seamless and reliable barrier against water ingress.

Fully bonded systems offer numerous advantages, including superior watertightness, longevity, and resistance to movement. Their installation process was optimized to reduce the work steps and improve productivity.

The major improvements this new tunnel waterproofing membrane SikaProof®-110 offers are:

- Fully bonded preventing any water migration
- Weldability of the membrane
- Optimized timesaving fixation

As tunnel construction continues to evolve, it is likely that further innovations will emerge, making tunnel waterproofing even more efficient and reliable, ensuring the safety and sustainability of underground infrastructures for generations to come.

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