INFLUENCE OF STRUCTURAL AND OPERATIONAL CONSTRAINTS ON THE EFFECTIVENESS OF BLOCK BACKFILLING: FINDINGS FROM WATERPROOFING OF A DEUTSCHE BAHN TUNNEL

C. Rhein, G. Vollmann & M. Thewes
Institute for Tunnelling and Construction Management, Ruhr University Bochum, Bochum, Germany
H. Schälicke & C. Camós-Andreu
Prof. Dr.-Ing. Kirschke GmbH & Co. KG, Ettlingen / Munich, Germany
A. Decker
Ed. Züblin AG, IU – Tunnel Construction Division, Stuttgart, Germany
C. Christoph
DB, Technical Project Management Wendlingen-Ulm (I.GT(5)), Stuttgart, Germany

ABSTRACT: The “Große Wendlinger Kurve” (engl.: Wendlingen Large Curve) is a single-track railway tunnel with a length of approx. 770 m. The tunnel, which was excavated over approx. 660 m using the new Austrian Tunnelling Method (NATM), has a pressure-retaining waterproofing system, which consists of sheet waterproofing membranes (SWM), protective layers, external joint seals, and an in-situ concrete inner lining. A grouting system was installed over a length of around 225 m, which was used for a systematic block backfilling of the tunnel lining prior to the rise of groundwater level. The same waterproofing system was installed in the remaining 435 m of the tunnel, but in these sections, neither the installation of a grouting system nor the systematic block backfilling was carried out. In this case only crown gap grouting was carried out, which allows a direct comparison of the two approaches.

Different components of the grouting system (e.g. injection hoses) were tested on particular areas of the cross-section and analysed with regard to possible advantages and weak points in order to compare the functionality of the respective system types.

A videoscopic examination of 179 grouting devices in the Wendlinger Large Curve Tunnel shows that, on average, approximately 1.72 impairments per metre of examined grouting pipe section could be observed. Squeezing and bending are the causes of the majority of these impairments, with significant differences between sub-sections of the cross-section and construction phases. Placing the concrete for the side walls and crown significantly increases not only the overall impairment density but also, for example, the occurrence of collapsed bends in the grouting pipes, indicating a strong influence of the construction processes on system functionality. A comparison of three systems for grouting pipes shows different impairment patterns and suggests that material stiffness and deformability determine vulnerability to bending and squeezing. Overall, corrugated pipes appear to be the most robust, while fabric hoses exhibit the highest impairment frequency, underscoring the need to optimise the components and details of the grouting system for reliable systematic block backfilling in future projects.

1. MOTIVATION AND RESEARCH QUESTION

The suitability of systematic block backfilling (SBB, see section 2.3) as opposed to the use of a control and injection back-up on an as-needed basis (CIB, see section2.2) has been discussed in Germany for some time (1–6).

In this context, sheet waterproofing membranes (SWM) systems, their components and associated injection and grouting equipment have already been analysed in detail as part of a research collaboration between Deutsche Bahn (DB) and Ruhr University Bochum (RUB). Based on fundamental research at national and international level, combined with a comprehensive expert survey (3), a large number of planning and construction factors that have a decisive influence on the tightness of the structure were examined. SBB was considered a "possible measure to complete the waterproofing system" (3), but its effective impact could only be achieved in combination with improvements to the entire waterproofing system. Furthermore, need for research was identified, among others, regarding the design and execution of grouting systems. Further investigations focused on previous practical experience with the CIB, in particular on the vulnerability of the system to faults and their causes (5). These investigations indicated the need for optimisations, which should be investigated in pilot applications. For the general implementation of SBB in future tunnel projects, some planning and execution aspects should be examined in greater depth on the basis of practical applications.

With this goal in mind, this article reports on the experience gained with the planning and execution of the waterproofing system at the "Große Wendlinger Kurve" (eng. "Wendlingen Large Curve", WLC, see section 3). This conventionally constructed railway tunnel on the new Wendlingen–Ulm line (within the Stuttgart-Ulm / Stuttgart 21 high-speed railway project) was systematically backfilled over a length of 225 m, before the ground water control was stopped and the original water level was restored. On the remaining 435 m, only crown gap grouting (CGG) was carried out.

This article focuses on the planning constraints (sections 2 and 3), and the influences of the construction process and system components on the functionality of a grouting system (section 4). In addition, recommendations are made for a possible future implementation of SBB.

2. RELEVANT SEALING TECHNOLOGY BASICS AND NEED FOR INVESTIGATION

2.1 COMPONENTS OF A WATERPROOFING SYSTEM WITH PLASTIC SEALING MEMBRANES

The waterproofing of conventionally constructed double-shell railway tunnels with SWM in Germany is generally regulated in Deutsche Bahn Guideline "DB-Ril 853.4101" (7) with additional references to ZTV-ING, Part 7 (Tunnel Construction) (8), Section 5 (Waterproofing). Details on planning and execution are supplemented by the "Recommendations for waterproofing systems in tunnel construction" of the German Society for Geotechnical Engineering (9).

These generally stipulate that for installation of SWM, the surface of the sprayed concrete must be prepared by a compensating layer of sprayed concrete applied to the outer lining. A protective layer of geotextile fleece must be fixed onto this waterproofing substrate. The actual SWM waterproofing is then fastened to this protective layer. In the invert, this system is supplemented by an additional tunnel-side protective layer of SWM before the in-situ concrete inner lining is constructed. This structure, schematically illustrated in Figure 1, is constructed in two steps, first in the invert and then in the tunnel arch, along the sidewalls to the crown, as can be seen in Figure 2.

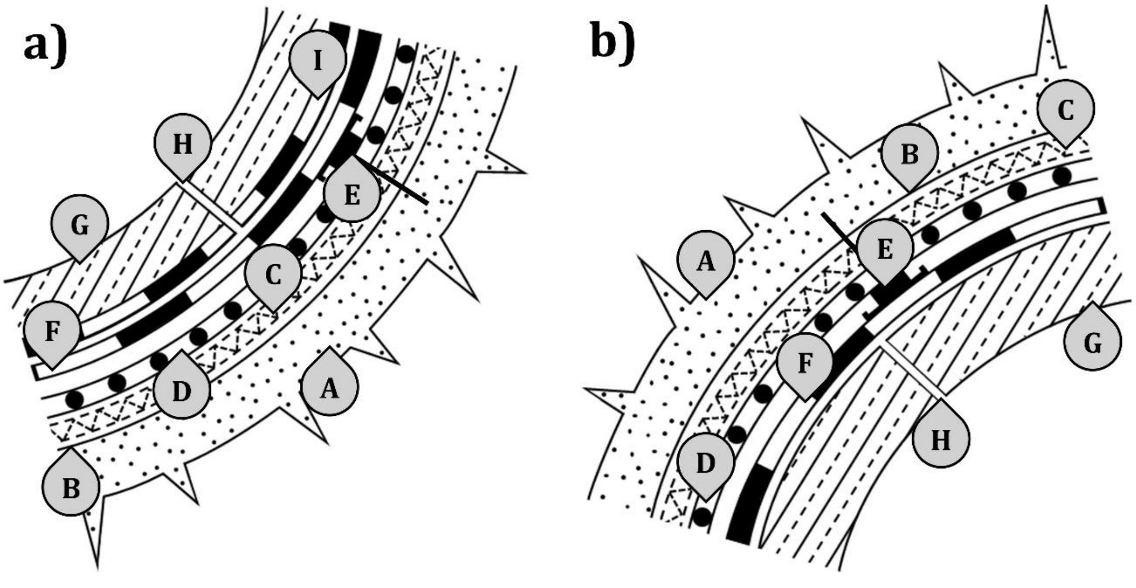

Figure 1:Structure of a tunnel construction with SWM waterproofing in the invert (a) and in the tunnel arch (b), based on (9) and (2): A – sprayed concrete outer lining; B – waterproofing substrate; C – drainage elements, if required; D – protective layer on the rock side; E – fixing elements; F – plastic waterproofing membrane; G – concrete inner lining; H – grouting pipe; I – protective layer on the tunnel side; based on (9)

The geotextile nonwoven fleece, which is fixed to the waterproofing substrate, as a protective layer (Figure 2 a, No. 1), is fastened to the sprayed concrete using suitable fixing elements. These usually consist of shot-fired nails and plastic discs called rondels. The rock-side protective layer serves to further compensate for any irregularities in the surface of the waterproofing substrate. It also protects the SWM from damage, when it is pressed against the substrate by the concrete pressure during the placing concrete of the final lining.

