Waterproofing and drainage systems for transport tunnels – A review of current practices

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Waterproofing and Drainage Systems for Transport Tunnels – A Review of Current Practices

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Abdichtungs- und Dränagesysteme für Tunnel – Rückblick auf die gegenwärtige Praxis

Grundwasser ist ein bedeutender Faktor in der Planung und beim Bau von Tunneln, der sowohl die temporären als auch die langfristigen Bedingungen beeinflusst. Dies ist insbesondere bei bergmännischen Tunneln unter Grundwasser der Fall, wo dauerhafte Wasserhaltungssysteme erforderlich sind, um den Betrieb und die geforderte Lebensdauer zu gewährleisten. Dieser Beitrag stellt den gegenwärtigen internationalen Stand der Technik dar, welcher der Planung von dauerhaften Abdichtungs- und Dränagesystemen zu Grunde liegt, insbesonders für solche, die bei konventionellen Baumethoden zur Anwendung kommen. Die geläufigsten Systeme sowie einige neue Konzepte und Produkte werden nachfolgend beschrieben.

Groundwater constitutes a main factor in the design and construction of tunnels, affecting both temporary as well as long-term conditions. This is particularly the case for mined tunnels below groundwater, where the provision of a permanent water control system is required to guarantee the specified operational conditions and durability. This paper aims to present a brief review of the international practices currently applied regarding the design of permanent water control systems for mined underground transport tunnels. The most typical systems are presented and some recent developments are outlined.

Waterproofing and drainage systems of tunnels are designed to provide either complete watertightness, in order to exclude water inflow, or to drain the groundwater in a defined way. Following measures (or a combination of them) are generally applied:

- Permanent drainage system collecting, and guiding the groundwater to a secondary system located outside the tunnel,
- Reduction of water inflow during construction by means of grouting to limit the amount of water,
- Provision of a watertight in-situ concrete lining, with joint sealing elements,
- Provision of waterproofing systems based on the use of membranes (flexible sheets, fixed by mechanical means and more recently sprayed and semi-liquid membranes).

Based on the above, two different systems are distinguished with respect to the way to deal with the groundwater, although different criteria regarding the degree of tightness, safety and costs, can be found:

- Open type system for drained tunnels: The groundwater is collected outside the tunnel and guided into a drain conduit alongside the tunnel abutment,
- Closed type system for watertight tunnels: This system consists of an overall waterproofing barrier, which isolates the tunnel completely from its hydraulic environment and eliminates inflow of water.

In central Europe, in particular in Austria, Germany, Switzerland, Italy and France, both systems are in general associated to tunnels designed with a double shell lining (primary shotcrete lining and secondary/permanent in situ concrete lining). However, such systems can also be used with single or double-shell (monocoque) shotcrete linings, as discussed in the following sections.

Choice of system

Each project has its own characteristics, requirements and conditions, which pose designers, clients and contractors with the challenge to define, specify and implement an adequate and efficient waterproofing system. In general, the choice of system and the criteria used for the selection are defined by each particular client, considering relevant aspects and the local project's technical-economical standards. Among these factors the following issues are of importance.

Tunnel usage

The first aspect to define is the degree of watertightness required, which is controlled by the tunnel function and associated service and operational conditions. The requirements for the degree of tightness will usually be higher for tunnels used by people, for the storage of valuable and sensitive equipment, or for tunnel sections electrified or affected by frost (portal zones, pedestrian tunnels) (4).

In Germany, following institutions have published recommendations on the acceptable degree of tunnel tightness (moisture characteristics and permissible daily leakage rate): Stuttgart Otto-Graf Institute, STUVA and German Federal Railway Authorities (4). In other countries, the degree of tightness is usually defined by the client and agencies on a standalone basis.

Geological, hydrogeological and environmental conditions

The amount of water inflow and the magnitude of the water pressure is of main relevance, as it may determine the type of system to be used and its characteristics. In general, the open type system is used for low water inflow, where no maintenance problem is expected. This is mainly the case of tunnels in low permeable ground where water percolates mainly through main discontinuities (allowing injection treatment). Besides these aspects, it is also important to consider the water aggressivity and climate aspects, such as the occurrence of freeze/thaw cycles, which can cause cracking of the lining and reinforcement corrosion, the risk of ice falling from tunnel roof and damage of tunnel installations.

