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Lifecycle Oriented Construction and Maintenance of Traffic Tunnels – Strategy Assessment to Develop Tunnel Drainage Systems with Low Calcification and Minimal Required Maintenance

Tobias Gamisch
Research Assistant/Doctorate, Swiss Federal Institute of Technology Zurich, Switzerland

Gerhard Girmscheid
Professor for Construction Management and Process Technology in Civil Engineering,
Swiss Federal Institute of Technology Zurich, Switzerland

Abstract

Scaling in tunnel drainages causes high cleaning and repair expenses, constrains traffic and can endanger tunnel and roadway stability. Based on deductively explained scaling processes, and taking the special demands of the new preventive maintenance method "hardness stabilization" into account, design requirements for drainages have been developed with the aim of achieving "low scaling", "durability" and "maintenance support". Hardness stabilization reduces the failure probability of the drainages by decreasing scaling risk, whereby the stability of both the tunnel and the transportation route is increased. Using hardness stabilization, a reduction of more than 46 per cent in maintenance expenses can be achieved and the repair expenses will be sustainably reduced, the drainage durability can be significantly increased, the utilization capacity is enhanced and the life cycle of the whole structure is increased. The presented methods and guidelines therefore have a great life-cycle effect for tunnels and can, furthermore, be transferred to other structures.

Keywords

Tunnel drainage, Scaling, Maintenance, Durability, Water-hardness stabilization

1. Introduction

Free-drained tunnels are an economical alternative to pressure-tight and pressure-controlled drained tunnels. The inner shell has only to ensure permanent rock support (Girmscheid, 2000). But significantly higher maintenance costs accrue for newer free-drained tunnels than for tunnels built in the 19th and early 20th centuries. The higher maintenance expenses are caused by scaling in the drainage pipes, which must be removed regularly since drainage operability will otherwise be restricted. As a result, water can escape out of the manholes and seep into the roadbed, leading to impaired stability as a result of the combination of moisture and dynamic strains. Therefore traffic safety is endangered and expensive repair measures will become necessary. Furthermore water pressure can build up on the tunnel shell due to constriction of ground drainage; this endangers the stability of the tunnel shell (Girmscheid 2000). But the cleaning works create high costs and restrict the utilization of the structures. The cleaning methods place a severe strain on the pipes, which has already caused widespread damages in many tunnel drainages within a comparatively short period of operation, involving high repair costs (Girmscheid et al, 2003).

1.1 State of Art

All tunnel-drainage systems have specific scaling appearances even if water is drained in different ways. Apart from variable scaling appearances in the pipes, heightened scaling can very often be found in the manholes. Moreover, clear interdependencies between increased scaling and special tunnel structures (e.g. ventilation shafts, portals, cross cuts, profile enlargements, rescue galleries) can be observed, which indicate that the choice of construction materials influence scaling.

The precise scaling causes were previously unknown, which is why often inadequate solutions only could be suggested. Depending on the individual combinations of different influences a solution measure can have both a positive and negative effect. As far as is known today, there is no generally valid solution for reducing scaling in tunnel drainages, which is why individual solutions have to be developed for every single tunnel. This is also why tunnel operators weren't able to do more than regularly remove the accruing scale in the past.

The sewage technology methods used for cleaning the drainage systems are only moderately qualified for dealing with the often hard, partially very hard scale in tunnel drainages. Table 1 shows post-sediment pipe cleaning methods presently used, their fitness for different scaling forms and their impact on the durability of tunnel drainages.

In recent years the scaling problem has received more and more attention. The operators were looking for solutions to remove the accruing scale as efficiently and economically as possible, and prompted research to both explain scaling causes and develop solutions to prevent/reduce high maintenance and repair expenses. The following results were developed at the Swiss Federal Institute of Technology Zurich (ETH Zurich) on behalf of the German Railways involving Austrian Federal Railways.