The actual sealing element, a single-layer, circumferential SWM (Figure 2 a, No. 2), is the primary waterproofing. In tunnels designed to withstand long-term hydrostatic pressure, this element generally has to have a thickness of 3 mm (8).

The SWM is usually fastened by spot welding it to the rondels. Thus the final lining is completely enclosed by the waterproofing membrane. In the area of the circumferential construction joints, an external 600 mm (8) large waterstops (waterbars, Figure 2 a, No. 3) are welded onto the membrane, dividing the waterproofing system into isolated compartments.

After installing the waterproofing system, the secondary lining concrete is placed. Like the waterproofing system, it is placed separately in invert and tunnel arch construction sequences (Figure 2 a, No. 4.1, Figure 2 b, No. 4.2). The final lining is thus separated by a longitudinal construction joint between these two construction sections (see Figure 1). The construction of the final lining is separated into block sections, resulting in the circumferential block joints encased by joint seals (or waterbars, waterstops) that should limit water infiltration to the individual compartment, in case of water leakage.

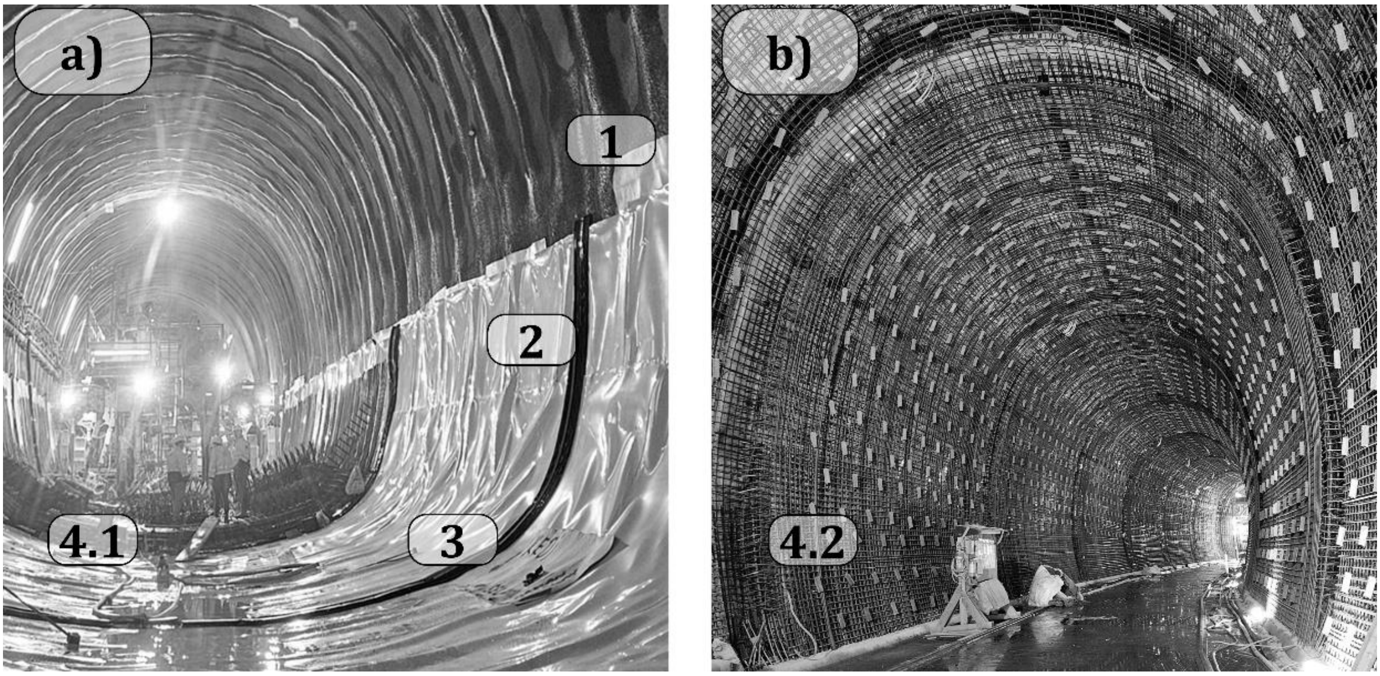

Figure 2: Components and work sequences for the SWM system of the Wendlingen Large Curve, in the invert (a) and tunnel arch (b) (source: IB Kirschke)

2.2 COMPONENTS OF A GROUTING SYSTEM

When the groundwater pressure exceeds 1 kPa above the bottom edge of the tunnel, according to current regulations in Germany, conventionally built water-pressure retaining railway tunnels must be equipped with control and injection equipment in accordance with Ril 853.4101 (7) and ZTV-ING, Part 7 (8). The control and injection back-up (CIB) is a grouting system that therefore mainly consists of grouting nozzles and radial pipes, as shown in Figure 3 b. These penetrate the final lining at a grid spacing of 3 m (8) and thus allow direct access to the isolated compartments , in the area between the SWM and the outer surface of the inner lining. According to DB Ril (7), this generally allows compartment-by-compartment localisation of leakage in the SWM after construction of the inner lining. Should leakage occur, grout can be injected into the compartment through these pipes, for remedial waterproofing (7).

Furthermore, injectable hoses are installed between the barrier ribs of the waterbars (Figure 3 a) to be able to retrofit the longitudinal compartment sections as required. This type of hose should also be provided in the longitudinal construction joints. In all cases, hoses and pipes must be routed as directly and radially as possible to the inside of the final lining.

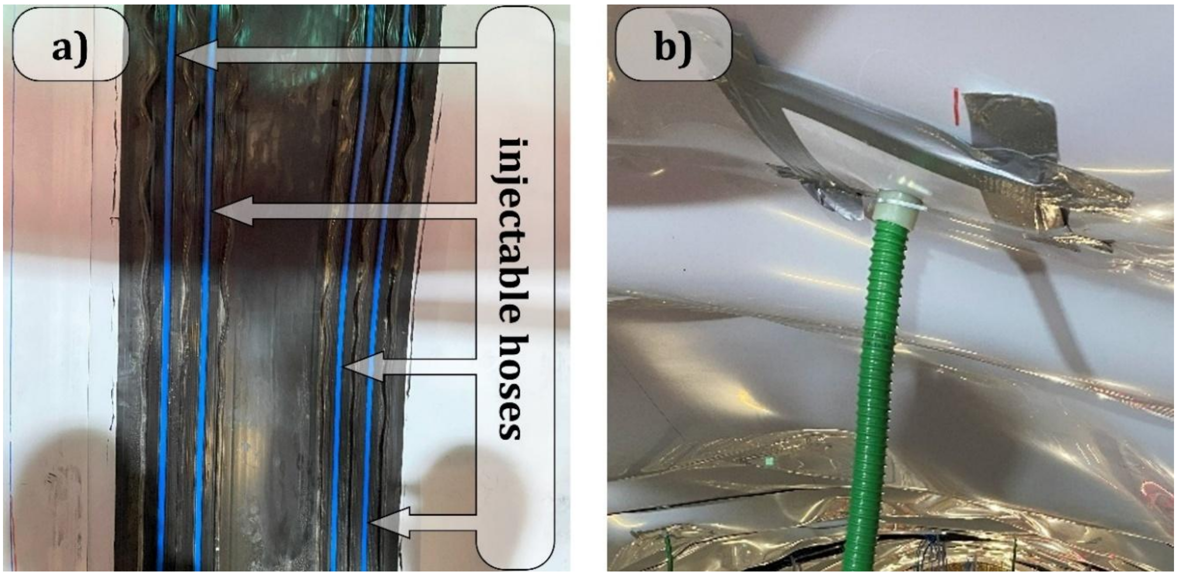

Figure 3: Components of the grouting system at the Wendlingen Large Curve, in the joint (a) and in the compartments (b) (source: IB Kirschke)

2.3 OBJECTIVE OF AN SBB AND COMPARISON WITH OTHER GROUTING MEASURES

Based on the current regulations in Germany, a CGG must be carried out by default after 28 (7) or 56 (8) days before the original groundwater level is restored. This procedure targets the filling of the cavity in the crown (crown gap) caused by the concreting process and technology. For this, a low-shrinkage grout (cementitious mortar or slurry) is used. Requirements for the material properties can be found in ZTV-ING Part 3, (10) Section 5. The grouting is carried out through the “spy holes” remaining after the fresh-in-fresh concreting along the crown line (Image4 a).