The issue of the environmental impact caused by tunnelling is increasingly gaining significance in the last years, in particular when a permanent draw-down of the groundwater table or pollution of the environment due to construction and operation is expected. In central Europe, for instance a growing trend exists to specify completely watertight tunnels (in urban areas where tunnels are below the groundwater table and under hydrostatic pressure (2). This trend can be explained by the improvement of waterproofing techniques, on one side, and due to the increasingly higher serviceability, durability and environmental requirements on the other.

Economical aspects

The relationship between the investment and the costs of operation and maintenance of a system on a long-term basis is also an important factor to be considered. Watertight tunnels are more expensive and difficult to construct, whereas drained tunnels may require ancillary structures, such as pumping systems and maintenance, entailing more expenditures in the long term. In many regions, especially in developing countries, financing resources and the labour costs can also be decisive in the determination of the permanent waterproofing system.

Description of waterproofing and drainage systems

Drainage

For the open type system, drainage includes the provision of longitudinal drainage pipes, covered with granular material or porous concrete, located at either tunnel sidewall (outside of the inner lining). Alternately, drainage pipes or void formers can be installed below the tunnel invert, as proved effective in the Black Hill Tunnels for the Hong Kong's Mass Transit Railway Corporation, as reported in (8). The water collected by the longitudinal drains is diverted through a system of cross drainages to the main drainage pipe provided below the tunnel invert. Transport tunnels are also provided with an independent internal drainage system to collect condensation, leakage, spilled water and other fluids inside the tunnel.

In case of high water pressure, the concept of pressure relief by permanent drainage can be adopted to reduce the water head by the installation of a drainage system with pressure relief valves or high level outcrops. This is the case at the Farchant Tunnel, in Garmisch-Partenkirchen, Germany, where a relief pipe system was used to limit the high water pressure (up to 40 m water column), reducing the lining thickness and reinforcement (9).

Fig. 1 View of waterproofing membrane installed at the Plabutschtunnel in Austria.

Bild 1 *Ansicht der eingebauten Abdichtungsfolie, Plabutschtunnel, Österreich.*

Waterproofing

The waterproofing system consists of a geotextile and of a waterproofing membrane, thermally welded to the plastic discs. The shotcrete surface is previously smoothed by the application of a gunite layer of 3 to 5 cm to cover irregularities and any protruding elements, such as bolt heads. The geotextile is locally fixed to the shotcrete lining by means of nailed plastic discs and provides protection to the membrane against damages during concreting the inner lining and creates a layer of high permeability to collect the groundwater. If water inflow is high, additional geodrains are installed to prevent the build-up of water pressure on the tunnel lining.

The waterproof membrane (consisting of PVC, TPO, FPO, PE, LDPE, ECB, Carbofol, among others) constitutes the actual water barrier and is provided with a signal layer to detect potential damages during concreting. The membrane is installed in modules, mutually connected by means of thermal welding (either with hot air or automatic equipment). After installation of each module, a rigorous check of the membrane welding is carried out by means of pneumatic tests. The dimensions of modules are limited to make installation easier and to create isolated compartments by means of bulkheads to allow later an easier identification of damages. Additionally, the system is complemented by the installation of joint sealings (usually PVC-based) and systematic cement- or chemical-based injections through previously installed injection tubes to fill existing voids between the membrane and lining and imperfections (Figure 1).

Fig. 2 Installation of the final concrete lining at the Dernbach Railway tunnel in Germany.

Bild 2 *Einbau der Ortbetoninnenschale, Dernbacher Eisenbahntunnel, Deutschland.*

In case of water pressure beyond 6 bar or presence of highly aggressive water, the installation of two waterproof membranes is recommended. The first layer is smooth and the second provided with nap foils to create an annular space between both membranes (6). This allows the system to be checked during all stages of construction, even after the installation of the inner concrete lining. If leakages occur due to defective execution of welding connections or due to membrane puncturing, the system can be repaired by injections of viscous material through special tubes. The disadvantage of this system are higher costs, which can be up to threefold of the single membrane system.

Fig. 3 Internal view of an underground station constructed with double-shell shotcrete lining at the Metro Santiago in Chile.