Table 1: Post-sediment Pipe-cleaning Methods of Sewage Technology Applied for Tunnel Drainage Cleaning, Their Efficiency and Their Impact on Durability

Cleaning Method	Efficiency	Impact on durability
High-pressure water flushing with fixed nozzles, with 150 l/min at 120 bar at nozzle	Appropriate for silty, soft and medium-hard deposits with low to high quantity	Low risks for damaging the pipes
High-pressure water flushing with vibrating nozzles, with 150 l/min at 120 bar at nozzle	Appropriate for hard deposits with low to medium quantity around the whole pipe profile; not for complete filled pipes	Low risks for damaging qualified, sufficiently embeded pipes
Highest-pressure water flushing with rotating nozzles, with 700 bar (in extreme 1000 bar) at high-pressure pump	Appropriate for hard deposits with low quantity on bottom of the pipes	High risk for cutting the wall of the pipes in case of stagnant nozzle
Rope and chain flails; Rope and chain scrapers	Appropriate for hard deposits with medium quantity around the complete pipe profile; not for complete filled pipes	Medium risk for damage the pipes at correct use; high risk for damage non-round pipes as well as in case of uncorrect usage
Drilling cutters, Impact drilling cutters	Appropriate for medium and hard deposits with high quantity (esp. complete filled pipe profile)	High risk for milling and cutting off greater pieces of pipe wall

1.2 State of Research

Currently there are only a few research works focusing on the causes of scaling in tunnel drainages. In Switzerland Wegmüller (2001) was one of the first to address with this problem. But most of the waters analyzed are ascending deep-ground waters, which is why his results can be transferred only partially to tunnels influenced by descending seepage/ground water. Ascending ground water not only generally has a significantly higher temperature but also a much higher degree of mineralization than descending water.

More research activities can be detected in the field of designing and building tunnel drainages to cope with the problem of scaling; most of them use the inductive method. Recommendations for building new tunnel-drainage systems were derived from observations in existing tunnels (Kirschke, 2001; Naumann et al, 2002; Abel, 2003). In addition to these inductive optimizing approaches, some experimental research works exist, which are simulating scaling in parts of tunnel drainages and analyzing the behavior of selected construction parts and materials (Maidl et al, 2002). First analyses that deal with the scaling problem caused by new building materials and construction methods are Chabot (2001) & Chabot (2002).

In the field of further improvement of post-sediment cleaning equipment only the manufacturers conduct continuous developments. Because the pipe cleaning devices are mainly used in sewage technology, the efficiency spectrum of the equipment only partially meets the requirements of the tunnel drainages and the scale to remove.

Research into the field of preventive maintenance methods for tunnel drainages started back at the end of the 20th century. In 1995 the method of water-hardness stabilization in tunnel drainages using liquid stabilizers was patented by Wegmüller (1995). This was followed in 2004 by the patent registration of hardness stabilization using stabilizer tabs (Wegmüller, 2004). Both patents of Wegmüller (1995 & 2004) must be recognized as an idea for applying the hardness stabilization to tunnel drainages; he does not invent any suitable, efficient and environmentally friendly anti-scaling agent.

One of today's most important inhibitors in many industrial applications is polyaspartic acid (PAsp), because of their high affinity of adsorption to mineral particles (Sikes et al, 1994), their relevance in biological processes (Sikes et al, 1991; Sikes and Wierzbicki, 1996; Ross et al, 1997; Wu and Grant, 2002; Burns et al, 2003), their excellent biodegradability (Ross et al, 1997) and production aspects (Mosig et al, 1997; Darling and Raksphal, 1998).

Many research works focusing on the efficiency of polyaspartic acid as an inhibitor in practical use were carried out with mineral deposit-forming salts with a known composition under well-known surrounding conditions, because most of them were executed in idealized tests in the laboratory (e.g. Sikes et al, 1991; Ross et al, 1997; Revellon et al, 2002; Wu and Grant, 2002; Burns et al, 2003). Only one phenomenological investigation of the effect of polyaspartic acid as a scale inhibitor in a real tunnel with variable environmental conditions previously exists (Maidl et al, 2004), which was conducted simultaneously to and independently from the investigations of the ETH Zurich. Although hardness stabilization in particular with liquid polyaspartic acid has been used for some years in tunnels, the cost-efficiency of this preventive maintenance method has not yet been decidedly verified.