Figure 4: Execution of the CGG (a) and SBB (b) on the WLC (source: IB Kirschke)

Even though the CGG has been an integral part of the regulations for years, experts often question the extent to which it fulfils its intended purpose (3). This leads to further discussion as to whether it would be more appropriate to systematically execute a block wise backfill using the grouting system before restoration of the groundwater level, starting in the invert and extending to the crown. ‘This measure is known as “systematic block backfilling” (SBB, Figure 4 b). SBB also covers the crown gap, so that it already includes the CGG required by the regulations.

In addition to a more favourable grouting direction, SBB offers better venting options during the grouting process. The air pressed out by the rising grout can escape through the spy holes in the crown. If, however, no SBB is carried out and a conventional CGG is used instead, the necessary venting cannot be ensured as the hardened crown gap grout can block the air outlet at the crown in the event of subsequent grouting, should that become necessary (5). Moreover, in this case, the pressure exerted by the ground water must be overcome, resulting in much higher grouting pressures compared to SBB during construction. The increase in grouting pressure can therefore have a negative effect on the design of the final lining (6). The SBB also has a preventive effect to protect the SWM on the tunnel side. The outside of the inner lining represents the tunnel-side bedding of the SWM. Therefore, any imperfections (e.g. excessive roughness, cavities, etc.) in the contact surface between the SWM and the final lining can generally lead to damage to the waterproofing, when the SWM is pressed onto this rough surface or – even worse – onto larger cavities with exposed reinforcement once the groundwater rises back to its original level. A particularly critical area is the construction joint between the invert and the sidewall. Due to the different hydrostatic concrete pressures during the construction phases of the final lining, there is a risk of fresh concrete flowing unevenly over the outer edge of the bench, between the invert concrete and the SWM, resulting in an extremely rough concrete edge. (3)

The primary objective of an SBB is therefore to fill and smoothen these areas and thus create an improved bedding for the SWM. This is intended to prevent damage to the SWM after the construction process of the inner lining. Practical experience shows that this can be achieved effectively with the help of SBB. In contrast to supplementary grouting via a CIB in case of need, SBB is therefore more of a preventive than a remedial measure, even if a certain ‘sealing effect’ of leaking defects in the SWM can be assumed. (3)

2.4 NEED FOR INVESTIGATION FOR PLANNING AND EXECUTION OF AN SBB

Considering all of the above aspects, it currently seems reasonable to give preference to SBB over conventional CGG and, if necessary, subsequent grouting via CIB.

However, for a SBB to fulfil its purpose, complete backfilling of the compartments is considered a fundamental requirement. In individual practical experiences and project implementations to date, however, considerable potential for optimisation of the grouting system has been identified due to high failure rates (5).

This publication therefore deals with the influences on the functionality of a grouting system that can result from the various construction conditions and the use of certain components such as grouting pipes and nozzles. This provides insights into which materials should be favoured or excluded when planning a grouting system to ensure maximum functionality and thus complete filling of the compartments.

In addition, these analyses are discussed by Rhein et al. (6) by comparing the methods of conventional CGG and SBB, based on the findings obtained. New planning constraints that arise for future SBB designs are also considered in this discussion, along with recommendations for future application of SBB (6).

2.5 LIMITATIONS OF THE STUDY

The findings presented in this article are based on a sample analysis of a single project. Due to the small sample size and the limited range of project-specific observations, the results should be viewed as indicative and serve as a basis for further analysis and investigation, the transferability of which needs further validation. Furthermore, the findings presented from the field observation data must also be further processed methodically in subsequent analyses with regard to their informative value, transferability, validity and significance.

3. WENDLINGEN LARGE CURVE PROJECT

The Wendlingen Large Curve Project (WLC) comprises an approximately 770-metre-long railway tunnel and is a connection to the new Wendlingen–Ulm line. The first 110 m were constructed using cut-and-cover methods, passing under the new line, while the subsequent 660 m section was excavated using conventional NATM. The maximum cover of the tunnel is approx. 17 m with a water pressure of up to 200 kPa above the tunnel invert. (11)

The conventionally built section has a water pressure-retaining waterproofing system consisting of SWM, protective layers, external joint waterbars and an in-situ concrete final lining. A grouting system was installed over a length of approximately 225 m (18 block sections) to backfill the compartment sections of the waterproofing system behind the final lining before restoring the natural groundwater level. The system is designed based on Ril 853 (7) and ZTV-ING (8).

Each block section had 24 grouting devices (8 in the base, 12 in the sidewalls and 4 in the crown) and 12 pairs of inspection holes, 6 of which were used for post-concreting and the remaining 6 for the SBB. Injectable hoses were arranged in between the barrier ribs of the circumferential joint waterbars, as shown in Figure 3 a. Inside a compartment section, the grid spacing between the grouting devices was approximately 5 m, based on the ZTV-ING (as of 2017) (12) on an experimental basis. The grouting devices each consist of a nozzle and a pipe as shown in Figure 3 b. The nozzles were spot-welded to the SWM and secured at the edges with adhesive tape to prevent concrete and cement paste from penetrating.

The three types of pipes shown in Figure 5 were used to investigate different system variants:

a) spiral hoses as the standard system,
b) fabric-reinforced PVC hoses
c) prefabricated systems with angled grouting nozzles and corrugated pipes

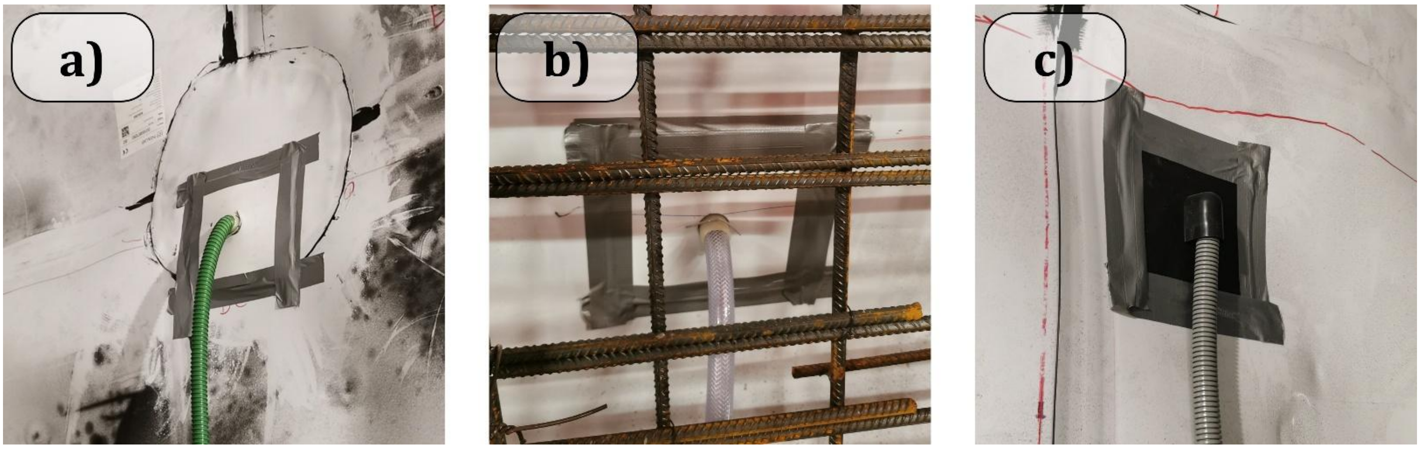

Figure 5: Grouting devices in the WLC project, a) with spiral hose, b) with fabric hose, c) as a prefabricated system consisting of prefabricated nozzles and corrugated pipe (source: Rhein)

Some of type c) pipes were supplemented by external swelling waterstops to reduce potential longitudinal grout or water migration as introduced by (13). The experimental variants were installed in two block sections in the tunnel arch. The standard system with spiral hoses was installed in the remaining 14 block sections in the tunnel arch and in all 18 block sections in the invert. All hoses have an inner diameter of approximately 19 mm (¾"). This creates a suitable test environment for evaluating the functionality of different grouting systems in different construction phases.