Bild 3 *Innenansicht einer bergmännischen Station mit zweischaliger Spritzbetonauskleidung, U-Bahn, Santiago de Chile.*

Final concrete lining

A watertight lining can also be provided by adequate reinforcement as has been used for subway tunnels ever since. The German Federal Railway Authorities, for instance, provide recommendations for the waterproofing systems either by the use of watertight concrete, waterproofing membrane systems or a combination of both measures, depending on the expected water aggressivity and pressure (13). Several international standards provide guidelines for the production of "watertight" concrete linings, such as the Austrian Concrete Society (12).

But to achieve a watertight lining, not only an adequate design and concrete admixture is required. Special attention also has to be paid to constructional aspects, such as the need of highly skilled personnel and additional measures for curing. Difficulties associated with the installation of watertight inner linings have been reported in (5), as experienced during the execution of several tunnels at the High Speed Railway Line Cologne-Frankfurt in Germany. Typical deficiencies are damages to the waterproof membrane, insufficient concrete compaction (due to the strong reinforcement) and torque of joint seals, which all are inherent to the construction process. Hence, when final linings are designed to be watertight, an extensive programme of remedial measures shall be defined in the contractual documents, as to avoid undesirable disputes during construction (Figure 2).

Development of lining techniques

Recently, a partly watertight type system has been proposed. This consists in the provision of water sealing measures to limit water ingress as suggested by Franzen and Celestino (3) for cases where tunnels do not necessarily need to be "completely dry" and it is sufficient to control the magnitude of water inflow. This can be achieved by either the provision of concrete linings, drainage systems or by a treatment of the ground.

In fact, in the last two decades, important developments have been made in terms of achieving more efficient lining techniques, particularly by replacing the expensive in situ concrete by high quality shotcrete. With the incorporation of low heat hydration concrete, microsilica for low porosity, a low w/c ratio and the use of steel or synthetic fibres, permeability of shotcrete can be as low as $1 \cdot 10^{-14}$ m/s (practically watertight). Studies carried out by STUVA (10]) recommend using shotcrete linings in areas with minor inflow of water or with groundwater pressure less than 1.5 bar. In some cases, additional sealing measures may be required in the form of sprayed-on or painted membranes, as shotcrete may locally not-be water tight due to cracks, poor execution and voids behind the reinforcement or at construction joints.

In Norway, for instance, the use of shotcrete linings for both structural and serviceability purposes is common practice. Astad et al. (1) provided "basic guidelines for the manufacturing of watertight shotcrete, its possible applications as well as its limitations" and suggested that shotcrete could be used for watertight linings. Also in Norway, it is common to design transport tunnels without any waterproofing system, installing free-standing lining systems to prevent ice build-up and shed the water away from the road track (2).

This solution is increasingly applied, above all in developing countries, such as Brazil and Chile, where single or double-shell shotcrete linings with low permeability have been extensively used for transport tunnels (Figure 3). Nevertheless, it should be noted that this solution is usually applied in cases of dry tunnels affected by local groundwater and situations where the subsoil presents low permeability and the water pressure is not significant.

Recent developments of waterproofing membranes

Developments have been made in the industry in the last few years, particularly with regard to sprayed-on membranes and the further development of bentonite based membranes.

Water-based elastic acrylic polymer waterproofing membranes have been developed in the last years. This is the case of the MS 340F membrane, which is sprayed on the tunnel surface, generally between an outer and inner shotcrete lining (Figure 4). The big advantage of this membrane is its double-sided bond strength (0.8 to 1.3 MPa), which guarantees the monolithic behaviour of the double shell lining and a potential saving in project costs (15). The membrane has already been installed in several projects worldwide, including tunnels in Brazil, Chile and Hong Kong (2).

Another system that is pushing its way in the industry is the bentonite based waterproofing membrane. This kind of membrane is widely used for cut and cover tunnels and underground buildings. There is skepticism in the tunnel industry regarding its use for mined tunnels, mainly due to considerations on material compatibility and durability due to bentonite migration. However, a solution to this problem has already been advised by manufacturers, with the development of bentonite membranes uniformly encapsulated between two geotextiles, preventing the bentonite to displace, after installation, and protecting it from construction related damages. This kind of membrane system has already been installed in some projects, such as the Athens Metro (14).

Fig. 4 Application of the sprayed-on membrane Masterseal at the La Polvora Road tunnel in Chile.

Bild 4 *Einbau der spritzbaren Masterseal-Abdichtung, Projekt La Polvora Straßentunnel, Chile.*

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