1.3 Research Gap and Objectives

Recapitulating experience to date, the design of a drainage system is a substantial factor for scaling, in addition to the influence of construction materials. Depending on the individual scaling quantity, expensive maintenance becomes necessary, which strains the drainages. Depending on their resistance damages develop, which cause high repair expenses to maintain operability and further maintenance ability. Apart from these fundamental design requirements for tunnel drainages, resulting from scale formation and cleaning, new maintenance methods also demand adjustments. Therefore a drainage has to meet the following three main criteria: *Low scaling – Durability – Support of maintenance methods*.

Because of unknown influences, largely unknown functioning mode und unaccounted commercial potential offered by the hardness stabilization, this preventive maintenance method is only used in very few tunnels at present. The mission, therefore, was to explain the functional mechanisms of polyaspartic acid in general, and in tunnel drainages in particular, and to conduct a practical reliability study of the theoretical findings. Based on the results of the practical tests, the expected maintenance expense had to be forecasted, allowing a comparison of the costs of any previous maintenance strategies with that of using hardness stabilization. Because of these prognoses reveal cost savings, the hardness stabilization shall be implemented in the previous maintenance strategy in future.

1.4 Research Methodology

In line with the general research framework for constructional production and maintenance science at the Institute for Construction Engineering and Management of ETH Zurich (Girmscheid, 2004), the chosen research approach comprises a model level between reality and theory, on which the complex reality can be reproduced abstractly (Heidelberger, 1998) and theorized (Duhem, 1998; Chalmers, 1982). Depending on starting point and objectives of the research both induction (Carnap, 1995) and deduction methods (Popper, 2002) were used to gather knowledge. Induction is suitable for structuring the complex diversity of reality (Ulrich et al, 1994). Derivation of explanations was conducted deductively, based on theory. The role of scientific natural research was to construe phenomenological parameters on an unobservable level – the theory (Kanitscheider, 1981).

2. Water-Hardness Stabilization – A Preventive Maintenance Method

Polyaspartic acid use for hardness stabilization inhibits, delays or prevents scale formation (Ross et al, 1997). Its effect is based on adsorbing onto lime crystals, interfering with crystallization processes, complexation of scale-forming ions and dispersing crystals (Gamisch and Girmscheid, 2005b). Theoretical considerations incorporating findings from in-vivo observations and in-vitro tests conducted by other research institutes lead us to expect a positive effect of polyaspartic acid on scale formation in tunnel drainages with the following results: By inhibiting and dispersing lime crystals, lower scaling should occur and should be rinsed out by the natural water flow. By influencing crystallization processes, the occurring scale should have modified characteristics (Sikes and Wierzbicki, 1996).
The qualitative investigations in the reference tunnels consistently demonstrated the expected positive effects of hardness stabilization: The quantity of scaling was lower than in the same period before. The hardness of the scale formed in spite of hardness stabilization was softer than before. For these reasons it was possible to extend the periods between cleaning measures and to utilize simpler cleaning measures more efficiently, which exert considerably less strain on the pipes (Tab. 1). A static comparison of maintenance expenses without and with hardness stabilization demonstrates the life-cycle effect (Fig. 1). Furthermore there is significantly less likelihood of damage occurring when using cleaning methods, which put less strain on the pipes. Therefore the repair expenses should also be significantly lower.