Prior to the SBB, which is reported by Rhein et al. (6), the grouting devices were ‘activated’. To do this, water was briefly injected into the grouting devices to open them, under high pressure of 3,000 kPa, while limiting the volume to a maximum of 10.0 l. The compartments were then grouted one after another, starting from the invert, moving up to the sidewalls and then to the crown, with maximum pressures and termination criteria (11) defined for each area, as reported in (6). During activation, the specified maximum pressure was actually reached in only 1 % of the grouting devices. It can be deduced from this that 99 % of the grouting devices potentially ensured a passage to SWM under the corresponding pressure conditions below the allowed maximum. This high rate of potential functionality of the grouting devices, as deduced herein, should be kept in mind when reviewing the videoscopic condition assessment presented below.

4. CONDITION ASSESSMENT OF THE GWK GROUTING EQUIPMENT

4.1 INVESTIGATION AND EVALUATION METHODS

4.1.1 Methods of data collection, investigation and quantification

For the investigation of possible causes for possibly limited functionality of individual grouting devices, videoscopic examination of the grouting devices were carried out as part of the field investigations at the WLC. These were carried out systematically in two block sections with the standard grouting system and in one section each with the experimental variants of the system before and after placing the concrete of the sidewalls and crown final lining at all accessible grouting devices. The systematic examination was supplemented by further random assessments in additional sections during the preparations for grouting. In total, more than 200 videoscopic examinations were carried out on a total of 117 grouting devices in nine different blocks at various times.

Data was collected using a waterproof handheld pipe camera (see Figure 7) with HD resolution (1080 P), integrated LED lighting, a frame rate of 30 frames per second and a camera diameter of 8 mm. The length examined was tracked using markings on the camera cable.

The impairments recorded during the videoscopic examination were assigned to categories using a specially developed catalogue (see Section 4.1.2). The frequency of the impairments that occurred was recorded in terms of their number and location and documented with regard to their category and the construction phase during which they were recorded. This method is intended to enable an objective quantification of the impairments that occurred and, subsequently, their evaluation with regard to their influence on the grouting.

4.1.2 Catalogue of possible impairments

The catalogue compiled in (6) is used as a summary of impairments that have occurred or are potentially expected during manufacturing and use of grouting systems. Each impairment recorded during the video-based field investigations is thus assigned to a previously defined category that describes the respective type of impairment.

This should allow the underlying types of impairments for the large percentage of grouting devices that has been documented as not functioning or not functioning adequately in the past (3, 5) to be empirically proven and quantified for the first time.

According to (6), the catalogue of possible impairments is based on a collection of previously documented impairments (2, 3, 5, 13) as well as additional impairments that were documented for the first time in the field study (6). Only impairments that may affect the subsequent grouting process are considered. Damage to the pipes that has no influence on the actual grouting process is for example not taken into account because no impact on the effectiveness of the grouting, as documented by Rhein et al. (5), is to be expected in such cases.

According to Rhein et al. (6) these are divided into a classification system in which, in addition to the types of impairment, their causes and effects are also differentiated, as shown by Figure 6. Thus, in addition to the simple recording of impairments, a systematic basis for the analysis and evaluation of grouting systems and their components is created. For a more detailed explanation of the classification system, the catalogue embedded in it and, in particular, the characterisation of the possible types of damage to be distinguished, (6) is recommended for further reading.

The heuristic nature of the classification system presented implies that it does not claim to be exhaustive. As described, the system is based on a comprehensive foundation of literature, project experience and expert knowledge. However, in the complex and highly project-specific reality of tunnelling, it is hardly possible to record all potentially relevant impairments. Some of the relationships between causes, impairments and effects presented in the system are also based on the authors' engineering assessments. These require further validation through systematic investigations beyond the field studies described here.

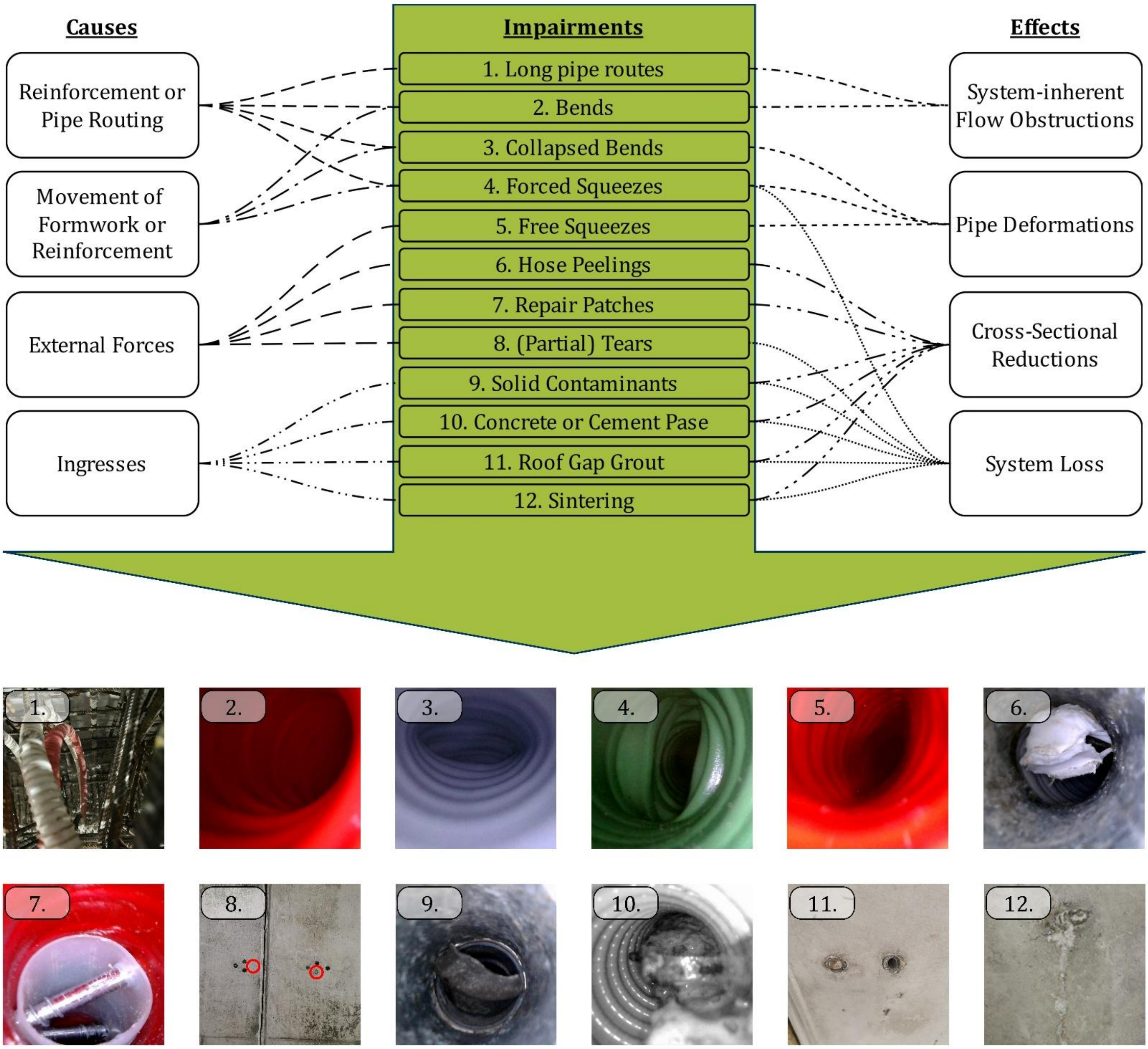

Figure 6: Heuristic classification system for cataloguing possible impairments to the functionality of individual grouting devices (top centre) with their causes (top left) and effects (top right), along with examples for every impairment covered by the catalogue (bottom) in the order which they are listed

4.2 RESULTS OF THE VIDEOSCOPIC EXAMINATION

4.2.1 Conducting system-comparative video-based examinations

Areas examined and timing

To obtain as comprehensive a sample as possible of both the grouting devices of the standard type grouting system and the two experimental variants, a total of four block sections were systematically examined. Two of these sections were equipped with the standard grouting system (sections 31 and 32) and one section each with the system with fabric hoses (section 34) and the system with corrugated pipes and angled connections (section 35) in the sidewalls and crown. In these four selected block sections, depending on accessibility and without disrupting the construction process, all 24 grouting devices installed were examined from the formwork unit before and after placing concrete for sidewalls and crown. This systematic recording was supplemented by random samples of individual, randomly selected grouting devices in randomly selected block sections. These random samples comprise 25 examinations, which were carried out during the preparation of the grouting through the already installed grouting packers, as shown in Figure 7.

Figure 7: Conducting a video inspection through a grouting packer (source: Camós-Andreu)

Documentation and evaluation methods

All examinations were fully documented on video, while additional information, such as section- and grouting device numbers, the length examined and comments on possible obstacles, was recorded in a protocol. Following the on-site work, all video files were viewed, the identified impairments and special features were recorded and saved as screenshots for further assessment.

4.2.2 Quantification and localisation of impairments

Frequency of different types of impairments

The following impairments were used for quantification and evaluation from the catalogue presented in section 4.1.2 by Figure 6:

- bends	(2.)
- collapsed bends	(3.)
- forced squeezes	(4.)
- free squeezes	(5.)
- hose peeling	(6.)
- repair patches	(7.)
- ingress of solid contaminants	(9.)
- ingress of concrete or cement paste	(10.)

The frequency of these impairments is analysed below based on the examination results regarding their location, their development over construction phases and any possible influence of the different pipe systems and assessed statistically.

As the accompanying measure was systematic block backfilling prior to the restoration of the groundwater level, no deposits of crown gap grouting material or sintering could occur, therefore these were not considered any further by this study. Long pipe routes were also not recorded as impairments, as these cannot be quantified without a reference value. The actual hose length examined was nevertheless documented. Although it appears possible to record breaks and partial breaks using video-based examinations, these were not encountered in the sample described. To count non collapsed bends during the review process, a maximum visibility distance of 40 cm into the hose was determined in the laboratory using the pipe camera and by recreating the boundary conditions on site. Bends are therefore only determined if their bending radii are within this distance.

A total of 366 impairments were identified during the systematic investigation in sections 31, 32, 34 and 35 (n = 179n – resulting from two examinations of 96 grouting devices each, minus 13 examinations that could not be carried out due to the construction process). The majority of impairments were due to forced squeezing (164) and collapsed bends (141). The lowest number of impairments was found as ingresses of solid contaminants (5). However, it should be noted that these usually are expected to mainly occur at a later, non-systematically observed point in time (see section "Temporal development of impairments"). The summary of the values of the impairments determined during the systematic investigation can be found in Table 1.

In addition to the absolute count data, which was collected in total before and after placing the concrete of sidewalls and crown, and the percentage shares determined from this, Table 1 also provides values for the relative impairment density. These values are used to make the absolute frequencies comparable with each respectively to standardise them. This linear stochastic density is obtained by dividing the absolute count values of the observations by the total length of the examined length of the pipes, which is 213.09 m in this case.

Table 1: Values for the absolute count data of impairments determined in the systematic examination and their relative stochastic density

	Bends	**Collapsed Bends**	**Forced Squeezes**	**Free Squeezes**	**Repair Patches**	**Ingresses of Solid Contaminants**	**Ingresses of Concrete or Cement Paste**	**Total**
Total [-]	141	13	164	21	6	5	16	366
Share [%]	38.52	3.55	44.81	5.74	1.64	1.37	4.37	100
Density* [1/m]	0.66	0.06	0.77	0.10	0.03	0.02	0.08	1.72

**) Based on the 213.09 m total length examined*

When looking at Table 1, it should be noted that the values for all pipe systems are recorded together. In addition, the state of placing concrete is disregarded in this summary. Thus, multiple examinations (of the same pipes) before and after placing concrete of sidewalls and crown are included. For better comparability, standardisation is carried out again for each aggregation of the sample based on the respective pipe length interval for every of the following scopes.

Sub-sectional distribution in the tunnel cross-section

The following section illustrates the frequency of occurrence of the individual impairments in the various sub-sections of the tunnel cross-section. For this purpose, and to exclude double measurements and other influences, only the observations made after placing concrete in sections 31 and 32 (where only spiral hoses were installed) are considered. Experimental pipe systems were not considered in this analysis, as they were only installed in sidewalls and crown but never in the invert. This results in a sample of n = 44 examinations for the analysis of the sub-sectional distribution of impairments, of which 15 were carried out in the invert, 24 in the side walls and 5 in the crown. All impairments determined in the sample described are summarised in Table 2 as a percentage of the total number.

It should be noted in advance that the proportions of the impairments observed in this sample differ only insignificantly (with values between 0.32 and 3.76 %) from those in the overall sample, so that they can generally be regarded as comparable. A total of 95 impairments were found in the 44 examinations, of which approximately 49 % occurred in the invert, approximately 38 % in the sidewalls and only approximately 13 % in the crown. This distribution is due to the fact that the pipe routes for grouting devices in the invert by default result approximately two to ten times longer pipes (between ~ 3.2 and ~ 6.10 m (11)) than those in the crown (~ 1.5 m (11)) and side walls (~ 0.6 m [10]). If the observations are standardised as before based on the pipe length examined, the density of impairments in the invert is significantly lower at 0.96 1/m than in the sidewalls (1.56 1/m) and the crown (2.69 1/m). These impairment densities for the respective types of impairments can be found in Figure 8.

In conjunction with Table 2, Figure 8, shows that even though most impairments are generally recorded in the invert (which is due to long pipe routes) the density of impairments increases gradually in the ascending sidewalls up to the crown.

Table 2: Percentage of damage observed in blocks 31 and 32 according to their location in the tunnel cross-section

	Bends	**Collapsed Bends**	**Forced Squeezes**	**Free Squeezes**	**Repair Patches**	**Ingresses of Solid Contaminants**	**Ingresses of Concrete or Cement Paste**	**Total**
Invert [%]	4	20	58.9	57.14	50	0	0	49.47
Side Walls [%]	46.15	80	25.64	42.86	0	100.00	0	37.89
Crown [%]	7.69	0	15.38	0	50.0	0	100.00	12.63
Quantity [-]	39	5	39	7	2	1	2	95
Total Share [%]	41.05	5.26	41.05	7.37	2.11	1.05	2.11	100.00

To assess the impairments causing the total distribution shown in Figure 8, the proportions of the total density distribution and the distributions per sub-section were analysed. This analysis shows that the total distribution (Figure 8, "Total") is significantly influenced (more than 41 %) by bends and forced squeezes. Looking at the individual cross-sectional sub-sections individually, bends dominate in the invert and the sidewalls with proportions of ~ 39 % and ~ 50 %, respectively. In the crown, on the other hand, forced squeezes have the biggest influence by ~ 50 %.

These types of impairments not only account for high percentages but also show significant variation between the cross-sectional sub-sections. This explains the observed distribution of the total density (invert < side walls < crown).

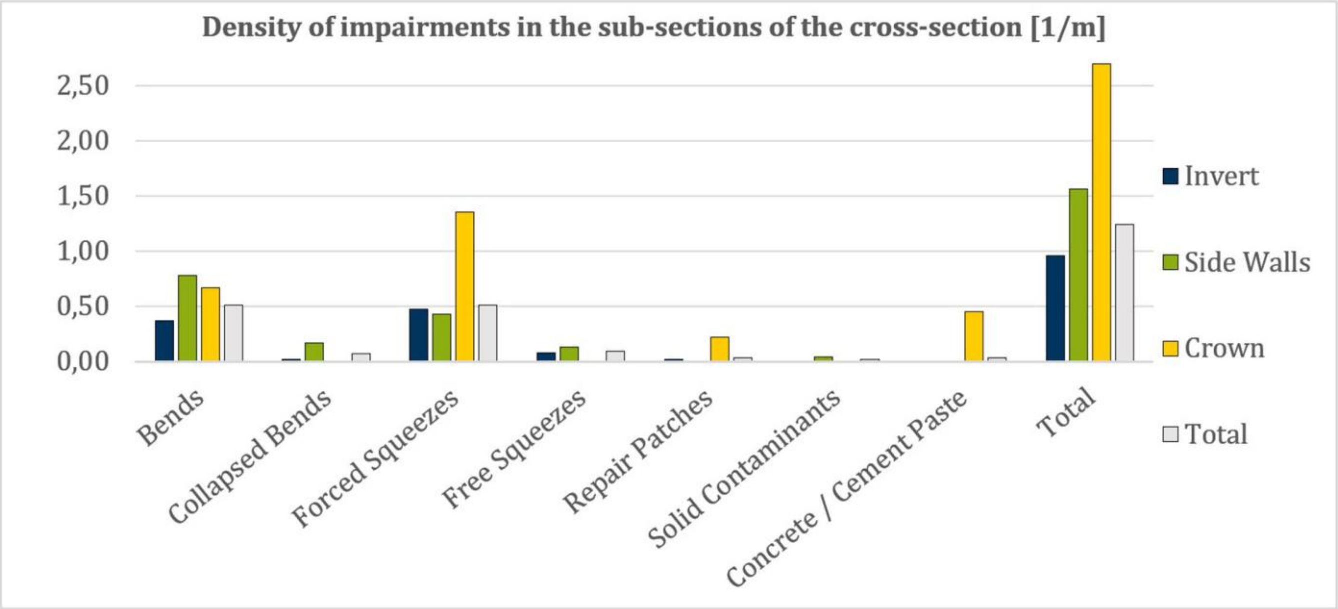

Figure 8: Density of the impairments observed in different sub-sections of the cross-section