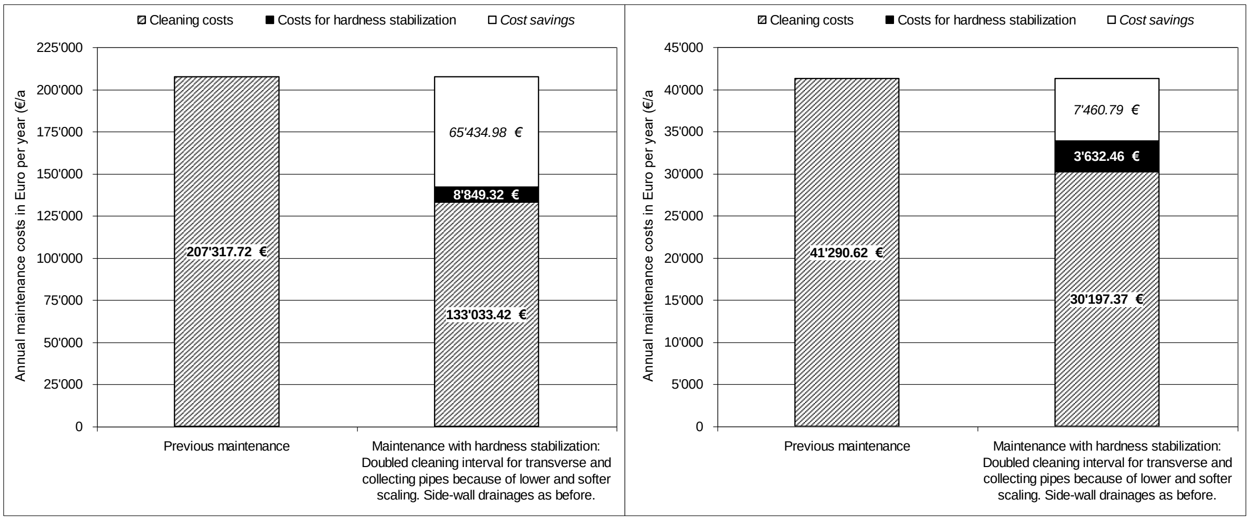

Figure 1: Comparison of annual maintenance costs with and without hardness-stabilization for two investigated tunnels

3. Conclusions – Requirements on Design of Tunnel Drainages

Based on the derived scaling causes, design requirements for new tunnel drainages could be concluded deductively to achieve the objectives low scaling, durability and support of maintenance. Every single part was analyzed and theoretically optimized. Subsequently the interactions between the parts were scrutinized. The interactions were balanced and a basic reversibly adjustable drainage system was created.

To prevent further changes in water mineralization the drainage packing, which covers the drainage pipes in the side walls, should be made of filter concrete, which is not cement-bounded and contains no limy aggregates as well as no fine materials and fractions respectively. But to prevent gravel falling into the pipes in case of damage, the washed round gravel should be bound using scaling-neutral resin. The drainage water should be strictly drained off the drainage packing (further contact with shotcrete).

The prevention of changes in water mineralization has to continue consequently in the pipes and manholes because every change can cause scaling. The pipes and gutters in the manholes should be made of scaling-neutral material too. Only circular pipes with a single layer pipe wall with heightened thickness should be used. The gutters in the manholes must be molded to pipe geometry (continue the circular profile), made of robust, scaling-neutral material and shouldn’t have sharp edges.

Furthermore, the pipes should be laid linearly without bends. Wide infiltration slots in drainage pipes can be reopened much more easily than small slots. A large pipe diameter permits the use of effective post-sediment cleaning methods, but leads to a low water flow/surface-ratio, where high evaporation and gas exchange can occur. That’s why the pipe diameter must be limited in the interest of low scaling. The diameter depends on the water infiltration and should be about 200 mm minimum to allow for cleaning.

In recent years the manhole distance was reduced in many tunnels to allow for increased cleaning, which leads not only to higher construction costs but also to higher aeration of the drainage water. Manholes generally influence water flow. Furthermore a piston effect from traffic leads to turbulences and aeration of drainage water. Therefore it is recommended that the cover of the pipe conductions in the manholes be sealed hermetically and a manhole distance of about 90 meters be executed.

To further reduce water aeration no waterfalls should be installed in the whole drainage system and turbulences should be avoided. Every pipe coupling should be molded accurately. The inner pipe wall and the gutter surface should be even and smooth. A laminar flow must be provided by an adequate slope.

Depending on the geology and hydrogeology, often only a low water quantity infiltrates over a drainage section of about 90 meters. Therefore a drainage system conducting the water from one section to the next is best for reducing evaporation and gas exchange with the atmosphere by providing a high pipe filling level. This water conduction is also necessary for the efficient use of hardness stabilization because the inflow at the beginning of the section transports the hardness stabilizer into the pipe. The more stabilized water that flows into a section the more infiltrated water can be stabilized, leading to less scaling.

But differently mineralized water can influence other water when mixed together, whereby massive scaling can occur. Depending on topography, geology, hydrogeology, changes in tunneling or sealing/drainage methods and special tunnel parts, differently mineralized drainage waters appear in many longer tunnels, which leads to scaling at the mixing points. Therefore such interacting waters must be separately drained off the tunnel. For these tunnels a basic reversibly adjustable drainage system was developed (Girmscheid and Gamisch, 2005a).

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