Temporal development of impairments

To describe the temporal development of the impairments depending on the influence of concrete placing, only the investigations carried out in the tunnel arch (side walls and crown) from the systematic observation are considered. Since the placing of concrete for the final lining in the invert had already been completed at the time of the video inspection, all impairments found in the invert could already have been influenced by placing concrete in the invert. This results in a total of n = 118 examinations, of which 57 were carried out before and 61 after placing concrete in the tunnel arch. Since it could not be ensured during the on-site investigations that the same pipe section was always recorded at all examinations before and after the placing of the concrete, the density of the impairments resulting from their number and the length examined is also used in the following presentation of results. The values for the impairment density are summarised in Table 3.

Table 3: Density of impairments in the vault before and after concreting

	Bends	Collapsed Bends	Forced Squeezes	Free Squeezes	Repair Patches	Ingresses of Solid Contaminants	Ingresses of Concrete or Cement Paste	Total
Before placing concrete [1/m]	0.40	0.05	0.40	0.08	0.02	0.02	0.00	1.10
After placing concrete [1/m]	0.81	0.16	0.52	0.07	0.02	0.02	0.23	1.84

As a result of placing the concrete in sidewalls and crown, there is a significant increase in the density of bends and collapsed bends. Overall, the density of all impairments increases from 1.10 1/m before to 1.84 1/m after placing concrete. As to be expected, concrete or cement paste deposits are only visible after concreting. These show a density of 0.23 1/m. The values from Table 3 are illustrated by Figure 9.

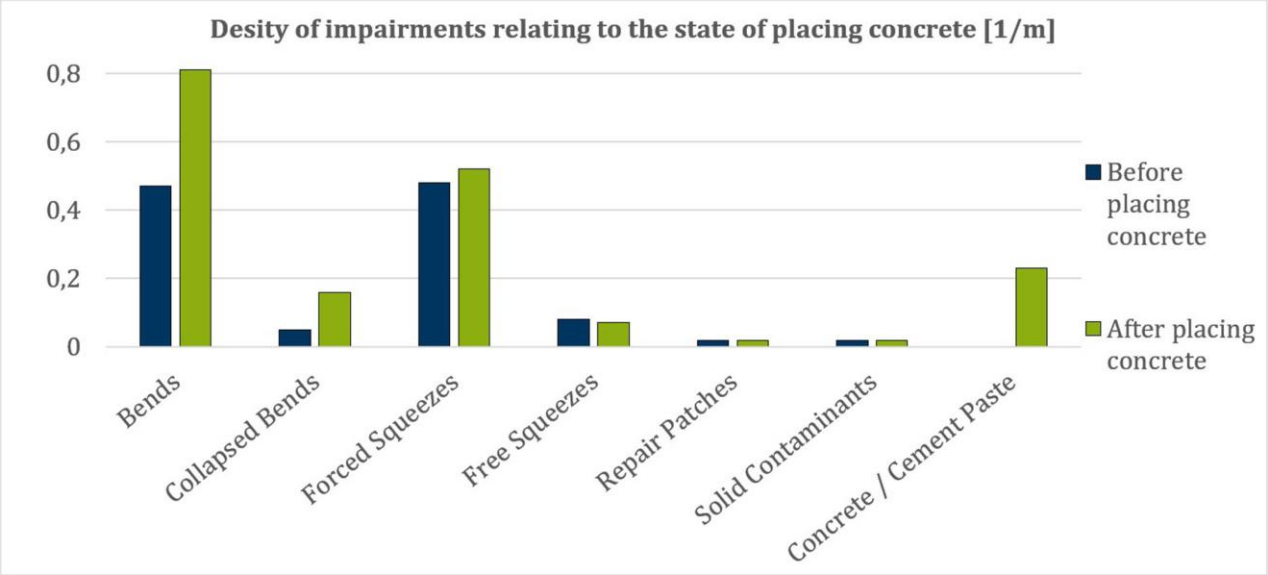

Figure 9: Density of the observed impairments before and after placing concrete in the sidewalls and crown

Reviewing Figure 9, it is evident that, placing concrete has an overall impact on the impairments to the grouting devices. However, based on the assessment presented, it is not possible to identify any influences from previous and subsequent construction stages. Still, it can be assumed that these may also impair the functionality of the grouting devices. For example, compared to the systematic examination, the density of solid contaminants increased significantly in the random supplementary examinations during the preparation of the grouting (0.05 1/m compared to 0.02 1/m). Furthermore, hose peelings, which were not encountered at all during the systematic examination, occurred in the supplementary random samples with a density of 0.08 1/m. This value, which appears low at first glance, is due to the long investigation distances. In fact, peelings that are not distributed over the pipe route but only occur once per grouting device were found in 72 % of the grouting devices examined as part of the supplementary sampling.

In addition, in 48 of the 92 systematic examinations after placing concrete, and thus in more than 52 % of the grouting devices, water infiltration was found, as described in (13). This can be interpreted as an indicator of a leaky rock-side closure of these grouting devices (see the adhesive tape in Figure 5). Impairments such as the ingress of crown gap grout and sintering, which could not be detected in this study due to the systematic nature of the grouting measures, could be facilitated by this.

Differences between the pipe systems

In addition to the sub-sectional distribution and temporal development of the impairments, the focus in the following is on the differences between the three pipe systems used. As fabric hoses and corrugated pipes were installed exclusively in the sidewalls and crown, for this comparative purpose, only the examinations carried out after placing concrete in the tunnel arch are used from the systematically assessed sample. Accordingly, n = 92 examinations were considered, of which 60 were carried out on spiral hoses, 16 on fabric hoses and a further 16 on corrugated pipes. Due to the different sample sizes, the differences between the hose types were also considered using the impairment density. The values for the impairment densities of the different pipe systems can be found in Table 4.

Table 4: Density of impairments in different pipe systems in the sidewalls and crown after placing concrete

	Bends	**Collapsed Bends**	**Forced Squeezes**	**Free Squeezes**	**Repair Patches**	**Ingresses of Solid Contaminants**	**Ingresses of Concrete or Cement Paste**	**Total**
Spiral hose [1/m]	0.60	0.07	0.80	0.13	0.04	0.03	0.04	1.82
Fabric hose [1/m]	0.35	0.44	1.06	0.09	0.00	0.00	0.88	2.83
Corrugated pipe [1/m]	1.20	0.00	0.06	0.00	0.00	0.00	0.06	1.32

Table 4 shows clear differences in the impairment density between the three pipe systems assessed. Corrugated pipes had the lowest overall impairment density at 1.32 1/m. While spiral hoses had a density of 1.82 1/m, which is almost 38 % higher, fabric hoses had an even higher density of 2.83 1/m, which is more than twice as high as for corrugated pipes.

Despite these differences, it is not possible to draw a general conclusion as to which pipe system was most severely impaired in terms of functionality. It can be seen from Table 4 that different types of impairments also occur more frequently in different hose systems. Corrugated pipes, for example, seem to be most prone to bending, but show hardly any other impairments in the sample presented. Spiral hoses also have a higher density of bends than fabric hoses. However, their density of forced squeezes and collapsed bends is significantly lower. Even if repair patches or solid contaminants are present, it should be investigated whether these differ depending on the hose system or whether the found here are due to sample size and hose length. The frequency and density of impairments alone do not provide any information about their severity and impact on the functionality of a grouting device. Therefore, further investigations in this regard were conducted.

4.2.3 Assessment of the severity of impairments

When reviewing the screenshots taken from the videos, it is noticeable that the impairments observed vary not only in density and frequency but in severity. The severity of the impairment was therefore quantified – whenever possible – in subsequent examination of the cross-sectional reductions in the grouting pipes by using digital image analysis as shown in Figure 10.

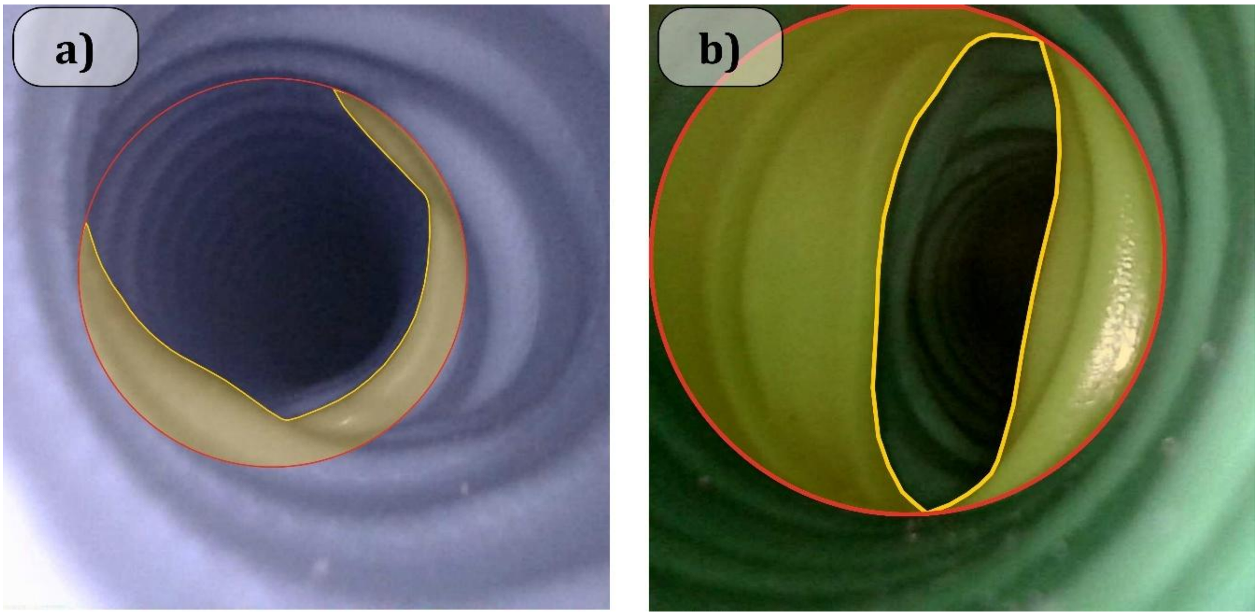

Figure 10: Examples for identification of cross-sectional reductions resulting from the impairments observed, in digital image analysis

The examples from Figure 10 show, how the cross-sectional areas that deviated from the original round cross-sectional footprint of the pipes were identified and measured. This assessment cannot be applied to the second most frequently observed impairment type, ‘bends’, which accounted for 141 observations in the impairment count, as these do not reduce the cross-section. These can only result in system-inherent flow obstructions due to the resulting pipe routing (see section 4.1.2, Figure 6). The reduced cross-sectional areas identified for the other impairments were compared to the areas of the original pipe cross-sections to obtain a value for the relative percentage reduction in cross-sectional area.

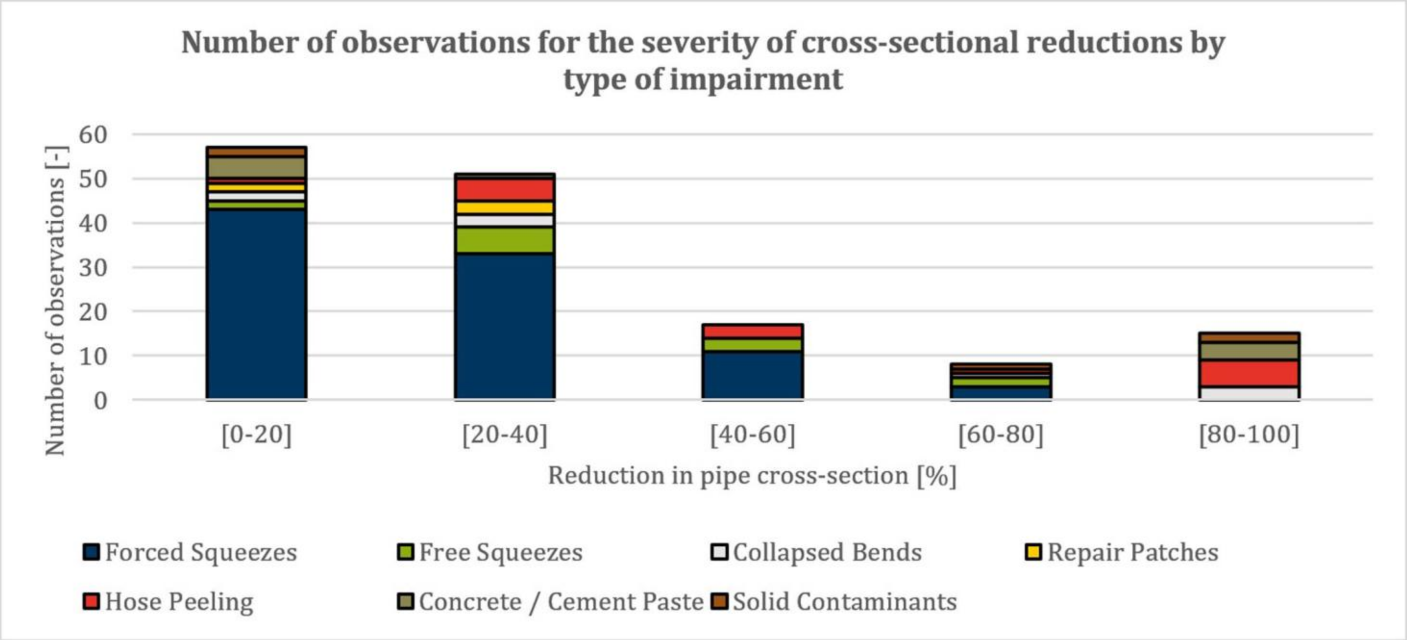

Figure 11: Histogram of the number of observations for the groups of percentual reduction of the grouting pipes cross-sections

The results of these analyses are shown in the histogram in Figure 11. In accordance with the procedure, these are strongly influenced by the number of observations. For the procedure described, only those screenshots were used in which the respective impairments were visible frontally and in full, showing the entire pipe cross-section. This could not be ensured in equal numbers for all types of impairment, which is why the relative distribution of the observed impairments must be evaluated individually for each type of impairment under the specific number of observations for further analysis.

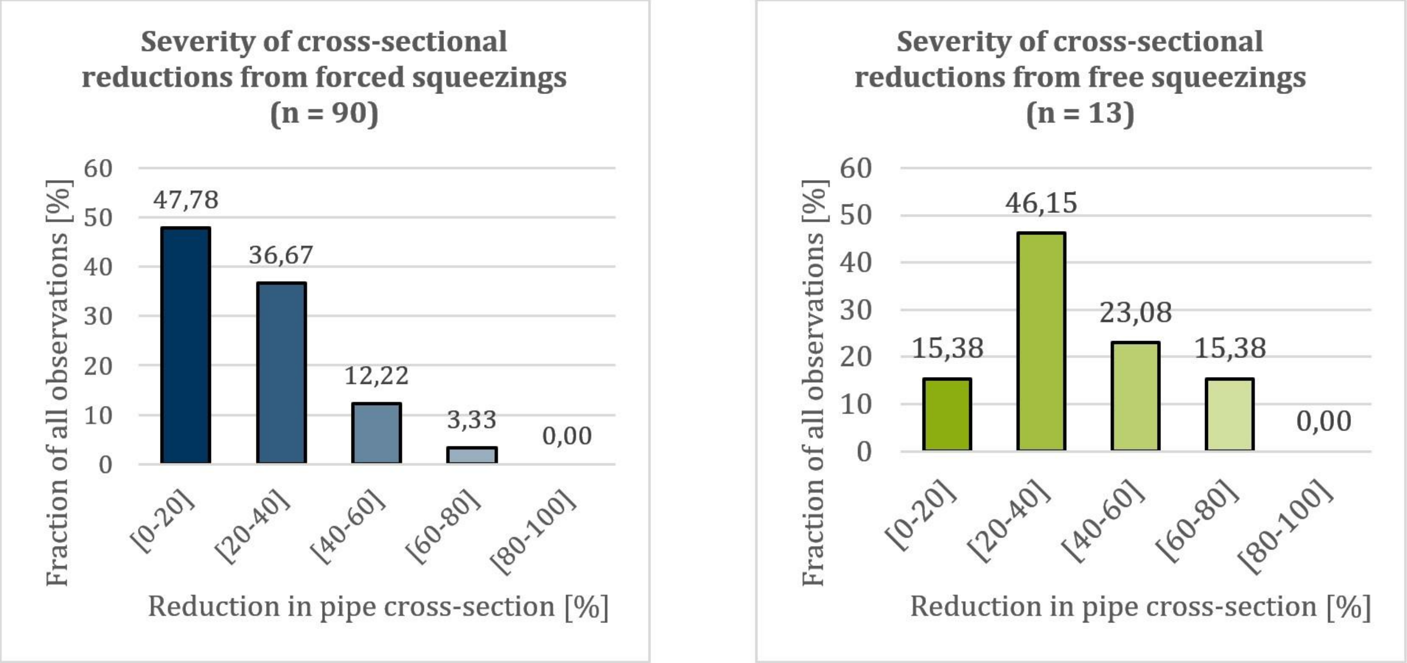

Figure 12: Histograms for the relative reduction in grouting pipe diameters observed for forced and free squeezes

Figure 12 therefore shows examples of the histograms of the relative number of observations for the different severity groups in histograms for the impairment types ‘forced squeezes’ and ‘free squeezes’, which occurred most frequently in the study described (see Section 4.2.2) alongside the bends that cannot be quantified here. For these types of impairment, the majority of the individual observations that occurred resulted in only a relatively small cross-sectional restriction of up to 40%.

Future studies will have to assess how this distribution manifests for other types of impairment and, in particular, how severely the relative cross-sectional reduction effectively impairs the functionality of a grouting device.

5. SUMMARY OF THE STATISTICAL ANALYSIS

The presented video examination of 179 grouting devices of the WLC revealed a total impairment density of 1.72 1/m, with forced squeezes (44.8%) and bends (38.5%) dominating. The video-based analysis provides quantitative insights into their sub-sectional and temporal distribution as well as the vulnerability of different pipe systems for the first time.

The analysis shows clear differences between the various areas of the tunnel cross-section. For example, despite the highest absolute number of impairments (49.5%), the standardised density of all impairments in the invert was 0.96 1/m – which can be attributed, among other things, to long pipe lengths (between 3 and 6 m). In the crown, on the other hand, the absolute number of impairments was lowest (12.6%), while the highest density of impairments (2.69 1/m) was found here in relation to the pipe length examined. This may be due to short pipe lengths (~ 1.5 m) and mechanical stress during the placing of the concrete. The combination of intermediate impairment numbers (37.9%) and intermediate density (1.56 1/m) for the side wall sub-section results from the complex hose routing through the reinforcement.

A comparison before and after placing the concrete in the side walls and the crown reveals effects of the concreting process, particularly in the following examples:

Collapsed bends show an increase in density of more than 200% (from 0.05 to 0.16 1/m). This development could be explained by movements of the formwork unit and concrete pressure. Furthermore, the occurrence of bends showed an increase of 72% (from 0.47 to 0.81 1/m) after placing concrete. This can possibly be attributed to hose displacement during the concreting process because of loose positional securing.

Ingresses of concrete or cement paste are naturally only detectable after the concrete has been placed, but in comparison they still have the third highest density (0.23 1/m), which indicates leaks in the rock-side closure. The presence of water in more than half of the grouting devices after the concrete was placed indicates that, in the case of crown gap grouting, which was not carried out here due to systematic block backfilling, significantly more paste could have penetrated the grouting devices and clogged them.

The impairments observed when comparing the different hose systems show clear differences between the systems. The corrugated pipes examined showed the lowest overall density (1.32 1/m) but are susceptible to bending (1.20 1/m). Fabric hoses show the highest density (2.83 1/m), mainly due to concrete or cement paste ingress (0.88 1/m) and forced crushing (1.06 1/m). The intermediate impairment density (1.82 1/m) was observed for spiral hoses. This is characterised by bends (0.68 1/m) and forced squeezes (0.84 1/m).

These results lead to the hypothesis that material stiffness may be a key factor in susceptibility to impairment. The fact that spiral hoses and corrugated pipes show many bends but few other impairments contrasts with the observations for fabric hoses, which show few bends but numerous other impairments. This could indicate that corrugated pipes and spiral hoses are able to bend around reinforcement bars and other embedded components of the final lining due to their structure, while fabric hoses tend to collapse when they come into contact with such embedded components, resulting in collapsed bends and forced squeezes.

Further evaluations are urgently needed with regard to the effects of the observed impairments. Although the majority of the observed impairments only result in minor reductions in the cross-section, it is questionable whether this trend also extends to all other impairments, as is the case with forced and free crushing, particularly with regard to the ingress of concrete and cement paste and hose peeling. Further investigations into this are already ongoing.

6. CONCLUSIONS

The main lesson to be learned from the Wendlingen Large Curve project is that the reliability of grouting devices can be ensured with careful installation. This is illustrated by the high proportion of more than 99% of potentially activatable grouting devices.

Despite the high activatability and qualified installation of the grouting system, the field study at the WLC revealed impairments to the system that are consistent with the findings of previous tunnel projects. Based on a field study using a videoscope, it was found that bends, forced squeezes and the ingress of concrete and cement paste into the grouting pipes were identified as numerically significant impairments. A negative influence of placing concrete in the functionality of the grunting pipes could also be demonstrated for individual types of impairment. However, an assessment of the severity of these impairments shows that the impairments observed mainly cause minor reductions in the pipe cross-section. A more detailed analysis of these observations according to the individual types of impairment and their actual impact on the functionality of the system is already being carried out.

Furthermore, during the project, different components of the grouting system were tested on selected sections of the cross-section and analysed for possible weak points in order to compare the functionality of the respective system types. Spiral hoses, fabric hoses and corrugated pipes were installed. In summary, the corrugated pipes can be described as the most robust variant and are recommended for future projects. Fabric hoses, on the other hand, performed the least well. These findings indicate that the grouting system is still at a moderate stage of development and that there is a need to increase its robustness, which means that further research is required.

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MÄHNER, Dietmar, Felix BASLER, and Laurenz BECKMANN-WÜBBELT. Longitudinal

Christian Rhein, M.Sc.
Institute for Tunnelling and Construction Management, Ruhr University Bochum, Bochum, Germany
Christian.Rhein@ruhr-uni-bochum.de

Dipl.-Ing. Hendrik Schälicke
Prof. Dr.-Ing. Kirschke GmbH & Co. KG, Ettlingen, Germany
Schaelicke@prof-kirschke.de

Dr. Carles Camós-Andreu
Prof. Dr.-Ing. Kirschke GmbH & Co. KG, Munich, Germany
Camos@prof-kirschke.de

Dipl.-Ing. Andreas Decker
Ed. Züblin AG, IU – Tunnel Construction Division, Stuttgart, Germany
Andreas.Decker@zueblin.de

Dipl.-Ing. Thomas Christoph
DB, Technical Project Management Wendlingen-Ulm (I.GT(5)), Stuttgart, Germany
Thomas.Christoph@deutschebahn.com

Dr.-Ing. Götz Vollmann
Institute for Tunnelling and Construction Management, Ruhr University Bochum, Bochum, Germany
Goetz.Vollmann@ruhr-uni-bochum.de

Prof. Dr.-Ing. Markus Thewes
Institute for Tunnelling and Construction Management, Ruhr University Bochum, Bochum, Germany
Markus.Thewes@ruhr-uni-bochum.de